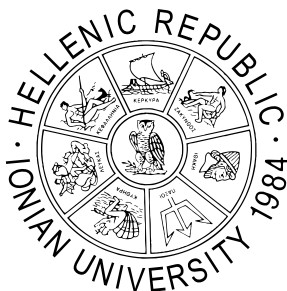


IONIAN UNIVERSITY

**Faculty of Information Science
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Ph.D. Thesis

Performance Enhancement on Topology-Transparent
TDMA MAC Policies for IoT Environments

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Abstract

We are living in the age of the Internet of Things, where millions of devices of different characteristics are connected to some kind of network and this number is growing rapidly. Some of these networks consist of nodes characterized by high mobility and in geographical areas where there is no centralized infrastructure to support their operation. Therefore, participating nodes must rely on suitable protocols which will allow them to communicate with each other without relying on centralized coordination. In addition, the applications running on the nodes may be numerous and with diverse, often conflicting, requirements in terms of network performance. In order for the underlying network to be able to support these applications, new medium access control protocols need to be designed and implemented, as existing ones are often unable to satisfactorily meet their requirements.

A protocol class that may be suitable for some applications is the class of topology-transparent TDMA protocols which, as their name implies, remain unaffected by topology changes due to node mobility. Their main advantage lies in the fact that when the neighborhood of a particular node changes, there is no need for re-calculation of the set of time-slots in which transmissions are allowed, thus eliminating a major disadvantage of the TDMA protocols, especially when they are implemented in a distributed network environment. However, this advantage comes with the trade-off of allowing packet collisions among the nodes, something that is usually not the case under traditional TDMA protocols. Moreover, another disadvantage of this class of protocols, is their relatively low throughput performance.

In this thesis, a study of existing topology-transparent TDMA medium access policies is presented. Subsequently, new policies are proposed which extend the existing ones in order to improve their performance. Initially, the Deterministic Policy, the first topology-transparent TDMA policy ever proposed, is implemented and evaluated in vehicular network scenarios, in order to demonstrate that such poli-

cies are indeed suitable to networks where their topology changes rapidly. Comparisons through simulations are conducted with another TDMA policy which has been specifically designed for vehicular networks but follows a more traditional method of allocating time-slots to nodes, i.e. taking into account the time-slots in which neighboring nodes are transmitting and recalculating the corresponding sets in a distributed manner when necessary.

Subsequently, two new policies are proposed which extend existing ones and aim to improve on their performance, but each one follows a different approach. The first approach is based on another existing TDMA topology-transparent policy, the Probabilistic Policy, which allows nodes to transmit during all non-assigned time-slots (in addition to their assigned time-slots) but under probability p . In the proposed policy, information from the immediate neighborhood of each node is used in order to identify time-slots during which, if a transmission takes place, it is almost certain that a packet collision will occur. This information is exploited in such way that each node eventually transmits probabilistically only in a subset of its non-assigned time-slots instead of all of them. It is shown that the proposed policy improves throughput when compared to that of the Probabilistic Policy, while at the same time fewer messages have been transmitted in total.

The second approach is based on another topology-transparent TDMA policy, the Adaptive Policy, which allows nodes to transmit in any particular non-assigned time-slot with probability $p = 1$, as long as the previous transmission during this slot was successful and until an unsuccessful one occurs. In the proposed policy each node again exploits information from its neighborhood and uses a selected fairness metric as feedback with the purpose of adjusting the transmission probability value in non-assigned time-slots. The decision for this adjustment is based on whether the node feels that has been treated fairly or not, when compared to its neighboring nodes.

Finally, an implementation of the Deterministic Policy in a real network consisting of low-cost devices is presented in order to evaluate the potential of applying similar policies in corresponding environments. It is shown that, despite the additional issues introduced by the transmission medium on a low-cost network, the implemented policy performs within the expected specifications.

Περίληψη

Ζούμε στην εποχή του Διαδικτύου των Πραγμάτων, όπου εκατομμύρια συσκευές διαφορετικών χαρακτηριστικών συνδέονται σε κάποιο δίκτυο και ο αριθμός αυτός αυξάνεται με γρήγορους ρυθμούς. Μερικά από αυτά τα δίκτυα αποτελούνται από κόμβους που χαρακτηρίζονται από υψηλή κινητικότητα και σε γεωγραφικές περιοχές όπου δεν υπάρχει κεντρική υποδομή για την υποστήριξη της λειτουργίας τους. Επομένως, οι συμμετέχοντες κόμβοι πρέπει να βασίζονται σε κατάλληλα πρωτόκολλα που θα τους επιτρέπουν να επικοινωνούν μεταξύ τους χωρίς να βασίζονται σε κεντρικό συντονισμό. Επιπλέον, οι εφαρμογές που εκτελούνται στους κόμβους μπορεί να είναι πολυάριθμες και με διαφορετικές, συχνά αντικρουόμενες, απαιτήσεις όσον αφορά την απόδοση του δικτύου. Προκειμένου το υποκείμενο δίκτυο να μπορεί να υποστηρίξει αυτές τις εφαρμογές, πρέπει να σχεδιαστούν και να εφαρμοστούν νέα πρωτόκολλα ελέγχου πρόσβασης μέσου, καθώς τα υπάρχοντα συχνά δεν μπορούν να ανταποκριθούν ικανοποιητικά στις απαιτήσεις τους.

Μια κλάση πρωτοκόλλων που πιθανώς να είναι κατάλληλη για ορισμένες εφαρμογές είναι η κατηγορία πρωτοκόλλων TDMA διάφανων της τοπολογίας τα οποία, όπως υποδηλώνει το όνομά τους, παραμένουν ανεπηρέαστα από αλλαγές τοπολογίας λόγω της κινητικότητας των κόμβων. Το κύριο πλεονέκτημά τους έγκειται στο γεγονός ότι όταν αλλάζει η γειτονιά ενός συγκεκριμένου κόμβου, δεν υπάρχει ανάγκη για εκ νέου υπολογισμό του συνόλου των χρονοθυρίδων στις οποίες επιτρέπονται μεταδόσεις, εξαλείφοντας έτσι ένα σημαντικό μειονέκτημα των πρωτοκόλλων TDMA, ειδικά όταν αυτά υλοποιούνται σε κατανεμημένο περιβάλλον δικτύου. Ωστόσο, αυτό το πλεονέκτημα έρχεται με την απαίτηση να επιτρέπονται συγκρούσεις πακέτων μεταξύ των κόμβων, κάτι που συνήθως δεν συμβαίνει στα παραδοσιακά TDMA πρωτόκολλα. Επιπλέον, ένα άλλο μειονέκτημα αυτής της κατηγορίας πρωτοκόλλων, είναι η σχετικά χαμηλή ρυθμικόδοση.

Σε αυτή τη διατριβή, παρουσιάζεται μια μελέτη υφιστάμενων TDMA πολιτικών

πρόσβασης μέσου διάφανων της τοπολογίας. Στη συνέχεια προτείνονται νέες πολιτικές που επεκτείνουν τις υπάρχουσες με στόχο τη βελτίωση της απόδοσής τους. Αρχικά, η Ντετερμινιστική Πολιτική, η πρώτη TDMA πολιτική διάφανη της τοπολογίας που προτάθηκε, εφαρμόζεται και αξιολογείται σε σενάρια δικτύων οχημάτων, προκειμένου ναδειχθεί ότι τέτοιες πολιτικές είναι πράγματι κατάλληλες για δίκτυα όπου η τοπολογία τους αλλάζει με γρήγορους ρυθμούς. Πραγματοποιούνται συγκρίσεις μέσω προσομοιώσεων με μια άλλη πολιτική TDMA που έχει σχεδιαστεί ειδικά για δίκτυα οχημάτων, αλλά ακολουθεί μια πιο παραδοσιακή μέθοδο κατανομής χρονοθυρίδων σε κόμβους, δηλαδή λαμβάνοντας υπόψη τις χρονοθυρίδες στις οποίες εκπέμπουν οι γειτονικοί κόμβοι και επανυπολογίζοντας τα αντίστοιχα σύνολα με κατανεμημένο τρόπο όταν είναι απαραίτητο.

Στη συνέχεια, προτείνονται δύο νέες πολιτικές που επεκτείνουν τις υπάρχουσες και στοχεύουν στη βελτίωση της απόδοσής τους, αλλά η καθεμία ακολουθεί διαφορετική προσέγγιση. Η πρώτη προσέγγιση βασίζεται σε μια άλλη υπάρχουσα πολιτική TDMA διάφανη της τοπολογίας, την Πιθανοτική Πολιτική, η οποία επιτρέπει στους κόμβους να εκπέμπουν κατά τη διάρκεια όλων των μη ανατεθειμένων χρονικών θυρίδων (επιπλέον των χρονοθυρίδων που τους έχουν ανατεθεί) αλλά με πιθανότητα p . Στην προτεινόμενη πολιτική, οι πληροφορίες από την άμεση γειτονιά κάθε κόμβου χρησιμοποιούνται για τον εντοπισμό χρονοθυρίδων κατά τις οποίες, εάν λάβει χώρα μια μετάδοση, είναι σχεδόν βέβαιο ότι θα προκύψει σύγκρουση πακέτων. Αυτή η πληροφορία αξιοποιείται με τέτοιο τρόπο ώστε κάθε κόμβος να εκπέμπει τελικά με πιθανότητα μόνο σε ένα υποσύνολο των μη ανατεθειμένων χρονοθυρίδων αντί για όλες. Δείχνεται ότι η προτεινόμενη πολιτική παρουσιάζει βελτιωμένη απόδοση σε σύγκριση με αυτή της Πιθανοτικής Πολιτικής, ενώ ταυτόχρονα μεταδίδει λιγότερα μηνύματα συνολικά.

Η δεύτερη προσέγγιση βασίζεται σε μια άλλη πολιτική TDMA διάφανη της τοπολογίας, την Προσαρμοστική Πολιτική, η οποία επιτρέπει στους κόμβους να μεταδίδουν σε οποιοδήποτε συγκεκριμένη μη ανατεθειμένη χρονοθυρίδα με πιθανότητα $p = 1$, εφόσον η προηγούμενη μετάδοση κατά τη διάρκεια αυτής της χρονοθυρίδας ήταν επιτυχής και μέχρι να προκύψει κάποια αποτυχημένη. Στην προτεινόμενη πολιτική, κάθε κόμβος εκμεταλλεύεται ξανά πληροφορίες από τη γειτονιά του και χρησιμοποιεί μια επιλεγμένη μετρική δίκαιης μεταχείρισης ως ανατροφοδότηση με σκοπό την προσαρμογή της τιμής πιθανότητας μετάδοσης σε μη ανατεθειμένες χρονοθυρίδες. Η απόφαση για αυτήν την προσαρμογή βασίζεται στο κατά πόσο ο κόμβος αισθάνεται ότι έχει αντιμετωπιστεί δίκαια ή όχι, σε σύγκριση με τους γειτονικούς του κόμβους.

Τέλος, παρουσιάζεται μια εφαρμογή της Ντετερμινιστικής Πολιτικής σε ένα πραγματικό δίκτυο που αποτελείται από συσκευές χαμηλού κόστους προκειμένου να αξιολογηθεί η δυνατότητα εφαρμογής παρόμοιων πολιτικών σε αντίστοιχα περιβάλλοντα. Παρουσιάζεται ότι, παρά τα πρόσθετα προβλήματα που εισάγονται από το μέσο μετάδοσης σε ένα δίκτυο χαμηλού κόστους, η εφαρμοζόμενη πολιτική λειτουργεί εντός των αναμενόμενων προδιαγραφών.

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Contents

A	Introduction	1
A.1	The Internet of Things (IoT)	2
A.2	Ad hoc networks and IoT	2
A.3	Medium Access Control challenges in IoT environments	3
A.4	Selecting a channel access scheme	5
A.5	Past Related Work	9
A.6	Contribution	16
A.7	Thesis Structure	18
B	Introduction to Topology-Transparent TDMA Policies	21
B.1	Useful Elements of Galois Field Theory	22
B.2	Topology-Transparent Policies Based on Galois Field Theory	23
B.2.1	The Deterministic Policy	23
B.2.2	Examples of networks operating under the Deterministic Policy	25
B.2.3	The Probabilistic Policy	32
B.2.4	The Adaptive Policy	32
C	Topology-Transparent Policies in Vehicular Networks	35
C.1	Vehicular Network Characteristics	35
C.2	VeMAC Description	37
C.3	Performance Evaluation	39
C.3.1	Network Topology, Traffic Characteristics and Evaluation Parameters	40
C.3.2	Simulation results for TiMAC vs. VeMAC	41

C.4	Conclusions	54
D	The Refined Policy	56
D.1	The Refined Policy	57
D.1.1	A frame example	58
D.1.2	Definitions	59
D.1.3	Set examples	60
D.2	Analysis of the Refined Policy	62
D.2.1	Throughput	62
D.3	The Individual Access Probability	65
D.4	Performance Evaluation	69
D.4.1	Experimental setup	70
D.4.2	Simulation results for RGG and SRGG topologies	71
D.4.3	Simulation results for regular topologies	75
D.4.4	Simulation results for various RGG topologies	76
D.5	Discussion and Conclusions	79
E	The Fairness-Aware Policy	83
E.1	Fairness Issues	84
E.2	Fairness Evaluation Metrics	86
E.2.1	The Jain's Index	86
E.2.2	The Envy Metric	86
E.3	The Fairness-Aware TDMA MAC Policy	88
E.4	Performance Evaluation	89
E.4.1	Evaluation Metrics	90
E.4.2	Throughput Evaluation	92
E.4.3	Network Fairness	92
E.4.4	Fairness and Maximum Number of Re-transmissions per Node	93
E.4.5	A Fairness Evaluation of the Refined Policy	95
E.5	Discussion and Conclusions	101
F	Low-cost Device Implementation of a Topology-Trans-	
	parent Policy	105
F.1	The Proposed System	105

F.1.1	Low-cost devices	106
F.1.2	Message types	108
F.1.3	TDMA parameters	108
F.1.4	Synchronization	109
F.2	Experimental Methodology & Results	110
F.2.1	Methodology	111
F.2.2	Results	112
F.3	Discussion and Conclusions	113
G	Conclusions and Future Work	116
G.1	Summary and Conclusions	116
G.2	Future Work Directions	118
	Appendices	138
I	Comparison Figures - Fairness	139
II	The OMNeT++ Discrete Event Simulator	145
III	Publication Table	152
IV	Glossary	154
V	Notations	157
VI	Abbreviations	161
VII	Index	163

List of Figures

B.1	The TDMA frame for every node in a network of $N = 25$ maximum nodes and $D = 4$ maximum neighbors operating under the Deterministic Policy. Each node has been assigned a unique polynomial and based on this polynomial a unique time-slot allocation has been derived.	27
B.2	An example of an ad hoc network.	28
B.3	A scenario with a frame of five random polynomials. Two different transmissions are depicted. Slots where a successful transmission takes place are marked with S and time-slots where transmissions collide and fail are marked with F. The $22 \rightarrow 4$ transmission succeeds in two out of five time-slots that takes place while the $0 \rightarrow 4$ transmission succeeds in four out of five time-slots.	28
B.4	A worst case scenario where each node may have only one successful transmission per frame. The corresponding time-slots where those transmissions take place are marked with S.	29
B.5	A best case scenario where the combination of polynomials provides a collision-free schedule. All 25 transmission attempts will succeed. .	30
B.6	In this scenario every possible collision takes place in the same time-slot. This leaves room for 20 out of 25 transmission attempts to be successful. The corresponding time-slots where those transmissions take place are marked with S.	30
C.1	Time-slot re-assignment under VeMAC.	38
C.2	Throughput as a function of traffic load for the highway (a) and the urban (b) vehicular environment for both VeMAC and TiMAC. . . .	42

C.3	Throughput as a function of traffic load for various common vehicle speed scenarios in highway environment for both VeMAC and TiMAC.	43
C.4	Throughput as a function of traffic load for various common vehicle speed scenarios in urban environment for both VeMAC and TiMAC. .	43
C.5	Throughput as a function of traffic load for random vehicle speed scenarios in urban and highway environments for both VeMAC and TiMAC.	44
C.6	Average value of maximum re-transmissions per node as a function of traffic load for both the highway and urban vehicular environments for both VeMAC and TiMAC with vehicles moving with randomly assigned speeds.	45
C.7	Average value of maximum re-transmissions per node as a function of traffic load for all vehicle speed scenarios in highway environments for both VeMAC and TiMAC.	46
C.8	Average value of maximum re-transmissions per node as a function of traffic load for highway scenarios and for random vehicle speeds and common vehicle speeds of 72km/h.	47
C.9	Average value of maximum re-transmissions per node as a function of traffic load for all vehicle speed scenarios in urban environments for both VeMAC and TiMAC.	48
C.10	Average value of maximum re-transmissions per node as a function of traffic load for urban scenarios and for random vehicle speeds and common vehicle speeds of 36km/h.	49
C.11	Distribution of re-transmissions over nodes for both the highway and urban vehicular environments and traffic load 0.5 for both VeMAC and TiMAC.	49
C.12	Distribution of re-transmissions over nodes for various speed scenarios in the highway environment and traffic load 0.5 for both VeMAC and TiMAC.	50
C.13	Distribution of re-transmissions over nodes for various speed scenarios in the urban environment and traffic load 0.5 for both VeMAC and TiMAC.	51

C.14	Distribution of re-transmissions over nodes for the scenarios where vehicle speed is 72km/h for both VeMAC and TiMAC in Highway and Urban scenarios.	52
C.15	Distribution of re-transmissions over nodes for the scenarios where vehicle speed is 108km/h for both VeMAC and TiMAC in Highway and Urban scenarios.	52
C.16	Distribution of re-transmissions over nodes in the highway environment for various network traffic load values and for the scenarios where vehicle speed is random.	53
C.17	Distribution of re-transmissions over nodes in the urban environment for various network traffic load values and for the scenarios where vehicle speed is random.	53
D.1	The frame for an example line network of three nodes (a , b and c) as appears under the Deterministic, Probabilistic and Refined Policies. It consists of three subframes and there are three time-slots for each one (0-1-2 , 3-4-5 , 6-7-8, respectively). Time-slots marked (i) with X correspond to assigned time-slots; (ii) with p correspond to those non-assigned time-slots that a node transmits according to the access probability. Time time-slots left blank correspond to those that a node is never allowed to transmit.	58
D.2	Regular graph example with eight nodes and four neighbors per node.	61
D.3	The frame corresponding to the network of fig D.2. It is assumed that $q = 5$ and $k = 1$. Consequently, eight 1st degree polynomials with coefficients 0, 1, 2, 3 or 4 have been randomly assigned to the network nodes.	62
D.4	Throughput as a function of the access probability p for the Random Geometric Graph topology. The two vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput under common p , respectively. The two horizontal lines correspond to the individual access probability scenarios, $\hat{p}_1(u)$ and $\hat{p}_2(u)$. Confidence intervals are no greater than 2.5%.	72

- D.5 Throughput as a function of the access probability p for the Soft Random Geometric Graph topology. The two vertical lines correspond to $p = 0.7$ and $p = 0.8$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput under common p , respectively. The two horizontal lines correspond to the individual access probability scenarios, $\hat{p}_1(u)$ and $\hat{p}_2(u)$. Confidence intervals are no larger than 3.91%. 73
- D.6 The total number of transmissions as a function of the access probability p for the Random Geometric Graph topology. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput, respectively. Confidence intervals are no greater than 0.13%. 74
- D.7 Average number of successful transmissions for assigned and non-assigned time-slots per node per frame as a function of the access probability p for the Random Geometric Graph topology. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput, respectively. Confidence intervals are no greater than 3.5%. 75
- D.8 Average throughput of ten networks for a 18-regular graph topology. The magnifying glass depicts the largest throughput value under common access probability, compared to both individual access probability values. 76
- D.9 Throughput evaluation for a RGG network topology with the following parameters: $N = 961$, $D = 25$, $k = 1$, $q = 31$ 77
- D.10 Throughput evaluation for a RGG network topology with the following parameters: $N = 1681$, $D = 23$, $k = 1$, $q = 41$ 78
- D.11 Throughput evaluation a RGG network topology with the following parameters: $N = 1849$, $D = 25$, $k = 1$, $q = 43$ 78
- D.12 Throughput evaluation for a RGG network topology with the following parameters: $N = 2209$, $D = 24$, $k = 1$, $q = 47$ 79

E.1	Four nodes in a chain topology. The status of two consecutive frames of theirs under the adaptive policy is depicted underneath them, including the events that take place during the fourth time-slot. Nodes b , c and d transmit data packets to its neighbor node towards node a .	85
E.2	Throughput as a function of the transmission probability. The upper and lower bounds of 95% confidence interval do not exceed 3.29% of the average values	91
E.3	Jain's index as a function of transmission probability. The upper and lower bounds of 95% confidence interval are below 1% of the average values when transmission probability is within ± 0.03 of the value which achieves maximum throughput for each policy.	91
E.4	Individual envy per node as a function of maximum number of consecutive re-transmissions under the probabilistic policy. Pearson's coefficient $r = 0.5194$	93
E.5	Individual envy per node as a function of maximum number of consecutive re-transmissions under the adaptive policy. Pearson's coefficient $r = 0.5380$	94
E.6	Individual envy per node as a function of maximum number of consecutive re-transmissions under the fairness-aware policy. Pearson's coefficient $r = 0.5394$	94
E.7	Throughput of the Fairness-Aware Policy in comparison to the Refined Policy.	96
E.8	Total transmissions of the Fairness-Aware Policy in comparison to the Refined Policy.	97
E.9	Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with the individual access probability $\hat{p}_1$ case. Pearson's coefficient $r = 0.27$. .	98
E.10	Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with the individual access probability $\hat{p}_2$ case. Pearson's coefficient $r = 0.22$. .	99
E.11	Individual envy per node as a function of the number of neighbors per node under the Refined Policy operating with the individual access probability $\hat{p}_1$ case.	100

E.12	Individual envy per node as a function of the number of neighbors per node under the Refined Policy operating with the individual access probability $\hat{p}_2$ case.	101
E.13	Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with common access probability $p = 0.03$	102
E.14	Individual envy per node as a function of maximum number of consecutive re-transmissions for a K-18 regular graph network operating under the Refined Policy with common access probability $p = 0.03$. .	102
F.1	A device of the considered system enhanced with an LCD screen. . .	106
F.2	The wiring between the Arduino and the RF modules that implements the device for both transmission (i.e, Tx-module data connected to pin 12) and reception (i.e, Rx-module data connected to pin 12). The antenna (ANT) along with the power supply pins (i.e., GND and VCC) are also depicted.	107
F.3	The TDMA frame of the implemented MAC protocol. Each time-slot (ts_i) ends with the guard period (t_g). The synchronization time (st) along with the frame guard period (t_{fg}) are also depicted.	109
F.4	Illustration of the synchronization mechanism within a synchronization period (st), among nodes r , u and v connected in a chain topology. Nodes wait for a certain amount of time (i.e., t_{dr} , t_{du} and t_{dv} respectively) before transmitting the time remaining until the first time-slot (i.e., t_0 , t_1 and t_2 respectively). The internal clocks c_u , c_v along with the transmission time t_{tx} are also depicted.	110
F.5	Throughput corresponding to various polynomial sets. In all cases, the throughput lays between the expected maximum (i.e., 0.2) and minimum (i.e., 0.04) values.	113
F.6	Average number of successful transmissions per frame per node corresponding to various polynomial sets. In all cases, the number of successful transmissions is between the expected maximum (i.e., 5) and minimum (i.e., 1) values.	114
I.1	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 53)	140

I.2	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 253)	140
I.3	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 266)	141
I.4	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 271)	141
I.5	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 310)	142
I.6	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 450)	142
I.7	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 662)	143
I.8	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 795)	143
I.9	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 803)	144
I.10	Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 893)	144
II.1	The OMNeT++ Integrated Development Environment.	148
II.2	The OMNeT++ Graphical Runtime Environment.	150

List of Algorithms

1	The GRAND algorithm	25
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Chapter A

Introduction

OVER the last two decades, wireless networking technologies have seen significant growth. Advances in semi-conductor technology have allowed for manufacturing electronic devices of reduced size, increased performance and power efficiency. This fact propelled the incorporation of wireless capabilities to all kinds of devices that may be used in everyday life, thus leading to the age of the Internet of Things (IoT) [1]. It is estimated that by 2030 over 500 billion devices will be connected to the Internet and equipped with IoT modules that allow device-to-device communication [2], thus forming various types of networks, including networks that lack infrastructure (ad hoc networks). The conceived applications that those networks will be required to support are countless and include smart cities [3], smart homes [4], smart transportation [5], smart agriculture [6], pollution reduction [7] and more. It is evident that a large portion of the IoT devices that are going to be implemented for the aforementioned applications will be mobile, thus the need for various types of Mobile Ad hoc Networks (MANET) has emerged. Those networks will have to support applications of diverse requirements and characteristics and this fact makes their design even more challenging than it already was. This thesis focuses on medium access control (MAC) policies for ad hoc networks. Over the years, various such policies have been proposed, however they are not always able to meet the requirements of modern IoT applications, so either the existing ones have to be revisited and modified accordingly or new ones have to be proposed.

A.1 The Internet of Things (IoT)

The origins of the Internet of Things (IoT) can be traced back to the 80s when some university students added sensors to a drinks vending machine with the purpose of tracking its contents remotely [8]. The term itself was initially proposed in 1999 when the idea of incorporating RFID chips on products was conceived [9]. Since then, a multitude of IoT applications have been conceived and many of them are already operational or under implementation. As mentioned, smart transportation, waste management and pollution reduction applications are already present and contribute towards the realization of the smart cities vision [10]. Smart agriculture is another area which may benefit from IoT applications. Those include smart monitoring, smart water management, supply chain management and many more [6].

IoT applications in healthcare are also already present and include remote diagnosis [11], monitoring [12], medication dispensers [13] and more. Disaster relief is a case where an IoT application may prove crucial, since it is very possible that under those circumstances no communication network infrastructure will be operational so the ability of various personal devices to communicate directly with each other might prove life-saving [14]. Wireless Sensor Networks (WSN) is another major area of research with various possible applications. For example this kind of networks may be used in various environmental applications which, among many others, include forest monitoring for early fire detection [15], water and air quality monitoring [16] and toxic gas detection [17].

The various devices supporting those applications may either operate using some pre-existing communication network infrastructure or communicate directly with each other. It is also possible that both communication paradigms may coexist and serve different purposes [18]. For example, in a smart city, vehicles are expected to access various services through some network infrastructure but at the same time inter-vehicle communication may also be used to improve the passengers' safety [19].

A.2 Ad hoc networks and IoT

The communication network paradigm under which every node communicates with each other without using any network infrastructure is commonly known as an ad

hoc network . The phrase “ad hoc” originates from latin and means “for this situation/when necessary/when needed”. Hence, an ad hoc network is formed spontaneously, when the need arises for a group of network nodes to communicate with each other and there is no network infrastructure in the area [20]. The spontaneous nature of an ad hoc network does not usually allow for instant deployment of cabling between the participating nodes so such networks are usually formed among nodes equipped with some sort of wireless capability. Thus, an ad hoc network is usually a wireless ad hoc network and those two terms can be used interchangeably.

The origin of ad hoc networks dates back to the 70s where the US army developed technology which allowed communication between its mobile elements in a battlefield [21]. Today, as the Internet of Things has already affected almost every aspect of our life, some sort of ad hoc network may be used in various applications. Moreover, most of those applications incorporate mobile nodes, thus the creation of a mobile ad hoc network is required among them. Node mobility leads to frequent network topology changes and this adds additional challenges to the design and operation of an ad hoc network.

Wireless ad hoc networks can be categorized, based on their area of coverage [22], into Body Area Networks (BAN) [23], Personal Area Networks (PAN) [24], Wireless Local Area Networks (WLAN) and Wide Area Networks (WAN). A BAN is a network where the nodes are devices that are worn or carried by a person. A PAN extends the connectivity of a BAN so that those devices can communicate with devices a few meters away. A WLAN typically covers an area of a few hundred meters. It is similar to a wired LAN, but a WLAN may also be implemented in an ad hoc fashion. A WAN may cover a very large area and may include a large number of nodes. A typical example is a Vehicular Ad hoc Network (VANET) which includes all the vehicles of a city [25].

A.3 Medium Access Control challenges in IoT environments

As mentioned earlier in some IoT scenarios, if the environment lacks network infrastructure, ad hoc networks may provide the only means of communication among the network nodes. Since ad hoc networks are wireless by nature, nodes have to share

the air as a common communication medium to transmit their messages. This fact, together with the fact that there is no central authority to organize the network, constitutes the design of communication protocols in those environments a challenging task [26].

In a centralized network, when a node wants to send a message to a distant node, the message is usually submitted to a nearby access point and is delivered to the destination through the network infrastructure. In an ad hoc network, unless the destination is inside the communication range of the source node, the message has to follow a multi-hop path, where each node has the additional task to act as a router and forward the message down the path until it reaches its destination. How the path is created is crucial and many routing protocols have been proposed over the years specifically for ad hoc networks [27]. However, in a shared medium, even the 1-hop communication between two neighboring nodes is already a challenging task. Moreover, reliable communication between 1-hop neighbors is the building block of a successful multi-hop communication. The OSI Layer responsible for the delivery of messages to 1-hop neighbors is the Data Link Layer which is basically divided into the MAC and LLC sub-layers [28]. Of the two, the MAC layer is assigned the task of controlling access to the physical medium. Since the medium used in ad hoc networks adds many challenges as already mentioned, the design of reliable medium access control policies in such environments is usually a difficult task.

MAC policy design for ad hoc networks has always been a challenging issue and various MAC policies have been proposed over the years for those environments. However, the diversity of the conceived IoT applications has created the need for new policies that will be more suitable to meet those requirements or for the existing ones to be improved, especially in scenarios where nodes demonstrate high mobility [29]. Depending on the application, various demands may have to be met when a new MAC policy is designed.

Network throughput is usually one of the most important factors to be considered. It is an important evaluation metric when designing or comparing MAC policies. Throughput represents the number of messages or data packets that are successfully transmitted in a given time interval. In an environment where the communication medium is shared among the nodes, throughput is expected to be relatively low because only one node may transmit if the transmission is to be successful. Throughput is also affected by the number of nodes that compete for access

to the medium because as data traffic increases collisions are more likely to occur.

Another important factor to be considered is the delay of the transmitted messages. From the moment a message is created, there are many factors which can add an amount of time to the total time needed until this message is successfully delivered to its destination. For example, when a message is created, it is usually added to a queue. Depending on the length of the queue, a corresponding delay occurs. Another reason for increased delays is the collision of messages within the shared medium. If there is the need for re-transmitting failed messages, then the time before the successful delivery of every message waiting in the queue increases.

Energy consumption may be a major consideration when designing a MAC policy. This is especially true in those IoT environments where the nodes have limited power sources. Some MAC policies are considered more energy consuming than others. For example, contention-based techniques where the nodes listen to the medium prior to transmitting consume more energy due to increased antenna activity. Moreover, when collisions occur and messages have to be re-transmitted, additional energy is consumed.

Another factor for consideration is that nodes must be treated fairly. This usually implies that nodes must have equal chance of accessing the medium when needed. If a considerable amount of time has passed and a particular node could not access the medium because it was busy, while at the same time other nodes were transmitting as expected, then it is considered that the former node is treated unfairly. This fact may be unacceptable for applications that have low delay requirements.

A.4 Selecting a channel access scheme

When designing a MAC policy, the first major decision is the selection of a channel access scheme. Contention based schemes like Carrier Sense Multiple Access (CSMA) are very popular in wireless networks [30]. In terms of throughput, they perform better when the network is sparse or the traffic load is low as there are not many nodes to compete for access to the medium [31]. They are easier to implement as no scheduling mechanisms are needed and no synchronization among the nodes is necessary [31]. On the other hand, energy consumption can be a problem given that, as already mentioned, nodes have to listen to the medium frequently prior to transmitting and re-transmit frequently due to message collisions [32]. The afore-

mentioned problems become even more evident as the network becomes denser and the traffic load increases. Another problem of contention based schemes is the fact that they cannot offer predictable delay boundaries [32], since from the moment a node has a message available for transmission, it is unknown when the channel will be free.

Another category of popular medium access schemes are the contention-free ones, Frequency Division Multiple Access (FDMA) being one of them. Under FDMA, the channel is divided in smaller channels with non-overlapping frequencies. To ensure that adjacent channels are not interfering with each other, guard bands are usually utilized between them. Then, two nodes must be synchronized to the same frequency before any transmission between them takes place. The frequency selection usually takes place with the use of a dedicated control channel and a synchronization algorithm is required for the nodes to exchange information there. Consequently, for an FDMA scheme to be implemented, complex hardware is required [33] which leads to increased energy consumption and high communication overhead [29].

Code Division Multiple Access (CDMA) is another contention-free scheme under which the nodes communicate through the same frequency and during the same time but each node uses a unique coding which allows for its messages to be distinguishable from other nodes' messages even when they are transmitted simultaneously. However, any two nodes have to agree upon a code before they are able to communicate, adding considerable overhead prior to transmissions [29], and time synchronization is also required among them [34]. Those problems are considered non-trivial in ad hoc networks, thus constituting the use of CDMA techniques in those environments a debatable subject [34].

Under Time Division Multiple Access (TDMA), time is split in frames and each frame in distinct time-slots and one or more of them are assigned to each network node. Then each node is allowed to transmit only during its assigned time-slots. This behavior allows for a fairer medium allocation when compared to contention-based policies [30]. Additionally, each node is guaranteed access to the medium after a predefined time interval and this leads to more predictable and time-bounded delays [29]. Another advantage of TDMA schemes is the reduced energy consumption [33]. Since each node is allowed to transmit only during its own time-slots, message collisions (thus re-transmissions) are minimized. Also, there is no need for listening to the medium prior to transmitting. On the downside, if TDMA is to operate prop-

erly, a careful time-slot allocation has to take place prior to the network's operation in a way that any pair of nodes able to interfere with each other's transmissions have no common time-slots assigned. This can be a difficult task even in a centralized topology, let alone in an ad hoc network. Moreover, when nodes are mobile, a time-slot re-allocation may be necessary and this adds additional overhead to the network operation [35]. Another problem of TDMA schemes is the need for clock synchronization among the nodes [36]. Every node must know exactly when each time-slot begins and ends or else there can be no communication in this manner. Finally, when the network is sparse or traffic load is low, throughput under TDMA is low because there are a lot of unused time-slots [30].

Despite the TDMA's drawbacks, the benefits are more than enough for the researchers to turn their attention towards creating or improving policies for IoT networks which are based on TDMA. For example, the energy efficiency provided by TDMA is essential on devices operating with limited power sources. Additionally, many applications have strict delay requirements which can also be met by a TDMA scheme. Regarding the clock synchronization, a solution might be available in specific scenarios. For example, in a VANET environment, if the vehicles are equipped with Global Positioning System (GPS) receivers, they can be provided the needed synchronization info [36].

To tackle with the time-slot re-allocation problem in network environments where nodes are mobile and the topology changes frequently, a number of TDMA topology-transparent scheduling algorithms has been proposed over the years. The purpose of those algorithms is to create a scheduling that is independent of the underlying topology. This means that each node is assigned a set of time-slots without taking into account the neighboring nodes' time-slot allocations. Consequently, it will not matter if the neighboring nodes change over time. Those algorithms guarantee a number of successful transmissions per node per frame, regardless of the underlying topology. However, this property comes with the trade-off of willingly allowing some packet collisions among the nodes, something not common under most TDMA schemes.

The study of existing TDMA topology-transparent policies and the proposal of new ones that improve on their predecessors is the main focus of this thesis. Specifically, TDMA topology-transparent policies based on Chlamtac-Faragò's seminal work [37] which introduced the idea of topology-transparent TDMA scheduling are

revisited here. Initially, this topology-transparent scheduling method as proposed in this work is incorporated in a MAC policy and this policy is evaluated in various VANET scenarios. Since VANET environments pose additional challenges due to the high mobility of the network nodes, the use of TDMA MAC policies which incorporate topology transparent scheduling might be a reasonable choice in applications where time-bounded delays are necessary, for example when a passenger safety related application needs to transmit a message to nearby vehicles as soon as possible. In a later section it will be shown that topology transparent policies might be a suitable candidate for VANET environments.

Additionally, two more TDMA topology-transparent policies (the Probabilistic Policy [38] and the Adaptive Policy [39]) are revisited which extend [37] and demonstrate improved throughput by allowing probabilistic transmissions during time-slots that have not been assigned to the nodes. However, those additional transmissions are the cause for increased collisions as well, thus leading to increased energy consumption. Furthermore, both policies require calculation of a suitable probability value, common to all nodes, prior to the network operation. Moreover, the Adaptive Policy is also shown to suffer from fairness issues. In later sections two new policies are proposed which extend the Probabilistic and the Adaptive Policy respectively and demonstrate improved performance while at the same time tackle their predecessors' aforementioned issues.

In the next section a literature review is presented which includes research areas closely related to the policies revisited or proposed in this thesis. The section begins with reviews of various TDMA MAC policies designed for VANET environments, followed by works which deal with the clock synchronization issue of TDMA. Subsequently, works related with fairness in wireless networks in general as well as in MAC protocols specifically are presented, followed by the presentation of policies which incorporate a probabilistic approach in their operation. Finally, existing topology-transparent policies are briefly described which are not based on Chlamtac-Faragò's aforementioned work [37] but instead propose alternative approaches for the creation of topology transparent schedules.

A.5 Past Related Work

Vehicular Networks

Vehicular networking has received a lot of attention in recent years. Several works address the problem of multiple access in those environments. TDMA-based approaches have recently gained a lot of attention [40], [41]. In particular, a novel time division MAC protocol is proposed in [41], called VAT-MAC, where the number of vehicles within a range is predicted in order to properly allocate the time-slots, avoiding collisions.

ATSA [42] is an adaptive TDMA protocol focusing on vehicular networks where sets of time-slots are formed depending on vehicles' directions. In this protocol, the frame length is dynamically adapted (shortened or doubled) in order to facilitate the optimal number of vehicles, aiming to reduce the probability of collisions. CFR in [43] tackles the problem of collisions and that of the hidden terminal by taking advantage of the driving status and traffic flow of each vehicle in the network in order to appropriately allocate time-slots. Another TDMA-based protocol is the self-organizing TDMA or STDMA [44]. Although limited to the highway case, it achieves some good results for various network densities by (re)allocating time-slots depending on the traffic load of the network. VeSOMAC is one of the first medium access protocols for inter-vehicular networks [45] [46]. It exploits the knowledge of vehicles' location and direction in order to minimize the delivery delay. VeSOMAC promises low-bounded time delay using an in-band control mechanism for exchanging TDMA frame information during the distributed MAC process.

One of the most eminent and widely used algorithms for vehicular networks is that of VeMAC [40], [47]. It is shown to outperform other known protocols, such as ADHOC MAC [26]. A more detailed description of VeMAC is presented in Section C.2 where it is also considered for evaluation against one of the policies that are proposed in this thesis.

The concept of splitting each frame in two disjoint sets is seen in [48], where each one is dedicated to a different vehicle direction. This solution is implemented in the control channel (CCH) of IEEE 802.11p [49]. Under this policy, nodes exploit their location in order to pick a time-slot, besides the appropriate sub-frame, thus improving their performance in terms of time delay. However, results on throughput are not considered.

Other works on TDMA-based policies for vehicular networks include the algorithms presented in [50], [51], [52], [53] (based on VeMAC), [54], [55], and [56]. Further detailed survey papers for in-depth analysis of particular MAC protocols, especially for problems related to vehicular networks and corresponding MAC policies, can be found in [29], [57], [58], [59] (dedicated to vehicle-to-vehicle communication), [60], and [18].

Fairness in Wireless Networks

Fairness in wireless networks is mostly attributed to resource allocation or sharing, its definition being rather difficult to be universally agreed, as each research topic is in need of a different approach. In addition, fairness can be tackled based on various perspectives, such as targeted or resultant fairness, short-term or long-term fairness, and system or individual fairness [61].

In terms of the amount of resources (e.g., time, throughput, etc.) that is allocated by each node, fairness can be further categorized to (i) absolute, where each node is allocated exactly the same amount of resources as any other node; and (ii) relative, where node requirements (for a resource) are taken into account; the latter categorization being extensively considered in bibliography (e.g., in [62] and more recently in [63]). Regarding absolute fairness, it is usually measured either by ‘Jain’s Index’, presented back in 1984 by Jain et al. [64], or by Shannon’s ‘Entropy’, which while it was not initially introduced for measuring fairness [65], it was later applied as such (e.g., in [66] and [67]). As for relative fairness, Radunovic and Le Boudec ‘Max-Min’ [68] has been widely implemented, along with ‘Proportional Fairness’ proposed by Kelly [69]. The measurement of the degree of individuals’ dissatisfaction regarding a resource allocation was considered in [70] as ‘envy’.

Most studies on fairness in wireless networks are based on the above metrics. In [71] Sangiamwong et al. adopt Jain’s Index considering throughput, input load and normalized throughput as allocated resources. Dianati et al. in [72] extend Jain’s Index by investigating the measurement of fairness and by proposing a new index to evaluate the degree of fairness for resource allocation schemes in wireless networks. Pham and Hwang in [73] approach the transmission power allocation in a way to maximize both energy and spectral efficiency by considering fairness at the same time. Zheng et al. in [74] show that the max-min fairness problem can be separated

into fairness sub-problems for flow rate and power control. In [75] two mechanisms are proposed taking into account fairness. The first one includes a data rate control scheme which considers fairness and throughput simultaneously while the second maximizes the total throughput by satisfying its fairness. Kalamkar et al. in [76] study fairness enhancement by (i) equal time allocation, (ii) minimum throughput maximization, and (iii) proportional time allocation revealing the trade off between throughput and fairness in wireless powered communication networks [77].

In [78] which extended [79], Guo et al. concentrate on fair time and power allocation in a wireless powered communication network where nodes transmit their information simultaneously. Three fairness criteria, named max-min, proportional and harmonic fairness, are considered there, while fairness among the energy levels of the users is also considered in [80] where a setup phase is described during which a transmitter broadcasts wireless energy to nodes. Proportional fair traffic splitting and aggregation in heterogeneous wireless networks is considered in [81], the same fairness metric being implemented in [82] where a radio resource block allocation optimization problem for cellular communications systems is presented.

Past work regarding fairness specifically in MAC protocols is presented next. In Sanabria's et al. work in [83], carrier sense multiple access with enhanced collision avoidance (CSMA-ECA) [84] is evaluated as a carrier sense multiple access with collision avoidance (CSMA-CA) extension for better short-term throughput fairness. The unfairness issue is resolved by allowing nodes to transmit more packets at once at higher backoff stages. Siddik et. al. in their recent work [63] propose a MAC protocol for vehicular ad hoc networks for speed-aware fairness. Each vehicle's velocity is considered for resolving fairness issues. A MAC protocol for 5G Cognitive Radio Ad Hoc Networks is given in [85] which considers fair data link allocation. This is achieved with the introduction of a revised RTS/CTS structure. In [86] the authors focus on designing a medium access control algorithm in multi-rate wireless local area networks for improving the efficiency and fair sharing of channel resources among the contending nodes. Their goal is achieved by setting each node's backoff counter to a deterministic value and allowing them to transmit multiple packets as soon as they successfully access the channel. A fairness-oriented MAC protocol for wireless local area networks is also given in [87] which under an enhanced virtual collision management mechanism, improves fairness of the Enhanced Distributed Channel Access (EDCA).

In [88] a TDMA based MAC protocol for underwater acoustic networks is proposed, which improves throughput at a small cost in fairness, revealing here that a trade-off might exist between them. In [89] the authors propose various TDMA policies for linear topologies in underwater acoustic networks while studying the impact of different fairness constraints to the network throughput. Finally, Sun et al. propose a joint non-orthogonal multiple access time division multiple access (NOMA-TDMA) scheme for Industrial Internet of Things (IIoT) which is shown to outperform traditional TDMA schemes in terms of both throughput and fairness.

Most of the presented past related work uses some fairness metric just for evaluation of the proposed schemes. It can also be seen that most of the work considering fairness, either studies it in a cross-layer optimization manner or is about CSMA-based policies while work studying fairness in TDMA policies is very limited. In Chapter E a TDMA-based topology-transparent MAC policy is proposed which uses a the earlier presented envy fairness metric [70] not only for evaluation but as feedback mechanism for dynamically changing the channel allocation among the network nodes.

Probabilistic Policies

While the main focus of most probabilistic-based works in the literature is on higher layers [90], the implementation of probabilistic approaches in MAC policies and transmission schemes has also been investigated over the past years. Regarding broadcast and flooding schemes for ad hoc networks, several schemes have been proposed [91]. It has been observed that those implementing a probabilistic approach are more suitable for most applications, due to a range of benefits they offer, such as low overhead, balanced energy consumption, and robustness against failures and mobility of nodes.

Probabilistic flooding [92], that bases packet broadcasting on a probability, has been the case for many works in the literature. For example, in [93] the authors present a probabilistic flooding variance that, based on an analysis on a proposed Markov chain, derives analytical expressions regarding the probability of a node to be operational or discharged.

Rahmati and Pompili in their work in [94] have studied the design of a MAC protocol based on a probabilistic Space Division Multiple Access (SDMA) method for

short/medium distances. This work is dedicated to the communication between Autonomous Underwater Vehicles (AUV) in underwater networks and provides, among others, a probabilistic time and space MAC scheme for the cases where the vehicles are non-spatially separable. Under this approach, clusters of those vehicles are formed and time sharing is applied to each cluster. Given a set of rules, the probabilities of each possible case are assigned. These probabilities will decide the next state of the vehicle.

In Zeng et al.'s work in [95], a probability-based multi-hop broadcast protocol is proposed to tackle reliability and latency issues. In this approach a higher forwarding probability is assumed for nodes farther from the source node by using a node's index number combined to other parameters.

A data dissemination approach based on clustering and probabilistic broadcasting has been proposed by Liu et al. in [96]. This work, targeting vehicular ad hoc networks, presented a clustering algorithm for the vehicles to exchange data. Then, after the clustering has taken place, a probabilistic forwarding approach is considered, under which each cluster member transmits to its cluster head with a calculated probability based on how often the same packet is received during a single interval. When receiving a packet, a cluster header further forwards it towards the final receiver.

Srivastava et al. in [97] proposed a probabilistic and beaconless algorithm. In this work, the forwarding probability of a packet is decided based on distance of nodes, angular orientation, movement direction and buffer load delay. This probability is then used to schedule the packet transmission, the packet holding the highest probability to also hold the highest priority.

A probabilistic MAC protocol has been proposed by Maliqi et al. in their work in [98]. There, relay operates under a demodulate-and-forward fashion. After simplifying the finite state Markov chain (FSMC) analysis of a deterministic protocol, then a probabilistic approach is considered that, based on two Bernouli distributed variables, decides whether a transmission will take place or not.

In [99], Liu et al. proposed a protocol for packet transmissions in IoT networks that, by exploiting local knowledge (i.e., nodes' neighbors), it prioritizes packet broadcasts according to their profits. The neighbor knowledge of nodes and a connectivity factor are the bases for calculating the probability that then determines whether a packet should be rebroadcasted to the neighboring nodes or not.

Chen et al. in [100] proposed a distributed full-duplex MAC protocol that enables an access point with the ability to switch between full-duplex and half-duplex mode. In this sense, a contention takes place among clients for accessing either full-duplex or half-duplex transmissions. This contention's outcome is determined by assigned probabilities that are calculated based on the clients' average traffic demands.

Dedicated to time division protocols, Gandino et al. in [101] presented a probabilistic alternative of Distributed Color System (DCS), earlier shown by Waldrop et al. in [102]. There, the proposed "reader-to-reader" protocol considers and theoretically studies a probability that is added to the initial Woldrop et al.'s idea, and is responsible for changing color (i.e., time-slots). In the same sense, Ferrero et al. in [103] implement the probabilistic method in the collision resolution routine of "Colorwave", showing the aspects of this approach for TDMA protocols.

In order to tackle the hidden terminal problem in two-hop IoT systems, Ye et al. in [104] proposed a MAC protocol that makes use of a time division multiple access logic for allocating time duration to nodes' groups. There, each group of nodes forms a token ring by adopting a probabilistic token passing scheme to distributively allocate time-slots for packet transmissions. The transmission time-slot allocation adapts to any changes on the number of nodes in the network.

Finally, Hu et al. in their work in [105] proposed a prediction-based TDMA protocol that is able to predict the network topology in the next frame in order to select the best node for a packet to be forwarded to. The latter selection is based on a probabilistic model discussed there that assigns the probabilities according to moving direction, speed and geographical location of nodes (vehicles in this case).

Topology-Transparent Policies

Regarding TDMA policies immune to the underlying topology, most works are based on the earlier mentioned Chlamtac and Faragó's original work [37] which is presented in detail in section B.2.1. In [106], Ju and Li propose an enhancement of the algorithm proposed in [37] which increases minimum guaranteed throughput with the trade-off of larger frame length.

Another independent approach for creating topology immune scheduling is Ju and Li's work in [107] where an algorithm based on latin squares is proposed. Their solution is suitable for multichannel systems.

In [108] Colbourn et al. formulate the problem of the creation of topology-transparent schedules as a combinatorial question and propose a solution based on Steiner systems. They conclude that their approach uses shorter frames for the same network parameters when compared to other solutions, thus improving delay and throughput for a given frame length but they also note that this approach is less robust to changes in neighborhood size and throughput degrades faster if D parameter is exceeded.

In [109] Xu et al. propose a scheduling algorithm based on balanced incomplete block design. They conclude that their algorithm is superior to [37] and [106] in terms of guaranteed throughput, minimum and maximum delay.

In Su and Yi-Sheng's work in [110] a scheme based on Chinese Remainder Theorem (CRT) is proposed. This scheme's main advantage is that it eliminates the requirement of knowing the maximum node degree D and only requires the maximum number of nodes N to be known. Additionally, the authors demonstrate that this scheme outperforms other schemes, especially in scenarios with harsh interference.

In [111] Qiao et al. extend [37] by employing learning-based approaches. The authors make use of artificial intelligence techniques for allocating time-slots to the nodes and utilizing unused time-slots, thus improving throughput.

In [112] Xiao et al. propose a topology-transparent scheduling scheme which uses polynomial rings. The proposed scheme improves on the theoretical bounds of maximum node degree with respect to the frame length, when compared to schemes based on the Chinese Remainder Theorem as well as to those based on Galois Fields. It is also shown that this scheme is a generic framework to policies based on both of the aforementioned schemes.

More recent works include [113] where Dash et al. propose a topology-transparent scheduling protocol for multi-hop wireless networks with MIMO-enabled transceivers and [114] where Deng et al. propose a combination sequence scheme and compare it with a Galois Field scheme and two schemes based on ALOHA and conventional TDMA respectively. The comparison is made with respect to delay constraints. The authors conclude that different schemes perform better depending on the network parameters.

Finally, in [115] Kar et al. present a survey of topology-transparent schemes. The authors analyze and discuss the various proposed schemes and a comparison

is made between them with respect to various evaluation metrics. Additionally, directions for possible future works are given. The authors conclude that if the proposed schemes are to be implemented in real wireless networks, the researchers should focus on optimizing the existing policies, turn them into full-fledged MAC protocols and test them in various scenarios.

Clock synchronization

GPS-based systems (or in general Global Navigation Satellite Systems - GNSS) is a well-established method to achieve time synchronization [116], [117], [36]. Meanwhile, they constitute a standard feature in modern vehicles, therefore their use in VANET infrastructures seems straightforward, e.g., for Basic Safety Messages (BSM) [118]. GPS as a source of time reference is discussed in [119], where the advantages of using GNSS for synchronization in VANETs are analyzed using the one-pulse-per-second (1PPS) signal method [120]. As discussed in [121], each 1PPS signal is considered as the reference instance of the start of a frame. Consequently, knowing the number of time-slots per frame, the number of frames per second, and the actual duration of a time-slot, each vehicle is able to detect the start time of a frame [122], [123]. Synchronization using GPS in TDMA application is also met in Automatic Identification Systems (AIS) [124] (see also in [125] for technical details regarding the actual implementation).

A.6 Contribution

In this thesis, existing TDMA topology-transparent policies for ad hoc networks are revisited and studied. Subsequently, new policies are proposed and existing ones are revisited, extended and their performance is improved in various aspects.

Initially, the Deterministic Policy is revisited with the purpose of evaluating its performance in VANET environments. Experiments through simulations are conducted in scenarios where the nodes are mobile vehicles in urban and highway environments. Additionally, a pre-existing and established TDMA MAC protocol, specifically designed for VANET environments, is also implemented and evaluated in the same scenarios with the purpose of comparing the Deterministic Policy with a policy that operates under a more traditional TDMA scheme. It is shown that

their throughput performance is comparable but the Deterministic Policy performs better in terms of delay.

The second revisited policy is the Probabilistic Policy. This policy, as already mentioned, improves on the Deterministic Policy in terms of throughput performance by allowing additional transmissions during the nodes' non-assigned time-slots under a common and fixed value of an access probability p . However, those additional transmissions cause additional collisions as well which in turn lead to increased energy consumption because the corrupted messages need to be re-transmitted. Furthermore, the fact that the value of the probability p has to be calculated and assigned to the nodes in a centralized manner and prior to the network operation is not suitable to the distributed nature of the network.

Motivated by the two aforementioned disadvantages of the Probabilistic Policy, a new policy is proposed, i.e. the Refined Policy, which extends it and improves its performance. Under the proposed policy, after utilizing information gained from the local neighborhood, nodes are able to identify time-slots which have been assigned to some neighboring node. Essentially, they become aware that if a transmission takes place during those time-slots, there is a high chance of collision, thus they refrain from transmitting during those time-slots. It is shown that under the Refined Policy throughput is improved when compared to the Probabilistic Policy, while at the same time the total number of transmitted messages is reduced, thus conserving energy.

An additional improvement proposed under the Refined Policy is the calculation of the access probability value in a distributed manner and while the network operates. As it is shown, this behavior increases throughput performance even more, while at the same time eliminating the need for calculation and assignment of a probability value prior to the network operation.

The third policy which is revisited in this work is the Adaptive Policy. Under this policy, system throughput is increased when compared to the Probabilistic Policy's throughput. However, as will be shown in the corresponding section, nodes are not treated fairly in terms of how often they are able to access the medium. Consequently, it is observed that some nodes monopolize the medium and manage to achieve very high throughput while at the same time there are nodes that experience increased collisions and need a lot of re-transmissions to deliver a message successfully.

Motivated by the Adaptive Policy's unfair behavior, the Fairness Aware Policy

is proposed. Under this policy, nodes become aware of their neighbors' performance. Possession of this knowledge allows each node to decide whether it has been treated fairly or not when compared to its neighbors. After this decision is made, each node adapts its transmission schedule accordingly with the purpose of achieving the best possible degree of fairness among itself and its neighbors. As will be shown, this behavior increases system throughput, when compared to the Probabilistic Policy's throughput, while at the same time preserving an acceptable degree of fairness among the network nodes.

Finally, an implementation of the Deterministic Policy on low cost devices is presented with the purpose of evaluating the policy in a real-world scenario. The policy is implemented in a small IoT network consisting of Arduino-based devices equipped with 433 MHz RF modules. Experiments are conducted which confirm the theoretical expectations of the Deterministic Policy, suggesting that topology-transparent policies may be considered when designing a MAC policy for IoT networks.

A.7 Thesis Structure

This thesis contains seven chapters. The first chapter contains introductory elements. The second one describes the topology-transparent policies revisited here. In the third chapter, one of the revisited policies is evaluated in various vehicular network scenarios. The fourth and fifth chapters present the two topology-transparent policies proposed in this thesis. The sixth chapter presents an implementation of a topology-transparent policy using low-cost devices. The seventh chapter contains the summary and conclusions of this thesis. Finally, some necessary appendices conclude the present work.

In Chapter B, elements of the Galois field theory are presented which form the basis of the Topology-Transparent Policies studied in this work. Then the Deterministic Policy as proposed by Chlamtac and Faragó's in [37] is described, followed by detailed practical examples. Finally, two extensions of the Deterministic Policy are described, the aforementioned Probabilistic Policy [38] and Adaptive Policy [39]. Those policies form the basis of two corresponding policies proposed in later chapters.

In Chapter C, the Deterministic Policy is incorporated in the proposed TiMAC protocol [126], [127]. Then, TiMAC's performance is evaluated in various VANET

network scenarios. The evaluation is conducted through simulations and TiMAC is compared against VeMAC [40], an established MAC protocol for vehicular networks.

In Chapter D, the Refined Policy is proposed [128], [129], [130]. This policy extends the Probabilistic Policy and improves on its performance in terms of throughput and energy consumption. The performance improvement under the Refined Policy is attributed to the fact that nodes are aware of its neighbors' time-slot assignments thus they are able to refrain from probabilistic transmissions in non-assigned time-slots that would take place in their neighbors' assigned time-slots.

In Chapter E, the Fairness-Aware Policy is proposed [131]. Under this policy, nodes make use of the envy [70] fairness metric to obtain feedback about the number of successful transmissions achieved by the nodes in the local neighborhood. Based on this feedback, nodes adapt the value of their transmission probability in non-assigned time-slots with the purpose of maintaining an acceptable level of fairness in medium sharing among the nodes. It is shown that, when compared to the Probabilistic Policy, throughput performance is increased while at the same time fairness is maintained in comparable levels.

In Chapter F an implementation of the Deterministic Policy is presented in a real-world network scenario consisting of nodes that are based low-cost electronic devices [132], [133]. Each one of those devices is based on an Arduino micro-controller and low cost transmitters and receivers. Although the network size and the quality of the electronic components introduce various limitations, the policy performance is shown to be within acceptable bounds, demonstrating the potential of using a topology-transparent scheme in low cost IoT networks.

Finally, in Chapter G the overall contribution of this thesis is summarized. Conclusions are drawn and directions for future research are discussed.

Chapter B

Introduction to Topology-Transparent TDMA Policies

IN this thesis, as already mentioned, existing TDMA topology-transparent Policies are revisited and new are proposed which improve on the existing ones. Every presented policy is based on Chlamtac and Faragó's original work [37]. This work utilizes properties of Galois Fields to propose an algorithm which allocates time-slots to the nodes in such way that no re-allocation is necessary when topology changes.

In this chapter, initially some useful elements of Galois field theory will be presented. Then, Chlamtac and Faragó's work [37] will be presented, which is also met in the literature as the *Deterministic Policy*, followed by the presentation of two existing policies that extend it, the *Probabilistic Policy* [38] and the *Adaptive Policy* [39]. Additionally, practical examples will be given, for the purpose of providing a better understanding of how the transparent scheduling works under specific network parameters. Finally, the revisited policies' disadvantages are described which constitute the motivation behind the current work and a short overview of the proposed solutions is presented.

B.1 Useful Elements of Galois Field Theory

In this section, some useful elements of Galois field theory will be presented, which constitute the basis of Chlamtac and Faragó's original work [37]. A deeper analysis of Galois field theory may be found in [134] and [135].

Definition 1 Let G be a set of elements and $\cdot$ a binary operation. G is called a group with respect to this binary operation if:

1. $(a \cdot b) \cdot c = a \cdot (b \cdot c), \forall a, b, c \in G$
2. An element e exists where $a \cdot e = a, \forall a \in G$
3. An element a^{-1} exists where $a \cdot a^{-1} = e, \forall a \in G$

The rules presented in 1 are called *the axioms of groups*. This group can also be denoted as $(G, \cdot)$. The $\cdot$ operation is called *multiplication* and $a \cdot b$ is called *the product* of a and b which can also be denoted simply as ab . In similar fashion, a group can also be defined with respect to a binary operation denoted as $+$. This group may also be denoted as $(G, +)$. The $+$ operation is called *addition* and $a + b$ is called *the sum* of a and b .

Examples of groups with respect to multiplication include the set of non-zero real numbers $\mathbb{R}^*$ and the set of non-zero rational numbers $\mathbb{Q}^*$. An example of a group with respect to addition is $\mathbb{Q}$.

Definition 2 Let G be a group and $\cdot$ a binary operation in G . If $a \cdot b = b \cdot a, \forall a, b \in G$ then G is called an *abelian group*.

Definition 3 If G contains an infinite number of elements, it is called an *infinite group*. If G contains a finite number of elements, it is called a *finite group*.

Definition 4 Let n be a positive integer. If $a^n \neq e$ stands for any n , then a is called an *element of infinite order*. If n can have such values that $a^n = e$, then a is called an *element of finite order* and the smallest of those values of n is called the *order* of a .

Definition 5 Let F be a set of elements and $\cdot, +$ two binary operations, called *multiplication* and *addition* respectively. F is called a *field* with respect to multiplication and addition if:

B.2. Topology-Transparent Policies Based on Galois Field Theory 23

1. $(F, +)$ is an abelian group
2. $(F^*, \cdot)$ is an abelian group and 0 is the zero of the group $(F, +)$
3. $a(b + c) = ab + ac, \forall a, b, c \in F$

The rules presented in 5 are called *the axioms of fields*. This field may also be denoted as $(F; +, \cdot)$. $(F, +)$ may be called the additive group of this field and $(F^*, \cdot)$ may be called the multiplicative group of this field.

The values $a+b$ and $a \cdot b$ are called *the sum* and *the product* of a and b respectively. The zero of the group $(F, +)$ is also the zero of the Field F .

Definition 6 *If F contains an infinite number of elements, it is called an infinite field. If F contains a finite number of elements, it is called a finite field of a Galois field.*

Let $\mathbb{Z}_q = \{0, 1, 2, \dots, q-1\}$. Let the binary operation $+$ be defined as $\text{mod}(q)$ of the addition of any two $a, b \in \mathbb{Z}_q$ and the operation $\cdot$ be defined as $\text{mod}(q)$ of the multiplication of any two $a, b \in \mathbb{Z}_q$. It can be proven [135] that for $\mathbb{Z}_q$ to be a field, q has to be a prime number or a prime number power.

In the next section it will be presented how the aforementioned elements of Galois field theory can be used for creating of topology-transparent TDMA schedules for an ad hoc network.

B.2 Topology-Transparent Policies Based on Galois Field Theory

B.2.1 The Deterministic Policy

The core idea behind the Deterministic Policy [37] is that each node is assigned a unique set of time-slots and is allowed to transmit during them without taking into account the neighboring nodes' time-slot assignments. Those assignments take place in such way that each node is ensured at least one successful transmission towards each one of its neighbors within every frame, regardless of which particular nodes are neighbors and even if all of them transmit every time they are allowed to.

The fact that the transmitting node is not interested in its neighbors' assignments constitutes this policy a topology-transparent one.

The first step towards setting up a network operating under the Deterministic Policy, is that each node u is assigned a unique random polynomial $f_u(x) = \sum_{i=0}^k a_i x^i$ where $a_i \in \{0, 1, 2, \dots, q-1\}$. The polynomial's coefficients (a_i) come from a finite Galois field of order q , where q is a prime number. Such a polynomial is uniquely associated with each node to derive its set of *assigned* time-slots Ω_u . Thus, each node is allowed to transmit during time-slot $i \in \Omega_u$, always assuming *heavy traffic load* in the sense that there are always data available for transmission. Apparently, it is not allowed to transmit during the *non-assigned* ones $i \notin \Omega_u$. The assigned polynomial may be seen as the unique ID of a network node that is already available before the network's operation.

The frame's length is fixed for all nodes and consists of q^2 time-slots. It is divided in q subframes s of equal length q . Each node u is assigned exactly one time-slot from each subframe s . The time-slot's position within each subframe s is given by $f_u(s) \bmod q$, where $s = 0, 1, \dots, q-1$. Consequently, $|\Omega_u| = q$. In [37] the algorithm 1 is introduced which accepts as input the network size N (total number of nodes) and the maximum node degree D (number of neighbor nodes) and derives the k and q parameters. Under algorithm 1, two conditions have to be satisfied. Firstly, there must exist enough unique polynomials for all nodes, so it must be satisfied that $q^{k+1} \geq N$. Secondly, there must be at least one time-slot for each possible transmission during which it will be successful. Let's suppose that node's u and node's v polynomials of degree k are equated, the new polynomial $f_u(s) \bmod q = f_v(s) \bmod q$ has at most k solutions, thus at most k common assigned time-slots exist among the two nodes. Since any node may have at most D neighbors, there can be at most kD time-slots where collisions may occur. Consequently, if $kD + 1$ time-slots are assigned to each node, there will be at least one successful transmission per time-slot. This is satisfied by the condition $q \geq kD + 1$.

Eventually, under the Deterministic Policy [37], it is guaranteed that every possible transmission will succeed at least once per frame regardless of the underlying topology.

Algorithm 1: The GRAND algorithm

```

1 Let  $q_1, q_2, q_3, \dots$  be the sequence of prime numbers or their powers;
2  $i \leftarrow 0$ ;
3 repeat
4    $i \leftarrow i + 1$ ;
5    $q \leftarrow q_i$ ;
6    $k \leftarrow \lfloor (q - 1)/D \rfloor$ ;
7 until  $k \geq 1$  and  $q^{k+1} \geq N$ ;

```

B.2.2 Examples of networks operating under the Deterministic Policy

Detailed examples of networks operating under the deterministic policy will be presented in this section, to provide a better understanding of how the parameters of this policy are calculated.

Let's assume a network of $N = 25$ nodes with a maximum number of neighbors $D = 4$. Let's also assume that $q_1, q_2, \dots$ to be the sequence of prime numbers or their powers, with the lowest of them being $q_1 = 3$. Using N and D as input, the Algorithm 1, which is called GRAND (Galois RAdio Network Design) and was proposed in [37], will execute. When it terminates, the values of $k = 1$ and $q = 5$ will have been calculated.

The value $k = 1$ defines that the polynomials which will be assigned to each node will be of 1^{st} degree, thus will be of the form $ax + b$. The value $q = 5$ defines that the polynomials' coefficients a and b will come from the Galois Field of order five, thus the only possible values for a and b can be any integer from the $[0, 4]$ interval. Additionally, the TDMA frame length will be $q^2 = 25$ time-slots, split into five subframes of five time-slots each.

The next step is the assignment of one polynomial to each node. The Algorithm 1 ensures that the number of polynomials is equal or greater to the maximum number of nodes. Consequently, each node will be assigned its own unique polynomial. Each polynomial corresponds to a unique set of time-slots within the TDMA frame. Every set of time-slots contains one time-slot from each one of the five subframes. For selecting the time-slot that will be assigned to each polynomial's corresponding

set, the number of the particular subframe must be set as the value of the x variable of the polynomial. Then, the solution of the polynomial gives the position of the time-slot that must be selected. Since the polynomials correspond to the Galois Field of order q , if the solution is equal or greater than q then the modulo q of the solution is used.

As an example, let's consider the polynomial $3x+4$. The corresponding positions of each time-slot selected from each subframe are calculated as follows:

- Subframe 0: $f(0) = (3 \cdot 0 + 4) \bmod 5 = 4 \bmod 5 = 4$
- Subframe 1: $f(1) = (3 \cdot 1 + 4) \bmod 5 = 7 \bmod 5 = 2$
- Subframe 2: $f(2) = (3 \cdot 2 + 4) \bmod 5 = 10 \bmod 5 = 0$
- Subframe 3: $f(3) = (3 \cdot 3 + 4) \bmod 5 = 13 \bmod 5 = 3$
- Subframe 4: $f(4) = (3 \cdot 4 + 4) \bmod 5 = 16 \bmod 5 = 1$

Fig. B.1 depicts the network nodes with their assigned polynomials and their corresponding time-slot allocations. To improve the readability of the depicted example, the polynomials have been assigned to the nodes in sequential order. However, this is not a requirement as the assignments may take place according to any procedure that is suitable to the particular application.

Now any five random nodes can be chosen as neighbors but it is guaranteed that even if they all transmit a message every time they are allowed to, there will be at least one time-slot within the frame where their transmission will be successful. To further demonstrate this, let's assume the network depicted in Fig. B.2 which is comprised of a selection of the nodes depicted in Fig. B.1. Let's consider the transmission $22 \rightarrow 4$. The nodes that are able to corrupt this transmission, provided they transmit at the same time, are nodes 0, 3, 19 and the receiver node 4 itself. Fig. B.3 depicts those nodes' frames. It can be observed that $22 \rightarrow 4$ will succeed in two out of the five total time-slots that is allowed to take place. It can also be observed in Fig. B.3 that the transmission $0 \rightarrow 4$ will succeed in four out of the five total time-slots.

As already mentioned, the Deterministic Policy guarantees that each particular transmission will be successful at least once per frame. As was observed in Fig. B.3,

B.2. Topology-Transparent Policies Based on Galois Field Theory 27

Node ID	Polynomial	Subframe 0					Subframe 1					Subframe 2					Subframe 3					Subframe 4				
		0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	$0x+0$	x					x					x					x					x				
1	$0x+1$		x					x					x					x					x			
2	$0x+2$			x					x					x					x					x		
3	$0x+3$				x					x					x					x					x	
4	$0x+4$					x					x					x					x					x
5	$1x+0$	x						x						x						x						x
6	$1x+1$		x						x						x						x	x				
7	$1x+2$			x						x						x	x						x			
8	$1x+3$				x						x	x						x						x		
9	$1x+4$					x	x						x						x						x	
10	$2x+0$	x							x							x		x							x	
11	$2x+1$		x							x		x							x							x
12	$2x+2$			x							x		x							x		x				
13	$2x+3$				x		x							x							x		x			
14	$2x+4$					x		x							x		x							x		
15	$3x+0$	x								x			x								x			x		
16	$3x+1$		x								x			x			x								x	
17	$3x+2$			x			x								x			x								x
18	$3x+3$				x			x								x			x			x				
19	$3x+4$					x			x			x								x			x			
20	$4x+0$	x									x					x				x				x		
21	$4x+1$		x				x										x				x				x	
22	$4x+2$			x				x				x										x				x
23	$4x+3$				x				x				x				x									x
24	$4x+4$					x				x				x				x				x				

Figure B.1: The TDMA frame for every node in a network of $N = 25$ maximum nodes and $D = 4$ maximum neighbors operating under the Deterministic Policy. Each node has been assigned a unique polynomial and based on this polynomial a unique time-slot allocation has been derived.

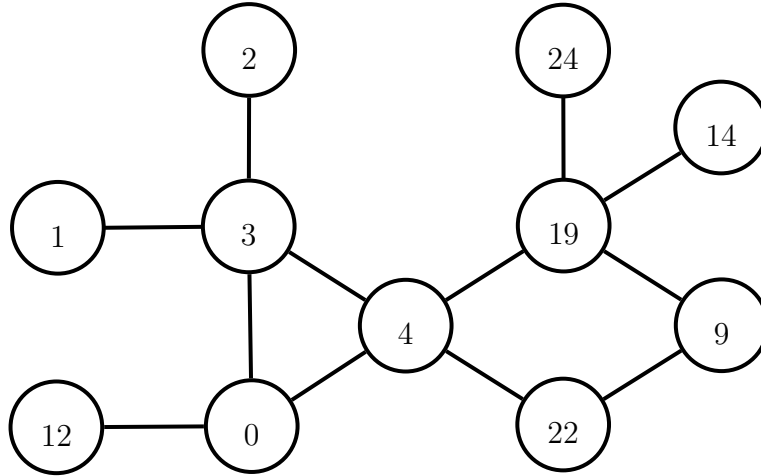


Figure B.2: An example of an ad hoc network.

Node ID	Polynomial	Subframe 0					Subframe 1					Subframe 2					Subframe 3					Subframe 4				
		0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	$0x+0$	x					x					x					x					x				
3	$0x+3$				x					x					x					x					x	
4	$0x+4$					x					x					x					x					x
19	$3x+4$					x			x			x								x			x			
22	$4x+2$			x					x			x									x				x	
$22 \rightarrow 4$				S				S				F								F				F		
$0 \rightarrow 4$		S					S					F					S					S				

Figure B.3: A scenario with a frame of five random polynomials. Two different transmissions are depicted. Slots where a successful transmission takes place are marked with S and time-slots where transmissions collide and fail are marked with F. The $22 \rightarrow 4$ transmission succeeds in two out of five time-slots that takes place while the $0 \rightarrow 4$ transmission succeeds in four out of five time-slots.

Node ID	Polynomial	Subframe 0					Subframe 1					Subframe 2					Subframe 3					Subframe 4				
		0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	$0x+0$	x					x					x					x					x				
6	$1x+1$		x						x					x						x		x				
10	$2x+0$	x							x						x		x							x		
17	$3x+2$			x			x							x			x								x	
22	$4x+2$			x				x				x								x				x		
			S					S						S	S											S

Figure B.4: A worst case scenario where each node may have only one successful transmission per frame. The corresponding time-slots where those transmissions take place are marked with S.

different transmissions have different number of successes even when they belong in the same neighborhood. Additionally, it is observed that both of the mentioned transmissions succeeded in more than the minimum guaranteed number of successes. Both of these facts can be attributed to the particular polynomials that have been assigned to the neighboring nodes. It can be observed that different combinations of polynomials produce different numbers of successful transmissions.

The example depicted Fig. B.3 contained a random selection of nodes. In this particular example, the total successful transmissions per frame are 14, provided each node always transmits when it is allowed to. Additional examples are given next to present some edge cases that may appear on some particular polynomial combinations, together with some interesting observations.

Fig. B.4 depicts a combination of polynomials which produces a worst case scenario in terms of total successful transmissions. It can be observed that each node succeeds only once per frame, thus leading to a total of five successful transmissions in the frame. It can also be observed that when a collision occurs, no more than two nodes participate.

Fig. B.5 depicts a best case scenario. Under this particular combination of polynomials no collision takes place and all 25 attempted transmissions are successful. It can be observed that the selected polynomials have one common coefficient ($a = 2$). This leads to the observation that for the 25 nodes depicted in B.1 there are 5 (or q) combinations of polynomials that provide a collision-free schedule for their corresponding neighborhoods.

Node ID	Polynomial	Subframe 0					Subframe 1					Subframe 2					Subframe 3					Subframe 4				
		0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
10	$2x+0$	x							x					x			x								x	
11	$2x+1$		x						x			x						x								x
12	$2x+2$			x						x		x							x		x					
13	$2x+3$				x		x						x							x		x				
14	$2x+4$					x		x						x			x						x			
		S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Figure B.5: A best case scenario where the combination of polynomials provides a collision-free schedule. All 25 transmission attempts will succeed.

Node ID	Polynomial	Subframe 0					Subframe 1					Subframe 2					Subframe 3					Subframe 4				
		0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
4	$0x+4$					x					x					x					x					x
9	$1x+4$					x	x						x					x							x	
14	$2x+4$					x		x						x			x							x		
19	$3x+4$					x			x			x							x				x			
24	$4x+4$					x				x			x				x					x				
							S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Figure B.6: In this scenario every possible collision takes place in the same time-slot. This leaves room for 20 out of 25 transmission attempts to be successful. The corresponding time-slots where those transmissions take place are marked with S.

B.2. Topology-Transparent Policies Based on Galois Field Theory 31

Finally, another interesting scenario is depicted in Fig.B.6. This particular combination of polynomials produces a schedule that provides 20 successful transmissions out of a total of 25. It is observed that all possible collisions take place during the same time-slot. It can also be observed that the selected polynomials have one common coefficient ($b = 4$), although it is not the same coefficient as in Fig. B.5. This also leads to the observation that there are $q = 5$ different combinations of polynomials that produce this kind of scheduling.

Now we will consider another example which will allow some additional observations. Let's assume a network with a maximum number of $N = 125$ nodes and a maximum number of $D = 2$ neighbors. Those values are given as input to algorithm 1 and the parameters $k = 2$ and $q = 5$ are calculated. Consequently, the frame length is $L = q^2 = 25$ and the polynomials that will be assigned to the nodes are of the 2^{nd} degree. The total polynomials of 2^{nd} degree that may exist with coefficients from the $GF(q)$ are $q^{k+1} = 5^3 = 125$, thus there are enough unique polynomials to be assigned to the nodes.

The additional observation here occurs if the frame lengths of both examples are compared while at the same time the total number of nodes N and the parameter k is taken into consideration. It can be observed that in the first example, where $k = 1$, the frame length is equal to the maximum number of nodes N while in the second example, where $k = 2$, the frame length is smaller than N . This observation can also be derived if we consider the required condition that enough unique polynomials must exist to be assigned to the nodes. When $k > 1$, the frame length (which will always be $L = q^2$) is smaller than the maximum number of nodes that may exist in the network (which is $N = q^{k+1}$) since in this case it will always be $k + 1 > 2$.

Cases with $k > 1$ will occur as N increases while at the same time D is relatively small. This observation is derived by studying algorithm 1. As N increases, q must increase until the condition $q^{k+1} \geq N$ stands. If D is relatively small, some value of $k > 1$ will eventually be calculated. If a network satisfies the conditions of having a small maximum number of neighbors D but a relatively large maximum number of nodes N , it is reasonable to assume that it will be a sparse network which spans across a relatively large area.

B.2.3 The Probabilistic Policy

The Probabilistic Policy [38] is based on the Deterministic Policy, consequently it follows the exact steps of its predecessor regarding the time time-slot allocation to the network nodes. However, under the Probabilistic Policy, nodes are allowed to transmit in both their assigned and non-assigned time-slots. During their assigned time-slots they may always transmit (as under the Deterministic Policy) but in their non-assigned ones they transmit according to a fixed *access probability* p common for all nodes. These additional transmissions utilize time-slots that would otherwise be left unused but at the same time transmissions that would otherwise be successful are now being corrupted. However, as shown in [38], a range of values for p exists where the additional successful transmissions outnumber the additional collisions and this allows for increased throughput when compared to the Deterministic Policy's throughput.

The authors provide analysis that leads to the derivation of equations for the calculation of the maximum achievable throughput and of the access probability value under which this throughput value can be achieved. They show that calculating maximum throughput with the use of those equations is hard, thus they additionally derive simplified equations through which an approximate throughput value can be calculated. For this approximation to be possible, the assumption is made that all nodes have the same number of neighbors which equals the average number of neighbors $|\bar{S}|$ in the network.

Regarding the access probability, since the exact value that maximizes throughput is also hard to be calculated, two equations are derived that calculate the boundaries of an interval of values that are certain to provide increased throughput when compared to the Deterministic Policy. Those equations calculate the aforementioned values as a function of the topology density metric which is introduced in this work and defined as $|\bar{S}|/D$.

B.2.4 The Adaptive Policy

To further increase throughput, the *Adaptive Policy* was proposed [39] which extends the aforementioned Probabilistic Policy. Initially, the Adaptive Policy operates similarly to its predecessor. However, after a successful transmission takes place in a non-assigned time-slot, the access probability for the particular node and time-slot

becomes 1. In the event of a collision, the value of the transmission probability for this time-slot reverts to the initial value that has been defined for the non-assigned time-slots of every node.

At the beginning of its operation the Adaptive Policy operates exactly like the Probabilistic Policy. After some time, nodes have gathered information regarding their neighboring nodes' transmissions and have adapted the probability value during those non-assigned time-slots that they successfully transmitted a message towards them. It is possible that two or more nodes have adapted their access probability in a particular time-slot or this time-slot may have been assigned to a neighbor node which did not transmit there during the previous frame because there were no data available at the time. In any case, sooner or later a collision will occur in this time-slot and every node that had adapted its access probability value there will revert to the initial one. Eventually, the system will enter a mode of operation where throughput performance is stable. This mode is referred to by the authors as the *steady-state* mode of operation. Prior to this mode, the system operates under the *transient* mode and the time interval that this mode remains active is defined as the *convergence period*.

Eventually, the Adaptive Policy performs better in terms of throughput when compared to the Probabilistic Policy, since it manages to transmit more frequently during non-assigned time-slots.

Chapter C

Topology-Transparent Policies in Vehicular Networks

AN IoT application which has received a lot of attention from the research community is vehicular networking. Soon, vehicles are expected to be able to communicate either through an underlying network infrastructure or directly with other vehicles in ad hoc fashion. The latter scenario is widely known as VANET (Vehicular Ad hoc NETWORKing).

In VANETs, network topology is expected to change very often, because nodes are characterized by high mobility. This fact constitutes the design of TDMA MAC policies for this environment a challenging task, due to the need of time-slot re-allocation. Consequently, it is possible that a topology-transparent policy is more suitable in this kind of environments.

In this section, the Deterministic Policy is incorporated into a TDMA MAC protocol (TiMAC) and is compared against another TDMA MAC protocol (VeMAC). The latter has been designed specifically for VANET environments but follows a more traditional approach when it comes to allocating time-slots to nodes.

C.1 Vehicular Network Characteristics

A vehicular network can be seen as a special case of a mobile ad hoc network in which the nodes (vehicles) typically move along predefined routes, i.e., roads. The evaluation of both policies considered in this chapter focuses on improving safety

through vehicle-to-vehicle communication, therefore the main evaluation metric is the delay of messages that are exchanged among vehicles.

Due to vehicular networks' mobility, a MAC protocol should be able to adapt to frequent topology changes and the various patterns of these changes (e.g., vehicles move along roads and not randomly). Two different environments may typically be considered: (i) highway (high speed environment with variable density of traffic and number of vehicles depending on time and day); and (ii) urban (lower speeds and higher density than the highway scenario).

The typical speed in vehicular network is e.g., between 35 km/h and 110 km/h in a urban environment, and e.g., between 70 km/h and 150 km/h in a highway environment. Such mobility characteristics – not typical in mobile ad hoc networks – may significantly affect the overall performance of the system (e.g., [136], [137], [138]). The fact that vehicles have, to some extent, a predictable behavior in terms of their movement, also limits the upper bound on the number of neighbor vehicles. For example, the worst case with respect to the number of neighbors is during a traffic jam in cross-roads. This remark is important and justifies the assumption made by TiMAC regarding a predefined maximum number of neighbors.

Another special characteristic of vehicular networks refers to the inherent capability of vehicles to include a GPS [139] device that can give accurate measurements with respect to position, velocity, direction, and time. In addition, due to their inherent battery recharging capabilities, vehicles have ample energy for operating their electronic equipment. This allows for use of devices that are able to offer adequate processing power and storage capacity. Consequently, even though energy consumption usually is an issue in most mobile ad hoc networks, this is not the case in their vehicle counterparts.

Finally, when the focus is on vehicular-to-infrastructure communication, there are different constraints with respect to performance (e.g., throughput may be more important than time delay) when compared to the case of vehicular-to-vehicular communication. For the latter case, and particularly for safety applications, as it is the case for the policies considered here, time delay plays a critical role. As it will be shown later, the number of re-transmissions under TiMAC is smaller than under VeMAC while at the same time their throughput performance is comparable. A detailed description of VeMAC is given in the following section.

C.2 VeMAC Description

VeMAC [40] is a TDMA protocol operating in a multichannel manner, thus suitable for both safety and non-safety applications. One channel is used for safety applications and the rest for non-safety ones. The TiMAC policy requires a single channel to operate and focuses on safety applications, thus it will be compared to VeMAC's single channel operation which is also used for the same purpose.

Time is divided into frames of fixed number of time-slots. As mentioned, node synchronization is achieved using GPS. GPS is also employed to determine the direction each vehicle is moving in. Each frame is divided into three separate sets of time-slots: L and R for those nodes moving on the left and right direction (or downwards/upwards) and S for those communicating with roadside units. Since the focus here is on vehicular-to-vehicular communication, the latter set will be omitted and all time-slots will be divided in only two sets (L and R).

The medium access control policy of a node (in this case a vehicle) realized by VeMAC is based on continuous transmissions (even in the absence of data) during time-slots that are marked as free within a frame by the one-hop and two-hop neighbors (i.e., the potential interference nodes due to the hidden terminal problem). Note that each node is aware of its direction (L or R) and competes for the corresponding set of time-slots within the frame. In particular, when a node enters the network, the first step is to become synchronized with its neighbor nodes and then keep track of their transmissions for one frame. When a node transmits during a particular time-slot, this time-slot is marked as being *occupied* by this particular node so as other nodes are not able to reserve it.

Those time-slots occupied by the transmitting node's one-hop neighbors are also enlisted within the header of each transmission. Eventually, each node is aware of the set of time-slots occupied by its two-hop neighbors after the first frame. The next step is to select one of the unoccupied time-slots and keep transmitting during this time-slot even if data are not available for transmission, since it is important to announce to its neighbor nodes the occupation of the particular time-slot and the piece of information regarding its neighbor nodes. Clearly, if no message is sent in a previously occupied time-slot, the corresponding node is either powered off or went out of range so this time-slot is now unoccupied, again.

Figure C.1 graphically illustrates an example of time-slot assignment under

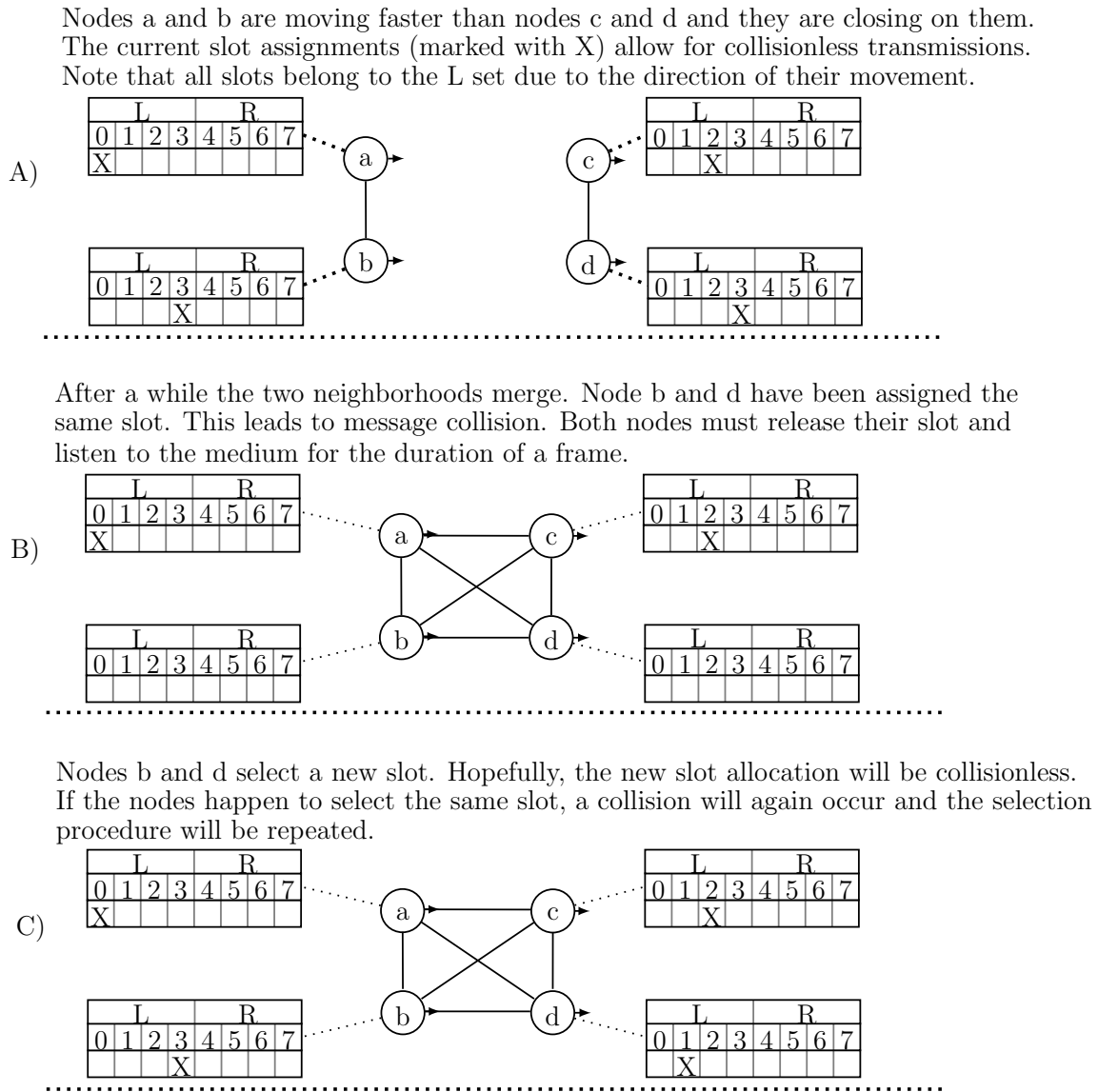


Figure C.1: Time-slot re-assignment under VeMAC.

VeMAC. Nodes in this example are depicted moving towards the same direction, thus each one competes for a time-slot from the set that corresponds to this direction (the L set). Initially, two separate networks are formed among them (node a with node b and node c with node d) and all four nodes are transmitting without experiencing collisions. However, nodes a and b are moving faster than nodes c and d , thus sooner or later the two distinct networks will merge into a single network (figure C.1.B). In the new network, nodes b and d are assigned the same time-slot. When a collision occurs, both nodes release their time-slot and listen to the medium for the duration of one frame. After this interval has passed, both nodes are able to randomly select a new time-slot that is not already occupied by some other node. It is possible that both nodes will select the same time-slot. In this case, a collision will again occur and the time-slot selection procedure will be repeated until the nodes select a different one.

In the previous example, two types of collisions were observed: access and merging collisions. Access collisions occur when two or more nodes in the process of randomly selecting their time-slot, select the same one. Merging collisions occur when nodes initially positioned out of each others two-hop neighborhood and occupying the same time-slot, suddenly come close enough so their transmissions collide. When a collision occurs (irrespectively of the type), the particular nodes occupying this time-slot release it and choose a new one (randomly) based on the information gathered during the last frame. The collision detection mechanism is based on listening the frame following a transmission. If a collision occurs, then the transmitting node will become aware of it since its own unique ID will not be included in the list sent by its neighbor nodes during the following frame.

C.3 Performance Evaluation

A program in the OMNeT++ simulation platform [140] has been developed for the evaluation of TiMAC in a vehicular environment, compared against VeMAC. In order to have a fair comparison, and given that the frame length value for TiMAC is derived following the algorithm presented in [37], the frame length for VeMAC is set to be equal to a TiMAC subframe length. This ensures that all nodes under both policies will carry out the exact same number of transmissions during a time interval that corresponds to a TiMAC frame's length.

The network size is set to $N = 1000$ vehicles. It is assumed that all nodes are perfectly synchronized for both protocols. Transmission range is the same for all vehicles and the maximum number of neighbor nodes is $D = 19$ for all simulation scenarios. Given these values, the algorithm in [37] outputs the values $k = 1$ and $q = 37$. Therefore, under TiMAC the frame size is set to $q^2 = 1369$ time-slots in every scenario. The corresponding frame length for VeMAC is $q = 37$. All considered scenarios correspond to averaged values for ten independent runs. The corresponding 95% confidence intervals are not depicted since their range is calculated to be less than 1% for the case of throughput and less than 8% for the case of the average number of retransmissions.

C.3.1 Network Topology, Traffic Characteristics and Evaluation Parameters

Two different network topologies are considered for the evaluation. First, a highway, 12 km long, containing two lanes of opposite directions. The node transmission range is set to 28 m. The distance between the two lanes is 10 m, so each vehicle may be in range with vehicles of the opposite lane, too. Each vehicle may move with medium, high or very high speed which corresponds to 72 km/h, 108 km/h and 144 km/h, respectively. For simulation purposes, when a node reaches the end of the road, it reappears in the same lane on the other side of the topology.

The second topology corresponds to an urban road network, 1200 m long and 1200 m wide, consisting of 4 (parallel) horizontal and 4 (parallel) vertical roads. Parallel roads are positioned 400 m from each other and crossroads are formed at the intersection of horizontal and vertical roads. Each vehicle may move with low, medium, or high speed which corresponds to 36 km/h, 72 km/h and 108 km/h, respectively. When a node reaches a crossroad, it randomly chooses one of the available directions excluding the opposite of its current one.

For both topologies, nodes' initial positioning and direction is randomly set. Each node is able to determine its moving direction and consequently to align itself with the proper subframe where it is allowed to transmit (in case the underlying protocol utilizes this information, like in the case of VeMAC). Finally, various scenarios are considered with respect to vehicle speeds. Those include scenarios where the speed is randomly chosen for each vehicle separately, as well as scenarios where the speed

is common to all vehicles. In any case, every selected vehicle's speed comes from the set of the aforementioned ones that correspond to each particular environment and remains unchanged until the end of each simulation run.

Traffic load hereafter corresponds to the probability that there is a data packet available for transmission for a randomly chosen neighbor destination at a particular time-slot, provided that the transmitting node is allowed to transmit during this time-slot, regardless of the chosen protocol. This probability (i.e., traffic load) is the same for all vehicles. If a transmission fails, the collided packets are re-transmitted at the next available time-slot. If the transmission succeeds (or there is no transmission at all), a new package is created according to the previously mentioned probability at the next available time-slot. The number of successful transmissions per node per time-slot is referred to hereafter as *throughput*. Note that the channel is assumed to be ideal, thus no re-transmissions are expected due to channel errors.

The maximum number of consecutive re-transmissions is used to compare the evaluated MAC policies as an indicative factor of time delay, since small numbers of re-transmissions indicates small time delays. Therefore, the number of re-transmissions will be used in the sequel as the delay metric. Each re-transmission corresponds on average to a delay of 100ms (depending on the exact time-slot position in the frame) which is an acceptable time delay value even if there is the need for re-transmissions.

C.3.2 Simulation results for TiMAC vs. VeMAC

Throughput Performance

Figure C.2 depicts throughput as a function of traffic load for both the highway and the urban vehicular environment. Vehicle speeds for these scenarios are randomly selected from the three available speeds corresponding to each environment. For the highway case (Figure C.2.a), as the traffic load increases, throughput under both VeMAC and TiMAC increases. This is expected since both protocols are TDMA-based and not contention-based ones. It is observed that for traffic load less than 0.6, the obtained throughput under TiMAC is about 3% larger than that under VeMAC, whereas as traffic load further increases the observed picture changes in favor of VeMAC (5% for the case of heavy load). This change is attributed (i) to the disjoint set of time-slots assigned to different directions under VeMAC (and

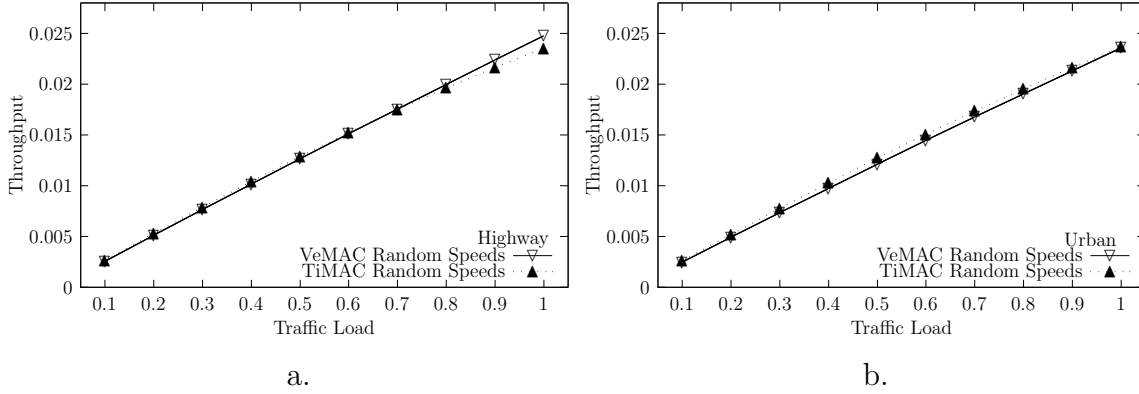


Figure C.2: Throughput as a function of traffic load for the highway (a) and the urban (b) vehicular environment for both VeMAC and TiMAC.

thus, as traffic load conditions increase, VeMAC behaves better than TiMAC in terms of throughput); and (ii) to the fact that as traffic load increases, the collision probability under TiMAC also increases (note that under TiMAC, nodes transmit only if there are data for transmission and not during every frame as it is the case under VeMAC). Nevertheless, it is observed, that the obtained throughput under both policies remains close.

Throughput remains close for the case of the urban environment too (Figure C.2.b), where it is interesting to see that in this case TiMAC outperforms VeMAC under all traffic load conditions by about 5% most of the time (falling down to a minimum of 0.4% increase for the case of full load). This is attributed to the fact that in an urban environment, traffic is not that predictable as it is the case for highways and therefore, the assigned time-slots under VeMAC that correspond to a certain direction should be reallocated to avoid collisions.

Figure C.3 depicts throughput as a function of traffic load for the scenarios where all vehicles are moving with the same speed in the highway environment. It can be observed that, under VeMAC (figure C.3.a), throughput performance decreases as the speed of the vehicles increases. However under TiMAC (figure C.3.b), it can be observed that throughput performance remains practically unchanged. This observation confirms that VeMAC's performance is sensitive to topology changes while TiMAC justifies its topology-transparent nature.

Figure C.4 depicts throughput as a function of traffic load for the scenarios where

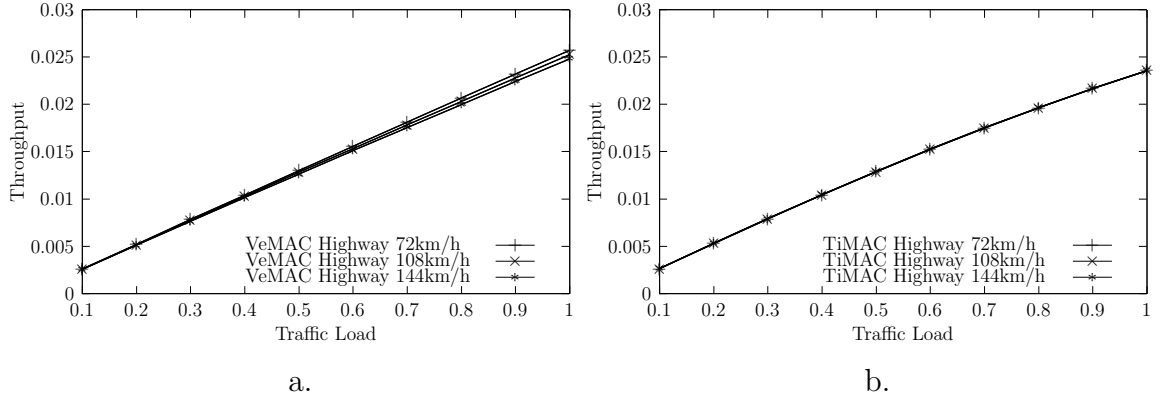


Figure C.3: Throughput as a function of traffic load for various common vehicle speed scenarios in highway environment for both VeMAC and TiMAC.

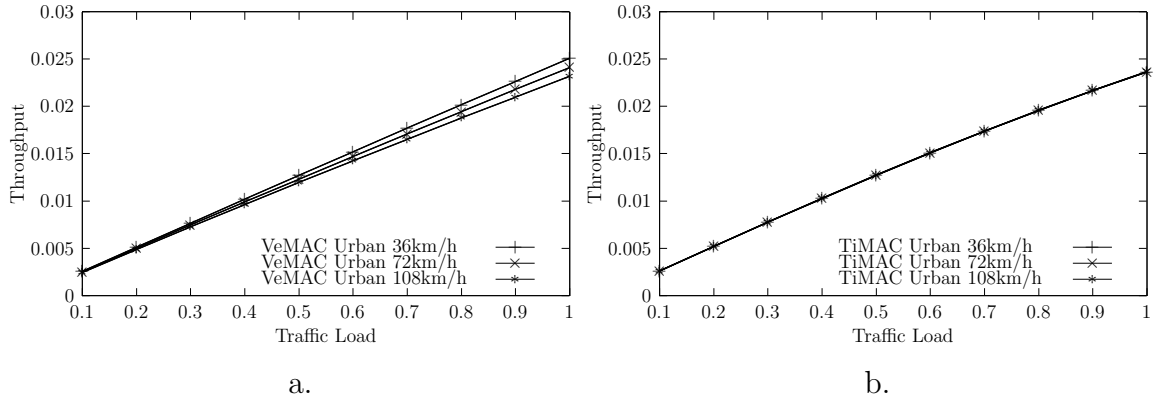


Figure C.4: Throughput as a function of traffic load for various common vehicle speed scenarios in urban environment for both VeMAC and TiMAC.

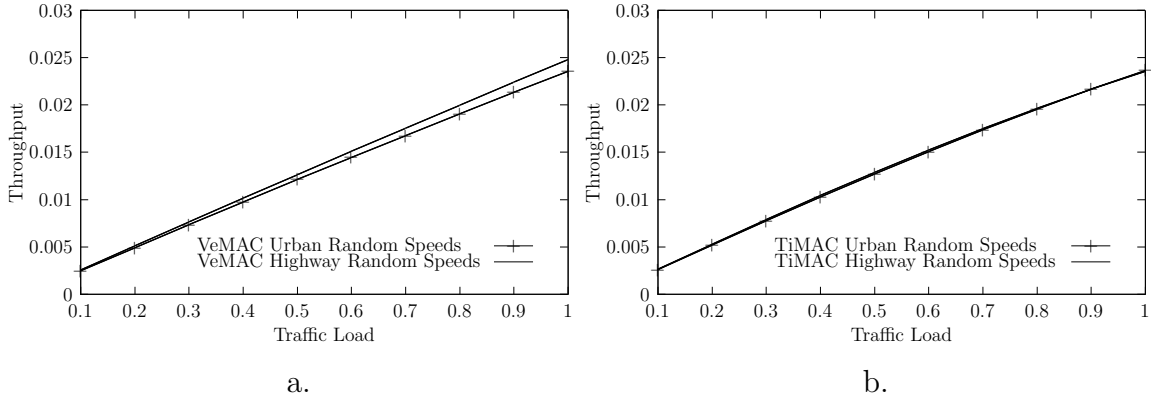


Figure C.5: Throughput as a function of traffic load for random vehicle speed scenarios in urban and highway environments for both VeMAC and TiMAC.

all vehicles are moving with the same speed but this time for the urban environment. Again it can be observed that, under VeMAC (figure C.3.a), throughput performance decreases as the speed of the vehicles increases. However, it can also be observed here that the performance difference among the three depicted speed scenarios is larger than the difference observed in figure C.3.a corresponding to the highway scenarios. This difference is not unexpected since the topology changes under urban scenarios are more unpredictable when compared to changes on the highway scenarios. Additionally, it is observed that TiMAC's performance is again practically unaffected by the topology changes.

Similar observations can be made in figure C.5 which depicts throughput performance difference when nodes operate under the same policy and the variable is the type of environment. Random vehicle speeds have been selected here and throughput is again depicted as a function of traffic load. It is confirmed (figure C.5.a) that VeMAC performs worse under the urban environments when compared to itself operating under the highway environments, due to the more unpredictable changes in topology. It is also confirmed (figure C.5.b) that TiMAC is unaffected by the network topology it is operating in, as long as the remaining network characteristics remain the same.

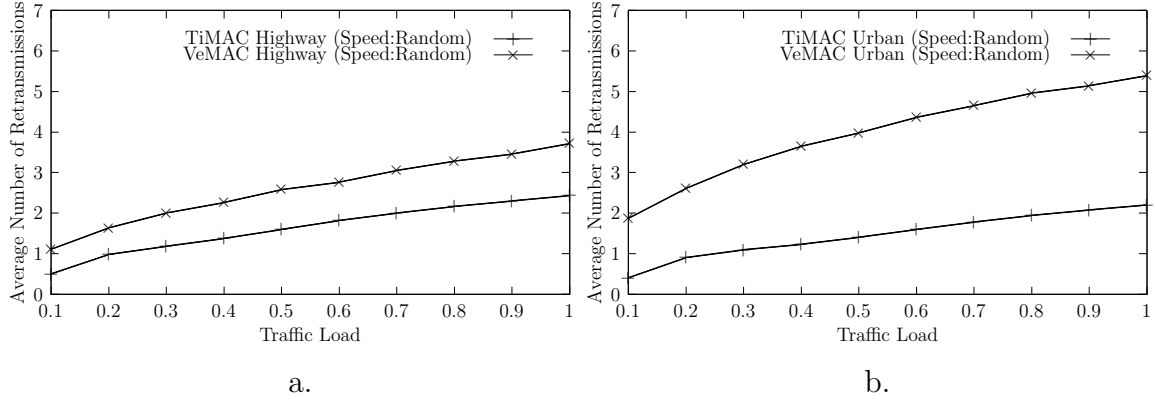


Figure C.6: Average value of maximum re-transmissions per node as a function of traffic load for both the highway and urban vehicular environments for both VeMAC and TiMAC with vehicles moving with randomly assigned speeds.

Delay Performance

The average value of the maximum number of retransmissions per node for the highway and the urban vehicular environments are depicted on the left and the right side of Figure C.6 respectively and for the scenarios where vehicles are moving with random speeds. It is clear that the (average) number of retransmissions under TiMAC is less than that under VeMAC (depending on the traffic load it is observed to be decreased more than 50%). Given that throughput is close for both VeMAC and TiMAC, the smaller number of retransmissions indicates that TiMAC can deliver (almost) the same amount of data with smaller delay than VeMAC.

Figure C.7 again depicts the average value of maximum re-transmissions per node as a function of traffic load but this time for all vehicle speed scenarios. Only the highway environment scenarios are depicted here. Figure C.7.a depicts the performance of VeMAC under those scenarios. It can be observed that, under the scenarios where the vehicles move with a common speed, the number of re-transmissions is comparable, although performance decreases as the vehicle speed is increases. However, when vehicles move with random speeds, a larger decrease in performance is observed as under this scenario about 150% more re-transmissions take place when compared to the common speed scenarios. On the contrary, TiMAC's performance (figure C.7.a) is comparable under all scenarios.

It can also be observed that, under the common vehicle speed scenarios in high-

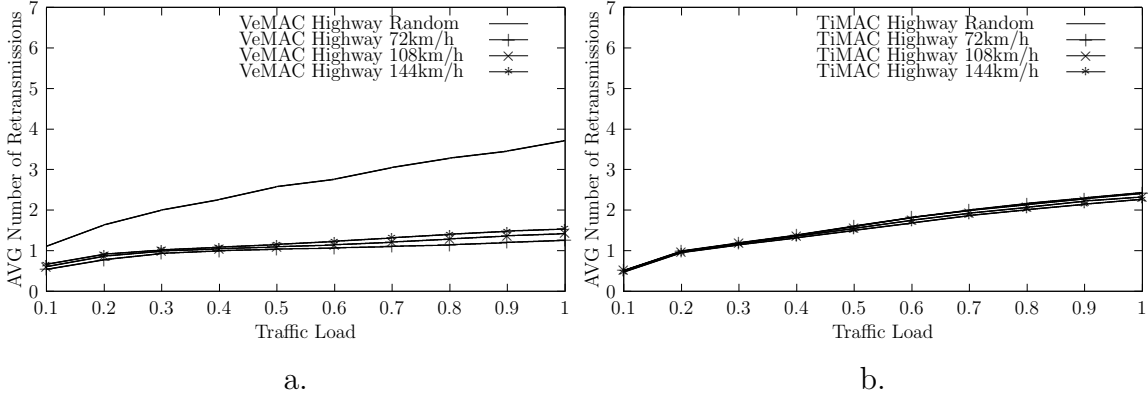


Figure C.7: Average value of maximum re-transmissions per node as a function of traffic load for all vehicle speed scenarios in highway environments for both VeMAC and TiMAC.

way environments, VeMAC clearly outperforms TiMAC in terms of average maximum re-transmissions. This can be attributed to the fact that, since all vehicles are moving with the same speed and those moving in opposite directions are assigned time-slots from different subsets, the topology is essentially unchanged. Consequently, under those scenarios and given enough time, VeMAC eventually manages to produce an optimal scheduling among the nodes. The situation is reversed under the random speed scenarios. If VeMAC's average number of re-transmissions value for the random speed scenario of figure C.7.a is compared with the corresponding value of figure C.7.b, it is observed that TiMAC performs better than VeMAC. More specifically, TiMAC's performance, as mentioned, remains unchanged when compared to the common speed scenarios but VeMAC's performance decreases to the point where TiMAC outperforms VeMAC by about 50%. Those observations are better depicted in figure C.8 where both VeMAC and TiMAC's average re-transmissions are depicted for the highway scenario and for random vehicle speeds and common vehicle speeds corresponding to 72km/h.

Figure C.9 depicts the average value of maximum re-transmissions per node as a function of traffic load for the urban environment and for all considered speed scenarios. The observations drawn here are similar to those made earlier in this section when urban scenarios were considered. Specifically, the urban environment favors TiMAC due to the fact that the topology changes here are more unpredictable

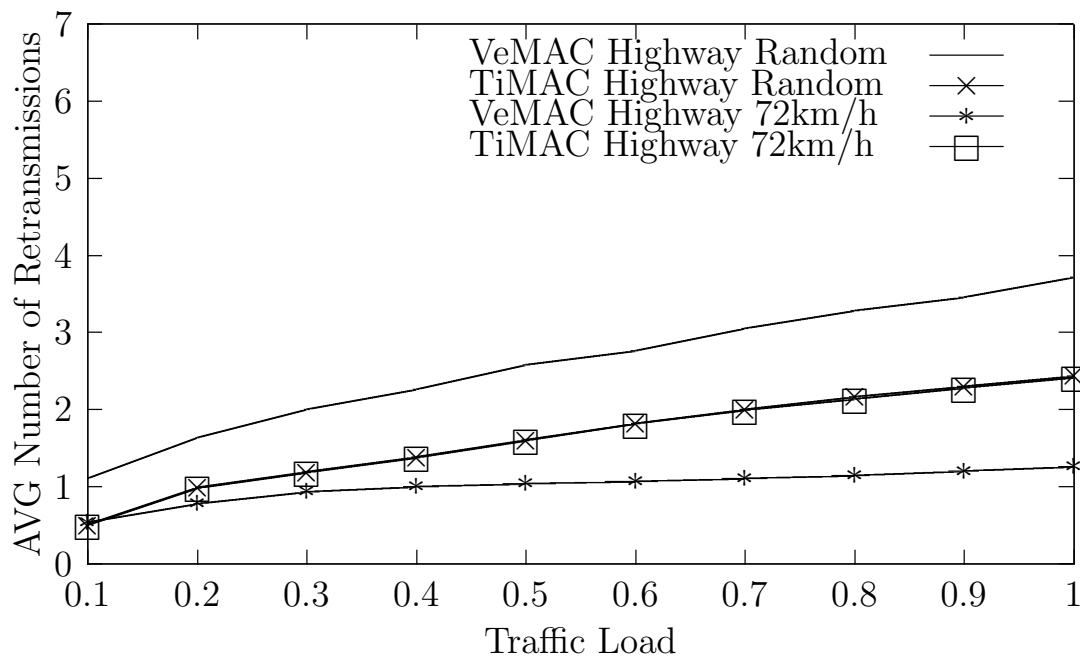


Figure C.8: Average value of maximum re-transmissions per node as a function of traffic load for highway scenarios and for random vehicle speeds and common vehicle speeds of 72km/h.

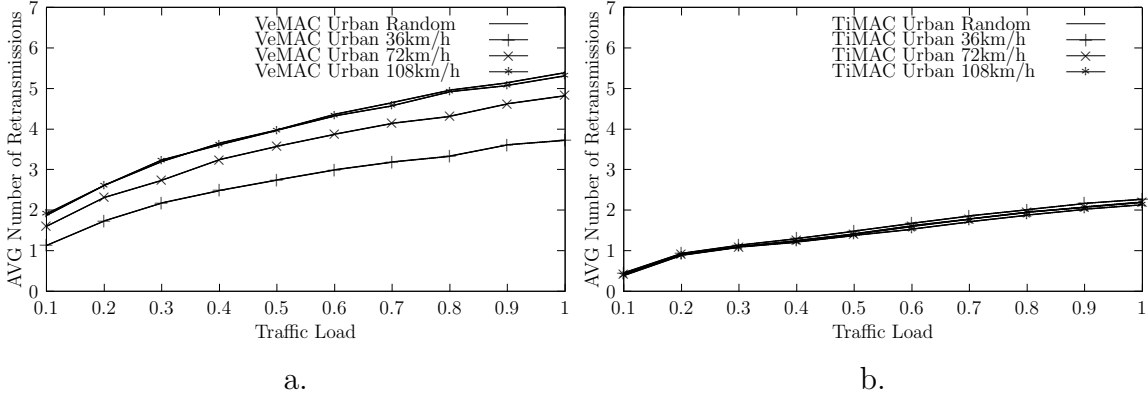


Figure C.9: Average value of maximum re-transmissions per node as a function of traffic load for all vehicle speed scenarios in urban environments for both VeMAC and TiMAC.

when compared to the highway environment. Consequently, TiMAC performs better in every scenario. As before, TiMAC's performance is practically unchanged in all scenarios, while VeMAC's performance decreases as vehicle speed increases. Finally, under VeMAC it is observed that the random speed scenario's performance is comparable to the one where vehicles are moving with the faster of the considered common speed scenarios.

In figure C.10 both VeMAC and TiMAC's average re-transmissions are depicted, corresponding to the urban scenario for random vehicle speeds and to the scenario of the lowest common vehicle speed which is 36km/h. It can be observed that, even when vehicles are moving with the lowest of the considered speeds, VeMAC shows about 70% higher maximum number of re-transmissions per node when compared to either of TiMAC's vehicle speed scenarios. When vehicles under VeMAC move with random speeds, the performance is about 150% worse when compared to TiMAC's performance.

Distribution of maximum numbers of re-transmissions

Figure C.11 depicts the obtained distribution of re-transmissions over nodes for both highway and urban vehicular environments. Vehicle speed for those scenarios is random and traffic load probability is 0.5. It is interesting to see that the majority of the nodes under TiMAC are concentrated near the average value, whereas under

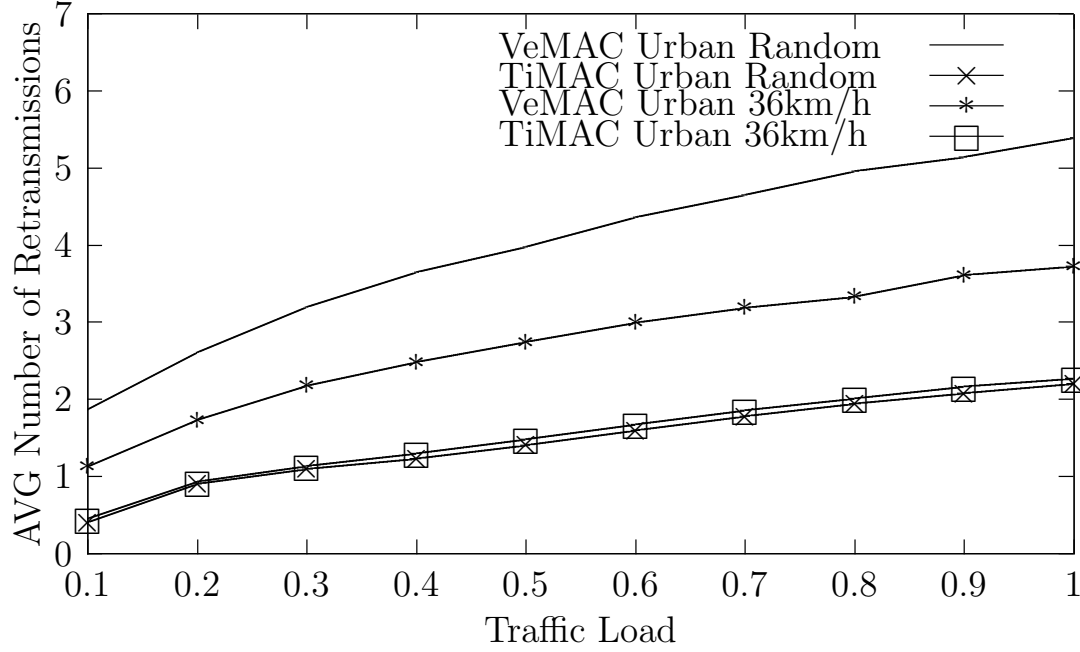


Figure C.10: Average value of maximum re-transmissions per node as a function of traffic load for urban scenarios and for random vehicle speeds and common vehicle speeds of 36km/h.

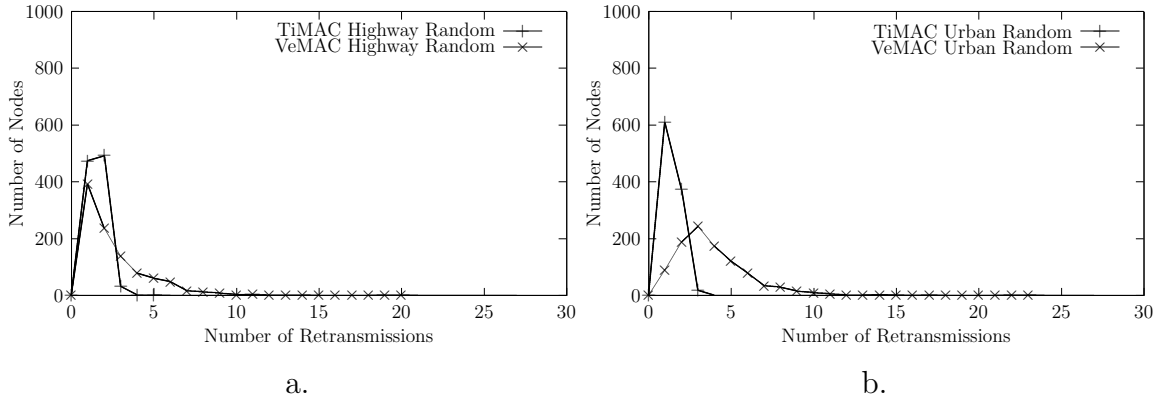


Figure C.11: Distribution of re-transmissions over nodes for both the highway and urban vehicular environments and traffic load 0.5 for both VeMAC and TiMAC.

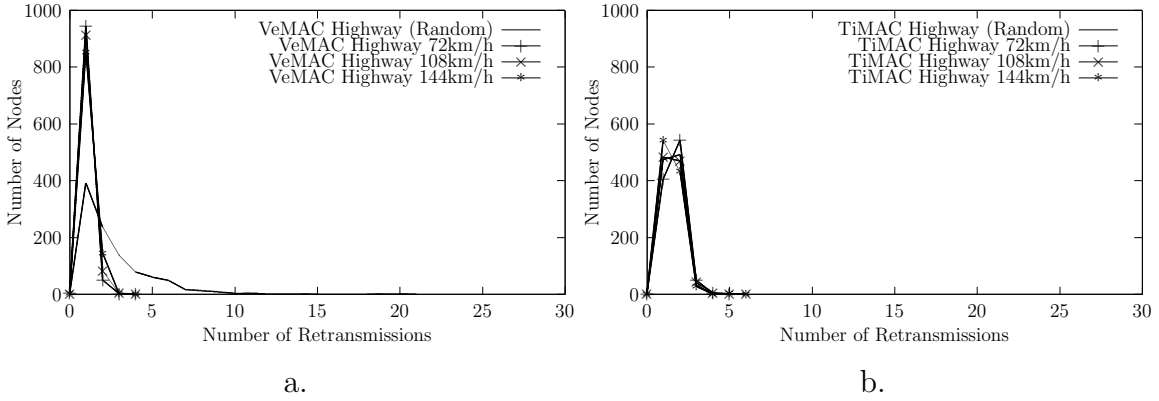


Figure C.12: Distribution of re-transmissions over nodes for various speed scenarios in the highway environment and traffic load 0.5 for both VeMAC and TiMAC.

VeMAC there is a large number of nodes whose re-transmissions are more than the corresponding average value (the averaged values are depicted in Figure C.6). Therefore, a random node under VeMAC is expected (on average) to re-transmit more frequently than under TiMAC, under the same conditions.

Figure C.12 depicts how each policy compares to itself in terms of the re-transmissions distribution when vehicles are moving with different speeds and with network traffic load 0.5. Under VeMAC (figure C.12.a) and for the common speed scenarios it is observed that all values are concentrated near the average value (about 1.2). About 950 out of the 1000 vehicles need no more than one re-transmission to deliver each message successfully and only a small number of them performs slightly worse with a maximum of four re-transmissions for some nodes. When vehicles are moving with random speeds, performance is decreased. Less than 400 vehicles need only one re-transmission while the majority need two or more. Additionally, it is observed that a small number of them needs as much as 20 re-transmissions before at least one of the messages is successfully delivered to the destination.

Under TiMAC (figure C.12.b), a similar performance is observed for all vehicle speed scenarios. Most vehicles need a maximum of one or two re-transmissions per message and only a handful of them need as much as six. Furthermore, similarly with earlier observations regarding the average value of re-transmission numbers, it is observed that VeMAC performs better than TiMAC when vehicles are moving with common speeds while TiMAC outperforms VeMAC in the random speed scenario.

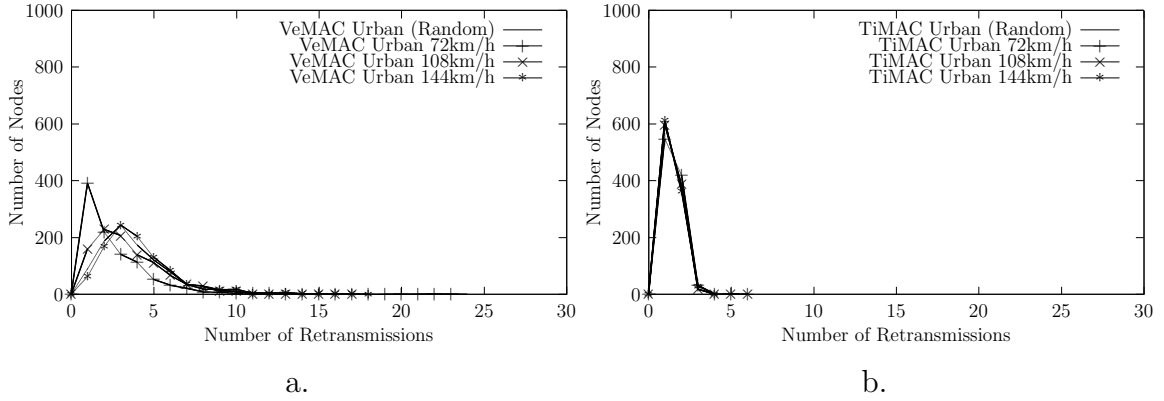


Figure C.13: Distribution of re-transmissions over nodes for various speed scenarios in the urban environment and traffic load 0.5 for both VeMAC and TiMAC.

Regarding the scenarios in Urban environments (Figure C.13), it is observed that TiMAC outperforms VeMAC for all speed scenarios. Under VeMAC, some vehicles need as much as 23 re-transmissions to successfully deliver some messages while under TiMAC the corresponding number is no more than six.

In figures C.14.a and C.15.a it is better demonstrated how VeMAC outperforms TiMAC in highway scenarios when vehicles move with a common speed since the topology there, as mentioned earlier, can be considered almost unchanged. The situation is reversed in urban scenarios as shown in figures C.14.b and C.15.b because vehicles change their direction of movement unpredictably, although their speed is common and unchanged as in the corresponding highway environment.

Figure C.16 depicts the distribution of re-transmissions over nodes in the highway environment with respect to the network load. Under VeMAC (figure C.16.a), it is observed that the majority of vehicles need more re-transmissions as the load increases. The same observation can be made for TiMAC (figure C.16.b).

Similar observations can be made for figure C.17. However, when comparing this figure with figure C.16, it can additionally be observed that TiMAC's performance remains comparable between the two environments while VeMAC's performance for the scenarios in the urban environment is worse than the corresponding ones in the highway environment for all considered traffic load values.

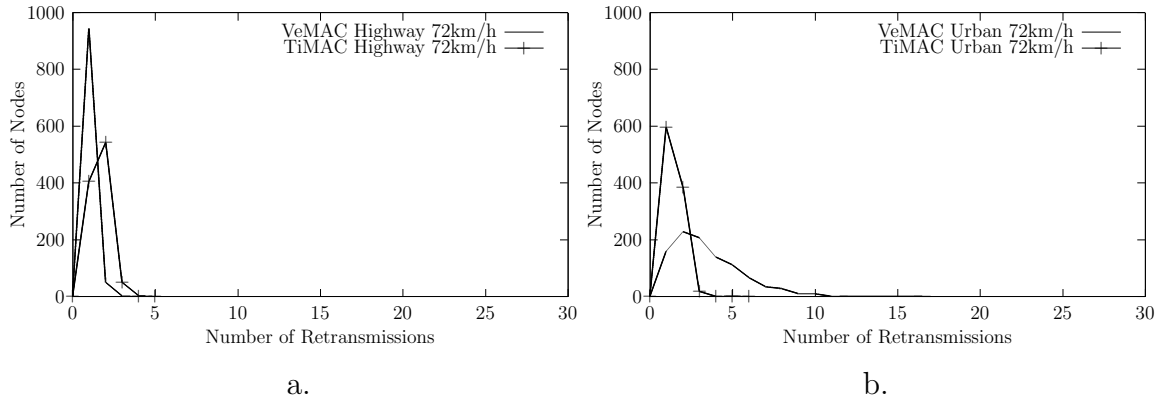


Figure C.14: Distribution of re-transmissions over nodes for the scenarios where vehicle speed is 72km/h for both VeMAC and TiMAC in Highway and Urban scenarios.

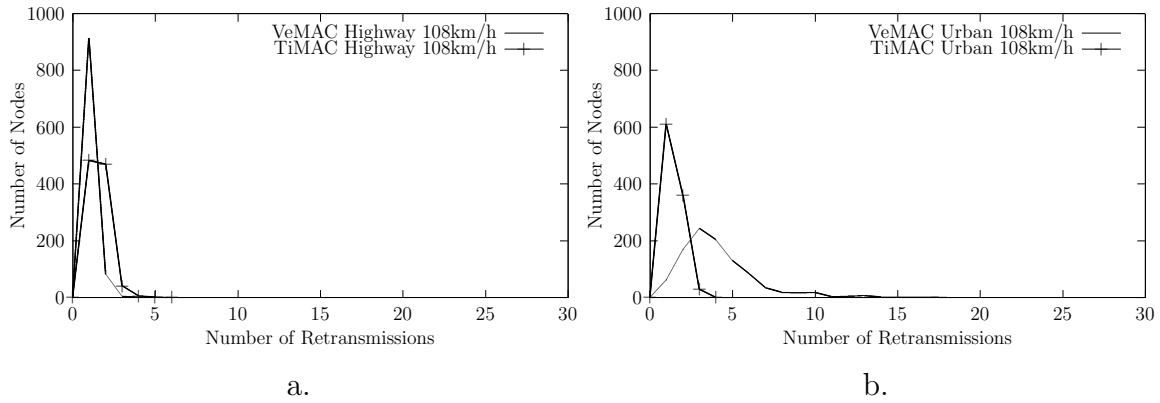


Figure C.15: Distribution of re-transmissions over nodes for the scenarios where vehicle speed is 108km/h for both VeMAC and TiMAC in Highway and Urban scenarios.

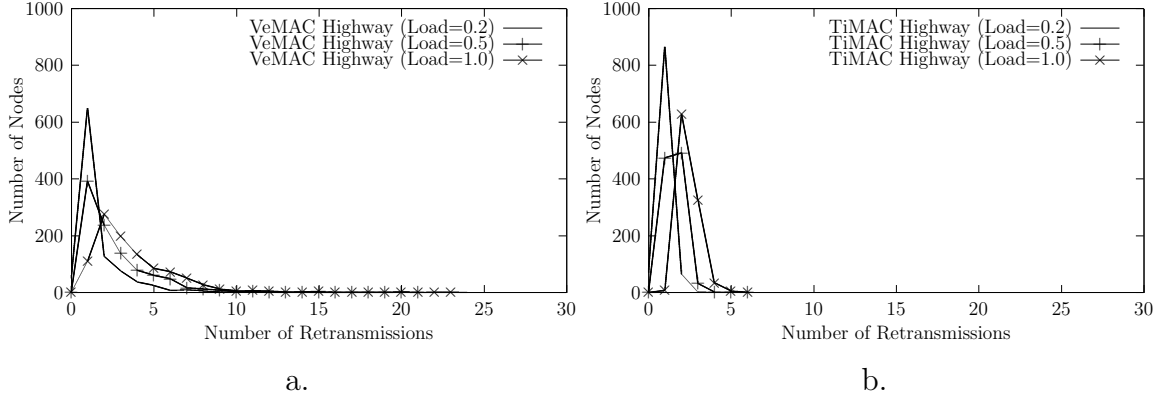


Figure C.16: Distribution of re-transmissions over nodes in the highway environment for various network traffic load values and for the scenarios where vehicle speed is random.

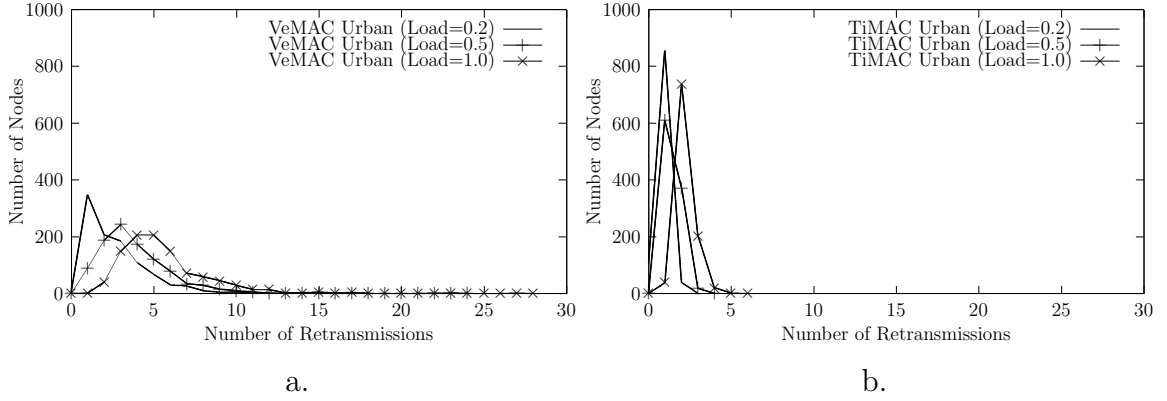


Figure C.17: Distribution of re-transmissions over nodes in the urban environment for various network traffic load values and for the scenarios where vehicle speed is random.

C.4 Conclusions

Vehicular networks are among the most demanding network environments when it comes to MAC policy design and the main reasons behind this are the fast-changing topology and the diversity of applications that have to be supported by the underlying medium access policy. Especially when passenger safety applications have to be considered, it is crucial that messages are delivered to their destinations within a certain time interval. This requirement has led the research community to consider TDMA-based policies as they are able to offer time bounded access to the medium. Moreover, the implementation of TDMA topology-transparent policies in vehicular network environments might also be a reasonable choice as those policies eliminate the need for time-slot re-assignment in mobile ad-hoc networks.

In this chapter, the Deterministic Policy (as was introduced in [37] and described in section B.2.1) is incorporated in a TDMA MAC policy (TiMAC) and this policy is evaluated in various VANET scenarios and compared against an already established VANET MAC policy (VeMAC). The two policies' primary difference is how they assign time-slots to the network nodes. TiMAC implements the Deterministic Policy's topology-transparent algorithm while VeMAC implements a more traditional time-slot assignment algorithm. The comparison results are summarized below.

In terms of throughput, both policies perform similarly. In highway environment scenarios, VeMAC holds an edge when network traffic load is high, while TiMAC performs slightly better under lower loads. This can be attributed to the fact that TiMAC, in contrast to VeMAC, does not transmit empty messages when there are no data available for transmission, thus it experiences less collisions than VeMAC as traffic load decreases. In urban environment scenarios where the topology changes are more unpredictable, TiMAC performs slightly better than VeMAC under every network traffic load, with their peak performance difference again being observed under medium loads.

When the policies are evaluated with respect to delay, various results are observed depending on the particular scenario. VeMAC performs clearly better than TiMAC in highway environments and when all vehicles are moving with identical speeds. This is an expected result since, under those parameters, the network topology can be considered unchanged for the duration of the particular simulation run and VeMAC eventually settles for an optimal time-slot allocation among the nodes. The

situation is reversed in highway scenarios with randomly chosen vehicle speeds as well as in all urban scenarios, as TiMAC performs better there.

An interesting observation can be made if both policies are compared against themselves with the variable being the rate of topology change. It can be observed that, as topology changes become more frequent and more unpredictable, TiMAC's performance remains practically unchanged while VeMAC's performance decreases. This behavior confirms TiMAC's (and thus the Deterministic Policy's) topology-transparent nature.

Based on these results, it may be proposed that topology-transparent policies can be considered as suitable candidates for vehicular network applications where passenger safety is the primary concern.

Chapter D

The Refined Policy

ONE disadvantage of TDMA policies is the low utilization of the communication channel in sparse network environments and this is also true for the Deterministic Policy [37]. To tackle this problem, the Probabilistic Policy [38] was introduced which allows nodes to additionally transmit during unused time-slots but under a predefined and common *access probability* p .

Although throughput under the Probabilistic Policy is increased under certain values of p , message collisions are also increased. A lot of those collisions occur during time-slots that under the Deterministic Policy a successful transmission would take place there. Another disadvantage is that the value of p has to be calculated and assigned to the nodes prior to the network operation and this procedure is not particularly suitable to MANET's dynamic and distributed nature.

In this chapter, the Refined Policy is proposed which extends the Probabilistic Policy by tackling its two aforementioned problems. Under the Refined Policy, nodes are able to refrain from probabilistic transmissions that would otherwise take place during some neighboring node's assigned time-slot, thus avoiding transmissions that would most probably cause a collision. Furthermore, a method for nodes to calculate their own *individual access probability* p is introduced. This calculation is carried out in distributed fashion and while the network operates.

It is shown that the Refined Policy performs better in terms of throughput when compared to the Probabilistic Policy while at the same time nodes experience fewer message collisions. Furthermore, it is shown that the use of the individual access probability calculation contributes to further throughput increase when compared

to the assignment of a common access probability to all nodes.

D.1 The Refined Policy

Under the proposed Refined Policy, nodes are allowed to transmit during the assigned time-slots as under the Deterministic and the Probabilistic Policies. Assuming a transmission from node u to its neighbor node v , denoted as $u \rightarrow v$, the aim is to derive a subset of the non-assigned time-slots $i \notin \Omega_u$ such that no other neighbor node will be allowed to transmit during its assigned time-slot.

Let F_u be the set of time-slots that have not been assigned either to the transmitting node u or any of its neighbor nodes; F_u will be referred to hereafter as *free time-slots*. A node u can derive set F_u by using information available inside the header of successfully received messages, specifically the ID of the source node that is the only information needed for the calculation of the coefficients of its assigned polynomial. This requires at least one successful transmission from each neighbor node before node u is able to calculate the complete F_u set. Having derived this set, transmission $u \rightarrow v$ may take place according to the access probability p . Thus,

The Refined Policy: Provided there are data available for transmission at time-slot i , then for transmission $u \rightarrow v$:

- *If time-slot $i \in \Omega_u$, then transmission $u \rightarrow v$ always takes place;*
- *If time-slot $i \in F_u$, then transmission $u \rightarrow v$ takes place with probability p .*

At the beginning of the network operation, each node is unaware of its neighbors. As already mentioned, nodes receive messages from their neighbors as part of the network's initialization process. Regardless of whether these messages are destined for this node or another one, the ID (i.e., the polynomial coefficients) of the transmitting node u can be extracted from the packet header. Consequently, the time-slot allocation can be calculated. The set of free time-slots F_u can then be derived by combining the time-slot allocations of every neighboring node. Initially, F_u contains all non-assigned time-slots but its contents are modified as successful transmissions are received. This adjustment is essential in dynamic topologies, as it allows node u to constantly adapt to neighborhood changes.

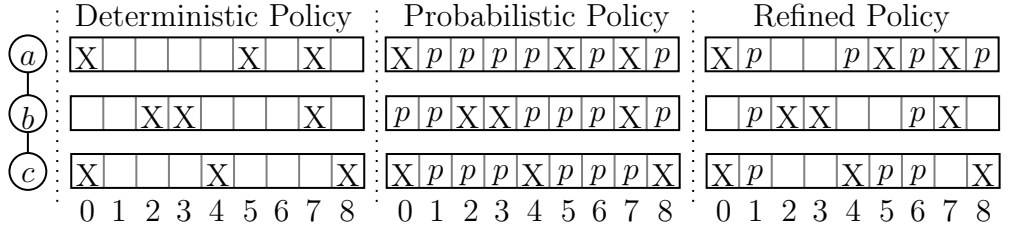


Figure D.1: The frame for an example line network of three nodes (a , b and c) as appears under the Deterministic, Probabilistic and Refined Policies. It consists of three subframes and there are three time-slots for each one (0-1-2 , 3-4-5 , 6-7-8, respectively). Time-slots marked (i) with X correspond to assigned time-slots; (ii) with p correspond to those non-assigned time-slots that a node transmits according to the access probability. Time-slots left blank correspond to those that a node is never allowed to transmit.

D.1.1 A frame example

The frame corresponding to a simple line network of three nodes (a , b and c) is depicted in Fig. D.1 to help visualize the key idea behind the Refined Policy. Therefore, the corresponding frames under all three policies are depicted. As observed from the first one corresponding to the Deterministic Policy, nodes can transmit only during the assigned time-slots (marked with X). It can be observed that a time-slot may be assigned to more than one node (e.g., time-slots 0 and 7). Consequently, when nodes a and c transmit during time-slot 0 towards node b (assuming all nodes operate under heavy traffic conditions), a collision will occur. Still, it is guaranteed that there will be at least one successful transmission for each node (e.g., time-slots 4, 5, 8).

For the frame under the Probabilistic Policy, nodes are allowed to transmit during non-assigned time-slots, which are marked with p . Probabilistic transmissions introduce collisions among neighbors for time-slots that transmissions would have been successful under the Deterministic Policy (e.g., a , b and c during time-slot 2). However, as shown in [38], there is a range of values for the access probability p that the additional successful transmissions compensate for the introduced collisions.

The third frame depicted in Fig.D.1 corresponds to the proposed Refined Policy. Every node is aware of its neighbors' assigned time-slots, i.e., the free time-slots, and will only transmit (with probability p) during these time-slots (in addition to

the assigned ones). This behavior prevents unfortunate transmissions that would almost certainly lead to collisions. For example, node a will never transmit during time-slots 2 and 3 knowing that these are assigned to node b . As it is shown later, the Refined Policy increases system throughput even compared to the Probabilistic Policy and at the same time reduces the overall number of transmissions.

D.1.2 Definitions

Some useful sets of nodes are defined next. Assuming transmission $u \rightarrow v$, the interest is on these transmissions that may *corrupt* $u \rightarrow v$ (i.e., a collision takes place).

- Ω_u : The set of time-slots assigned to node u .
- F_u : The set of free time-slots for node u .
- $AA_{u \rightarrow v}$: The set of time-slots that are assigned to node u as well as to at least one of its 1-hop or 2-hop neighbors, which can corrupt the transmission $u \rightarrow v$. Transmission $u \rightarrow v$ will always become corrupted during these time-slots.
- $AF_{u \rightarrow v}$: The set of time-slots that are assigned to node u and are not assigned to any node that can corrupt the transmission $u \rightarrow v$. It is likely that some 2-hop neighbor might perceive these time-slots as free and may transmit with probability p , thus corrupting the transmission $u \rightarrow v$. Such neighbor node cannot be 1-hop since every 1-hop neighbor of u is aware that these time-slots are assigned to node u , so they would not perceive them as free. The transmission during these time-slots will succeed provided none of these 2-hop neighbors transmits.
- $FA_{u \rightarrow v}$: The set of time-slots that node u perceives as free but are also assigned to one or more neighbors able to corrupt the transmission $u \rightarrow v$. These can only be 2-hop neighbors or node u would not perceive any of these time-slots as free. Transmission $u \rightarrow v$ will always fail during these time-slots.
- $FF_{u \rightarrow v}$: The set of time-slots that node u perceives as free and are not assigned to any node able to corrupt the transmission $u \rightarrow v$. Other nodes may also perceive these time-slots as free and may transmit, thus corrupting transmission

$u \rightarrow v$. These nodes will be either 1-hop or 2-hop neighbors to node u , including node v . The transmission during these time-slots will succeed, provided no other of the aforementioned neighboring nodes transmits simultaneously.

- $S_{u \rightarrow v}^{2hop}$: The set of nodes that are 2-hop neighbors to node u and are able to corrupt transmission $u \rightarrow v$.
- $S_i^{AF_{u \rightarrow v}}$: The set of nodes that may corrupt transmission $u \rightarrow v$ during time-slot $i \in AF_{u \rightarrow v}$. It is a subset of $S_{u \rightarrow v}^{2hop}$.
 - $|S^{AF_{u \rightarrow v}}|$: The average number of nodes that may corrupt transmission $u \rightarrow v$ for all time-slots in $AF_{u \rightarrow v}$ set.
 - $|S^{AF}|$: The average number of $|S^{AF_{u \rightarrow v}}|$ for all considered transmissions.
- $S_i^{FF_{u \rightarrow v}}$: The set of nodes that may corrupt transmission $u \rightarrow v$ during time-slot $i \in FF_{u \rightarrow v}$.
 - $|S^{FF_{u \rightarrow v}}|$: The average number of nodes that may corrupt transmission $u \rightarrow v$ for all time-slots in $FF_{u \rightarrow v}$ set.
 - $|S^{FF}|$: The average number of $|S^{FF_{u \rightarrow v}}|$ for all considered transmissions.

Based on the previous definitions, it is concluded that:

- $AA_{u \rightarrow v}$ and $AF_{u \rightarrow v}$ sets are mutually exclusive.
- $|AA_{u \rightarrow v}| + |AF_{u \rightarrow v}| = |\Omega_u| = q$.
- $FA_{u \rightarrow v}$ and $FF_{u \rightarrow v}$ sets are mutually exclusive.
- $|FA_{u \rightarrow v}| + |FF_{u \rightarrow v}| = |F_u|$.

D.1.3 Set examples

To further elaborate on the previous definitions that will be used later for the analysis of the proposed Refined Policy, an example network of eight nodes in a 4-regular graph topology is depicted in Fig. D.2. It is a ring topology where each node is neighbor to the two nearest left-side nodes and the two nearest right-side nodes.

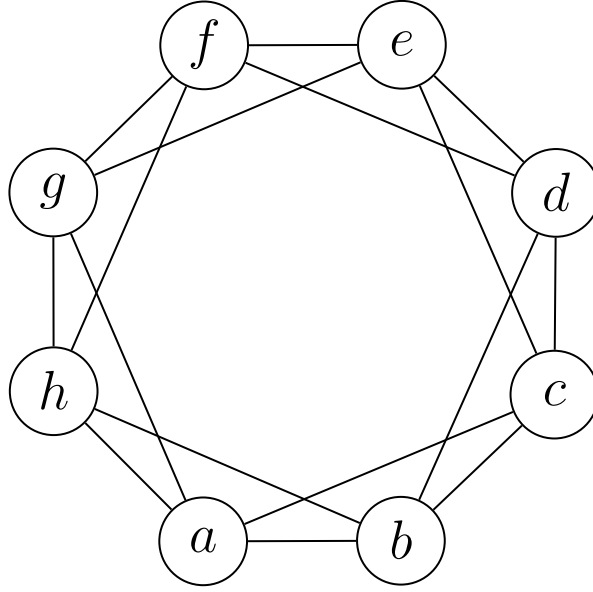


Figure D.2: Regular graph example with eight nodes and four neighbors per node.

Fig. D.3 depicts the frame state of all eight nodes illustrated in Fig. D.2. Similarly, as in Fig. D.1, X , p and empty boxes correspond to assigned time-slots, free time-slots and time-slots that no transmission is allowed, respectively. Table. D.1 depicts the size of the various sets defined earlier for all the four possible transmissions originating from node a .

Based on Fig. D.3 and Table. D.1, the following observations can be made:

- The value of $|AA_{u \rightarrow v}|$ depends on the receiver node, i.e., node v . For example, when transmission $a \rightarrow b$ takes place, $|AA_{a \rightarrow b}| = 2$, but when the transmission $a \rightarrow g$ takes place, $|AA_{a \rightarrow g}| = 3$.
- The same applies to $|FF_{u \rightarrow v}|$. For example when transmission $a \rightarrow c$ takes place, $|FF_{a \rightarrow c}| = 4$, while for the transmission $a \rightarrow h$ takes place, $|FF_{a \rightarrow h}| = 6$.
- $S_i^{AF_{u \rightarrow v}}$ is different for every time-slot. For example, when transmission $a \rightarrow c$ takes place during time-slot 5, $|S_{05}^{AF_{a \rightarrow c}}| = 2$, while for the same transmission during time-slot 20, $|S_{20}^{AF_{a \rightarrow c}}| = 1$. It is also observed that $|S_i^{AF_{u \rightarrow v}}|$ changes for different transmissions taking place at the same time-slot.
- The same applies to the $S_i^{FF_{u \rightarrow v}}$ set. For example, when transmission $a \rightarrow h$ takes place at time-slot 17, $|S_{17}^{FF_{a \rightarrow h}}| = 2$, but when the same transmission

Slot in frame	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Slot in subframe	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	
<i>a</i>	0x+0	X	<i>p</i>		<i>p</i>		X					X		<i>p</i>			X	<i>p</i>	<i>p</i>		<i>p</i>	X			<i>p</i>	<i>p</i>
<i>b</i>	1x+2			X	<i>p</i>					X			<i>p</i>			X	X	<i>p</i>	<i>p</i>		<i>p</i>		X			<i>p</i>
<i>c</i>	2x+4				<i>p</i>	X		X	<i>p</i>				<i>p</i>		X		X	<i>p</i>		<i>p</i>	<i>p</i>			X		<i>p</i>
<i>d</i>	3x+1		X				<i>p</i>		<i>p</i>		X		<i>p</i>	X			X			<i>p</i>	<i>p</i>	<i>p</i>			X	<i>p</i>
<i>e</i>	4x+0	X					<i>p</i>		<i>p</i>	<i>p</i>	X				X	<i>p</i>			X		<i>p</i>		X			<i>p</i>
<i>f</i>	1x+3				X		<i>p</i>	<i>p</i>		<i>p</i>	X	X				<i>p</i>		X			<i>p</i>			X		<i>p</i>
<i>g</i>	2x+2		<i>p</i>	X				<i>p</i>		<i>p</i>	X		X	<i>p</i>		<i>p</i>				X	<i>p</i>	X			<i>p</i>	<i>p</i>
<i>h</i>	3x+4		<i>p</i>			X		<i>p</i>	X			X		<i>p</i>	<i>p</i>				<i>p</i>	X	<i>p</i>		X		<i>p</i>	<i>p</i>

Figure D.3: The frame corresponding to the network of fig D.2. It is assumed that $q = 5$ and $k = 1$. Consequently, eight 1st degree polynomials with coefficients 0, 1, 2, 3 or 4 have been randomly assigned to the network nodes.

takes place at time-slot 24, $|S_{24}^{FF_{a \rightarrow h}}| = 4$. As before, $|S_i^{FF_{u \rightarrow v}}|$ changes for different transmissions taking place during the same time-slot.

- $S_{u \rightarrow v}^{2hop}$ depends on the relative position of nodes u and v in the network. For example, when transmission $a \rightarrow b$ takes place, $S_{a \rightarrow b}^{2hop} = \{d\}$ but when $a \rightarrow c$ takes place, $S_{a \rightarrow c}^{2hop} = \{d, e\}$. It can also be observed that $|S_{u \rightarrow v}^{2hop}|$ is either 1 or 2. these values can be generalized for any K -regular graph which follows the current example's ring topology fashion. Thus, it can be observed that $|S_{u \rightarrow v}^{2hop}|$ is an integer value between 1 and $\frac{K}{2}$.

D.2 Analysis of the Refined Policy

An analytical expression regarding throughput of the proposed Refined Policy is presented next before deriving an analytical expression for the access probability.

D.2.1 Throughput

The first step is to calculate throughput for a particular time-slot i and a particular transmission $u \rightarrow v$. This corresponds to the probability of transmission $u \rightarrow v$ being successful and is denoted as $P_{R,i,u \rightarrow v}$. When node u transmits towards node v during time-slot i , this time-slot may either be assigned to u or perceived as free by

	$v = b$	$v = c$	$v = g$	$v = h$
$ F_a $	8	8	8	8
$ AA_{a \rightarrow v} $	2	2	3	3
$ AF_{a \rightarrow v} $	3	3	2	2
$ FA_{a \rightarrow v} $	3	4	3	2
$ FF_{a \rightarrow v} $	5	4	5	6
$ S_0^{AF_{a \rightarrow v}} $	0			0
$ S_5^{AF_{a \rightarrow v}} $	1	2	2	1
$ S_{10}^{AF_{a \rightarrow v}} $		0		
$ S_{15}^{AF_{a \rightarrow v}} $			0	
$ S_{20}^{AF_{a \rightarrow v}} $	1	1		
$ S_1^{FF_{a \rightarrow v}} $			2	2
$ S_3^{FF_{a \rightarrow v}} $	3	2		2
$ S_{12}^{FF_{a \rightarrow v}} $			2	2
$ S_{16}^{FF_{a \rightarrow v}} $	3	2		
$ S_{17}^{FF_{a \rightarrow v}} $	3			2
$ S_{19}^{FF_{a \rightarrow v}} $	4	4	4	
$ S_{23}^{FF_{a \rightarrow v}} $			2	2
$ S_{24}^{FF_{a \rightarrow v}} $	4	4	4	4
$ S_{a \rightarrow v}^{2hop} $	1	2	2	1

Table D.1: The size of various sets for the network of Fig. D.2 and the frame assignment of Fig. D.3.

u . Furthermore, this time-slot may or may not be assigned to another node that can corrupt the transmission. In the latter case, for the transmission to be successful, no node able to corrupt it should transmit at the same time. These cases correspond to all four possible outcomes for transmission $u \rightarrow v$ during time-slot i , thus,

$$P_{R,i,u \rightarrow v} = \begin{cases} 0, & i \in \Omega_u, i \in AA_{u \rightarrow v} \\ (1-p)^{|S_i^{AF_{u \rightarrow v}}|}, & i \in \Omega_u, i \in AF_{u \rightarrow v} \\ p(1-p)^{|S_i^{FF_{u \rightarrow v}}|}, & i \notin \Omega_u, i \in FF_{u \rightarrow v} \\ 0, & i \notin \Omega_u, i \in FA_{u \rightarrow v} \end{cases} \quad (D.1)$$

Throughput regarding transmission $u \rightarrow v$ for all time-slots, denoted as $P_{R,u \rightarrow v}$, is defined as the average of $P_{R,i,u \rightarrow v}$,

$$P_{R,u \rightarrow v} = \frac{1}{q^2} \sum_{i=0}^{q^2-1} P_{R,i,u \rightarrow v} \quad (D.2)$$

As $S_i^{AF_{u \rightarrow v}}$ and $S_i^{FF_{u \rightarrow v}}$ sets vary by time-slot i , average values are considered next in order to proceed with the analysis. The validity of this average analysis will be demonstrated later using simulation results. Hereafter, it will be assumed that $|S_i^{AF_{u \rightarrow v}}| = |S^{AF_{u \rightarrow v}}|$ and $|S_i^{FF_{u \rightarrow v}}| = |S^{FF_{u \rightarrow v}}|$.

Any node u is assigned q time-slots. Out of these time-slots, $|AA_{u \rightarrow v}|$ have been assigned to at least one neighbor able to corrupt $u \rightarrow v$. Consequently, a successful transmission will take place during $|AF_{u \rightarrow v}| = q - |AA_{u \rightarrow v}|$ assigned time-slots, provided none of the $|S_i^{AF_{u \rightarrow v}}|$ nodes transmits (with probability p). Eventually, the number of successful transmissions during the assigned time-slots of node u for the transmission $u \rightarrow v$ is $|AF_{u \rightarrow v}|(1-p)^{|S^{AF_{u \rightarrow v}}|}$. Similarly, the number of successful transmissions $u \rightarrow v$ during time-slots not assigned to node u as well as to any node able to corrupt it can be calculated. As mentioned earlier, there are $|FF_{u \rightarrow v}| = |F_u| - |FA_{u \rightarrow v}|$ such time-slots, during which node u must transmit with probability p and $|S_i^{FF_{u \rightarrow v}}|$ nodes must not transmit (probabilistically), for a successful transmission to take place. Consequently, the number of these time-slots is $|FF_{u \rightarrow v}|p(1-p)^{|S^{FF_{u \rightarrow v}}|}$. Eventually, the sum of Equation D.2 can be substituted by the two values calculated above, thus,

$$P_{R,u \rightarrow v} = \frac{|AF_{u \rightarrow v}|(1-p)^{|S^{AF_{u \rightarrow v}}|} + |FF_{u \rightarrow v}|p(1-p)^{|S^{FF_{u \rightarrow v}}|}}{q^2} \quad (D.3)$$

System throughput P_R is defined as the average probability of success for all transmissions. It is actually the throughput for each transmission (i.e., $P_{R,u \rightarrow v}$) over

the total number of nodes (assuming that each node always transmits to the same neighbor node). Thus,

$$P_R = \frac{1}{N} \sum_{\forall u} \frac{|AF_{u \rightarrow v}|(1-p)^{|S^{AF_{u \rightarrow v}}|} + |FF_{u \rightarrow v}|p(1-p)^{|S^{FF_{u \rightarrow v}}|}}{q^2} \quad (D.4)$$

However, as already mentioned, sets $AF_{u \rightarrow v}$, $S^{AF_{u \rightarrow v}}$, $FF_{u \rightarrow v}$ and $S^{FF_{u \rightarrow v}}$ are different for each transmission. As before, average values of these sets will be considered next, their validity shown later at the evaluation section. That is, for the rest of the analysis it will be assumed that $|AF_{u \rightarrow v}| = |AF|$, $|S^{AF_{u \rightarrow v}}| = |S^{AF}|$, $|FF_{u \rightarrow v}| = |FF|$ and $|S^{FF_{u \rightarrow v}}| = |S^{FF}|$. Eventually, P_R , is given by,

$$P_R = \frac{1}{N} \sum_{\forall u} \frac{|AF_{u \rightarrow v}|(1-p)^{|S^{AF_{u \rightarrow v}}|} + |FF_{u \rightarrow v}|p(1-p)^{|S^{FF_{u \rightarrow v}}|}}{q^2} \quad (D.5)$$

$$P_R = \frac{|AF|(1-p)^{|S^{AF}|} + |FF|p(1-p)^{|S^{FF}|}}{q^2} \quad (D.6)$$

D.3 The Individual Access Probability

The Refined Policy, as presented in Section D.1, uses a common and fixed access probability p for transmitting in non-assigned time-slots. In this section, an analysis will be presented which calculates an *individual access probability* for each node in a distributed manner. Two cases are considered: first, each node u assumes that is part of a complete graph network topology and calculates its individual access probability (denoted as $\hat{p}_1(u)$) considering only its 1-hop neighbors; second, let D_u be node's u number of neighbors, each node assumes that is part of a K -regular graph network topology where every node has the same number of neighbor nodes as itself (thus $K = D_u$) and calculates its individual access probability (denoted as $\hat{p}_2(u)$) considering both its 1-hop and 2-hop neighbors.

The Complete Graph Case

Assuming a complete graph network topology under the Refined Policy, then every node is aware of the time-slot assignments of any other node in the network. Each node derives exactly the same F_u set since the available neighbor information is

common to all nodes. Consequently, every node u will transmit under probability $\hat{p}_1(u)$ in the same time-slots. For such a transmission to succeed, none of its D_u neighboring nodes must transmit at the same time. Note that, for the complete graph topology case as well as for the K -regular graph topology case considered next, $D_u = D$ for each node u . For a particular transmission $u \rightarrow v$ and for a time-slot i perceived as free by node u , throughput is given by,

$$P_{i,u \rightarrow v} = \hat{p}_1(u)(1 - \hat{p}_1(u))^{D_u} \quad (\text{D.7})$$

Studying the roots of the first derivative of Equation (D.7) with respect to $\hat{p}_1(u)$, the value that the maximum throughput is assumed can be calculated and is given by,

$$\hat{p}_1(u) = \frac{1}{D_u + 1} \quad (\text{D.8})$$

The K-Regular Graph Case

An analytical expression for $\hat{p}_2(u)$ will be derived next. In this case, both 1-hop and 2-hop neighbors are considered. However, knowledge of 2-hop neighbor count is not available. To compensate for this lack of information, every node u assumes that all nodes have the same neighbor count D_u as itself. This assumption essentially means that every node assumes that is part of a K -regular graph topology where $K = D_u$. A 4-regular graph network similar to Fig. D.2 will be considered for the derivation of $\hat{p}_2(u)$. It is a ring topology where each node is neighbor to the two nearest left-side nodes and the two nearest right-side nodes.

Considering the $u \rightarrow v$ transmission, whenever node u transmits probabilistically in a time-slot i which perceives as free, it has to assume that there are D_u additional nodes that might also transmit at the same time. The difference here (compared to the complete graph case) is that some of those nodes are 2-hop neighbors to node u and this means that node u is unaware whether time-slot i is also perceived as free by all transmitting nodes, or has been assigned to at least one of them. Consequently, there are two possible cases:

- Slot i has been assigned to at least one 2-hop neighbor of node u able to corrupt transmission $u \rightarrow v$, thus $i \in FA_{u \rightarrow v}$ set, as defined earlier in section D.1.3.

This means that $u \rightarrow v$ will always fail in time-slot i . Consequently, the best individual probability value for this particular time-slot should be $\hat{p}_2(u) = 0$.

- Slot i has not been assigned to any 2-hop neighbor of node u able to corrupt transmission $u \rightarrow v$, thus $i \in FF_{u \rightarrow v}$, as defined earlier in section D.1.3. This means that all D_u neighbors of node u might probabilistically transmit in time-slot i . Similarly to the complete graph case, the best individual probability value for this particular time-slot should be $\hat{p}_2(u) = \frac{1}{D_u+1}$.

Let the access probability of node u for a particular time-slot i when both 1-hop and 2-hop neighbors are considered, $\hat{p}_2(i, u)$ be given by,

$$\hat{p}_2(i, u) = \begin{cases} 0, & i \in FA_{u \rightarrow v} \\ \frac{1}{D_u+1}, & i \in FF_{u \rightarrow v} \end{cases} \quad (\text{D.9})$$

Since there are two distinct values which, depending on the particular time-slot, only one of them is correct, an average value will be calculated and used in every time-slot perceived as free. Let the average access probability $\hat{p}_2(u)$ when 2-hop information is acquired be given by,

$$\hat{p}_2(u) = \frac{1}{|F_u|} \sum_{\forall i \in F_u} \hat{p}_2(i, u) \quad (\text{D.10})$$

for each time-slot i given by Equation (D.9).

Node u perceives $|F_u|$ time-slots as free and will probabilistically transmit in them. Furthermore, every node has been assigned q time-slots from a total of q^2 . The probability of a time-slot not being assigned to two particular nodes at the same time can be calculated and is $\frac{q^2-q}{q^2}$ or $\frac{q-1}{q}$. Let $S_{u \rightarrow v}^{2hop}$ be the set of node u 's 2-hop neighbors able to disrupt $u \rightarrow v$ transmission. Those are the only nodes which may have been assigned a time-slot that is perceived as free by u . Consequently, the probability of time-slot i not having been assigned to at least one of the nodes able to corrupt the transmission is $(\frac{q-1}{q})^{|S_{u \rightarrow v}^{2hop}|}$. This probability can now be used for splitting the perceived as free time-slots in two groups:

- There are $|F_u|(\frac{q-1}{q})^{|S_{u \rightarrow v}^{2hop}|}$ time-slots that have not been assigned to any 2-hop neighbor node able to corrupt $u \rightarrow v$. For these time-slots it should be $\hat{p}_2(i, u) = \frac{1}{D_u+1}$.

- There are $|F_u|(1 - (\frac{q-1}{q})^{|S_{u \rightarrow v}^{2hop}|})$ time-slots that have been assigned to at least one 2-hop neighbor node able to corrupt $u \rightarrow v$. For these time-slots it should be $\hat{p}_2(i, u) = 0$.

Since the values of $\hat{p}_2(i, u)$ for the time-slots of the second group equal zero, those values can be excluded from the sum of $\hat{p}_2(i, u)$ in Equation (D.10). Consequently, Equation (D.10) can be written as,

$$\hat{p}_2(u) = \frac{1}{D_u + 1} \left(\frac{q-1}{q} \right)^{|S_{u \rightarrow v}^{2hop}|} \quad (\text{D.11})$$

The final step is the calculation of $|S_{u \rightarrow v}^{2hop}|$. However, this value corresponds to a particular transmission. Next, the average value denoted by $|S^{2hop}|$ will be considered. In the 4-regular graph network of Fig. D.2 it can be observed that any node may transmit to four possible destinations. The value of $|S_{u \rightarrow v}^{2hop}|$ changes depending on the positions of u and v in the topology. For the example of Fig. D.2, when the transmission $a \rightarrow b$ is considered, node d is the only 2-hop neighbor of node a able to disrupt this transmission, so $|S_{a \rightarrow b}^{2hop}| = 1$. When the transmission $a \rightarrow c$ is considered, nodes d and e are both 2-hop neighbors of node a and able to disrupt the transmission, consequently $|S_{a \rightarrow c}^{2hop}| = 2$. We can generalize the above observation for any similar K -regular graph topology. Depending on the transmitter and the receiver nodes' positions within the topology, $|S_{u \rightarrow v}^{2hop}|$ can be an integer value taking values from 1 to $\frac{K}{2}$. Since the target node is randomly selected, all values within the aforementioned interval have an equal probability of appearing. Consequently, the average number of nodes able to interfere and corrupt a (probabilistic) transmission is given by $|S^{2hop}| = \frac{1 + \frac{K}{2}}{2}$.

Following the calculation of $|S^{2hop}|$ and considering that $K = D_u = D$ for this type of network, the final form of the $\hat{p}_2(u)$ is derived as follows,

$$\hat{p}_2(u) = \frac{1}{D_u + 1} \left(\frac{q-1}{q} \right)^{\frac{1 + \frac{D_u}{2}}{2}} \quad (\text{D.12})$$

Each node u will derive its $\hat{p}_2(u)$ based on the assumption that every perceived as free time-slot i will also be perceived as free by every neighbor that has not been assigned this time-slot. However, it is possible that, due to locally obtained information, some neighbor may not perceive time-slot i as free and will never transmit in this time-slot. Consequently, the best value for $\hat{p}_2(u)$ may be slightly higher than

the one calculated with the use of Equation (D.12). However, this information is not available to node u . In the experiments section next, it is shown that the difference between the maximum achievable throughput and the one achieved with the use of $\hat{p}_2(u)$ is negligible.

D.4 Performance Evaluation

In this section, the proposed Refined Policy is evaluated through simulations against the Deterministic and the Probabilistic Policy in terms of throughput, total transmissions and successful transmissions during assigned and non-assigned time-slots separately. Additionally, the individual access probability calculation is evaluated, compared to a range of access probability values common to all nodes.

System throughput reflects the ability of a system to transmit as many messages as possible, so it always constitutes a primary evaluation metric. For the performance evaluation experiments, it is defined as the number of successful transmissions per node per time-slot, and the following Equation will be used next:

$$\text{throughput} = \frac{\# \text{ successful transmissions}}{\# \text{ nodes} \times \# \text{ time-slots}}$$

Each transmission directly impacts the transmitting node's energy consumption; therefore, it is of increased interest to evaluate the policies in terms of total transmissions. Fewer transmissions are expected under the Refined Policy since the number of non-assigned time-slots that a node can transmit is smaller than under the Probabilistic Policy.

Moreover, the number of successful transmissions during assigned or non-assigned time-slots is also used for evaluation purposes. Since nodes under the Refined Policy try to avoid transmissions during time-slots that are assigned to neighbors, it is expected that there will be an increase in successful transmissions during these time-slots. It is also interesting to investigate whether there will be a decrease in successful transmissions during non-assigned time-slots and how this decrement will affect the overall performance.

Finally, $\hat{p}_1(u)$ and $\hat{p}_2(u)$ will be used for the calculation of the individual access probability for each node and those scenarios will be evaluated against the scenarios where nodes transmit with a common access probability p .

D.4.1 Experimental setup

A simulation program was developed using the OMNET++ platform [140] and simulations are conducted to evaluate the proposed Refined Policy compared to both the Probabilistic and the Deterministic Policy. Three different network topologies are used, the Random Geometric Graph (RGG) [141], the Soft Random Geometric Graph (SRGG) [141] and the K-regular graph. Ten different networks are created for each topology.

For the RGG topology, each one of the ten networks contains $N = 1000$ nodes. The communication range is common for all nodes and is selected such that the maximum number of neighbors in the network is $D = 19$. These values are then used to derive $k = 1$ and $q = 37$. Eventually, the frame length is set to $q^2 = 1369$ time-slots, consisting of q subframes of length q . Given its unique ID and the values of q and k , each node can use the corresponding polynomial to derive its assigned time-slots. The simulation duration is 20 frames or 27380 time-slots.

For the SRGG topology, each one of the ten networks contains $N = 961$ nodes. Under the SRGG model, any pair of nodes may be connected under a *connectivity probability* $p(r) = e^{-(r/r_c)^\gamma}$, where r_c is the *connectivity radius* of each node, r is the particular pair's *euclidean distance* and γ is a constant related to the particular environment. For the simulations conducted here, $\gamma = 2$ and $r = 0.08$ are selected. The maximum number of neighbors in all SRGG networks is $D = 19$. N and D are used to derive $k = 1$ and $q = 31$ for those networks. Eventually, frame length is set to $q^2 = 961$ time-slots. The simulation duration is 20 frames or 19220 time-slots.

For the K -regular graph topologies, each one of the ten networks contains $N = 1000$ nodes and $K = 18$ is selected. The same parameters $k = 1$ and $q = 37$ are also used, leading to the same frame length ($q^2 = 1369$) and number of assigned time-slots per node as in the RGG networks. Note that every node calculates the same value for the individual access probability for this topology.

Finally, four additional RGG topologies with different N, D, k and q parameters were created where the throughput of the individual access probability case is again compared to the common probability case but as well as to the calculated throughput with the use of Equation D.6.

After the initial setup, the topology remains unchanged for the duration of each experiment. Node clocks are considered fully synchronized and each node operates

under heavy traffic load, meaning that there are always data available for transmission whenever a node is allowed to transmit. For the RGG and SRGG network topologies, node 0 is arbitrarily selected as the final destination node for each message. Thus, every node selects its target according to the shortest path leading to node 0. For the regular graph networks, each node randomly selects one of its neighbors prior to each transmission. The physical medium is ideal, so no packets are lost due to physical medium errors. Only collisions due to simultaneous transmissions take place. Each target node responds with an ACK message at the end of each time-slot and upon successful message transmission, thus notifying the source node for the successful reception.

D.4.2 Simulation results for RGG and SRGG topologies

Fig. D.4 and fig. D.5 depict throughput simulation results for the Random Geometric Graphs and Soft Random Geometric Graphs respectively, as a function of the access probability p (the Deterministic Policy corresponds to $p = 0$). The two horizontal lines represent throughput for the individual access probabilities $\hat{p}_1$ and $\hat{p}_2$ (the particular nodes u are omitted for notation simplification). It can be observed that throughput under the proposed Refined Policy is higher than under the Probabilistic Policy for any value of the access probability p . For the fixed access probability common to all network nodes, the maximum throughput under the Refined Policy is about 10% higher than under the Probabilistic Policy. However, throughput for both individual access probability cases is larger than the maximum throughput achieved under the common access probability. For the case of $\hat{p}_2$, throughput is observed to be slightly higher than for the case of $\hat{p}_1$.

Fig. D.6 depicts the number of total transmissions for the RGG scenarios and for all three policies as a function of the fixed access probability p that is common to all nodes (the Deterministic Policy corresponds to $p = 0$), as well as two horizontal lines representing the two individual access probability cases (i.e., $\hat{p}_1$ and $\hat{p}_2$). It can be seen that under the proposed policy, there are fewer total transmissions than under the Probabilistic Policy for any value of p . This is also the case for those values of p that each policy assumes the maximum throughput ($p = 0.8$ under the Probabilistic Policy and $p = 0.9$ under the Refined Policy). As can be observed, there are 8.4% fewer transmissions under the proposed policy. Regarding the individual

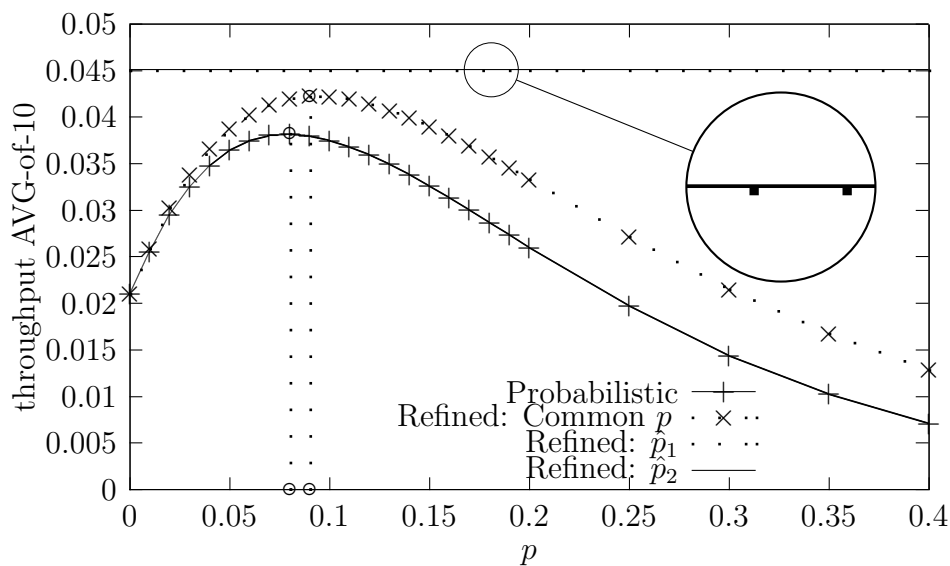


Figure D.4: Throughput as a function of the access probability p for the Random Geometric Graph topology. The two vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput under common p , respectively. The two horizontal lines correspond to the individual access probability scenarios, $\hat{p}_1(u)$ and $\hat{p}_2(u)$. Confidence intervals are no greater than 2.5%.

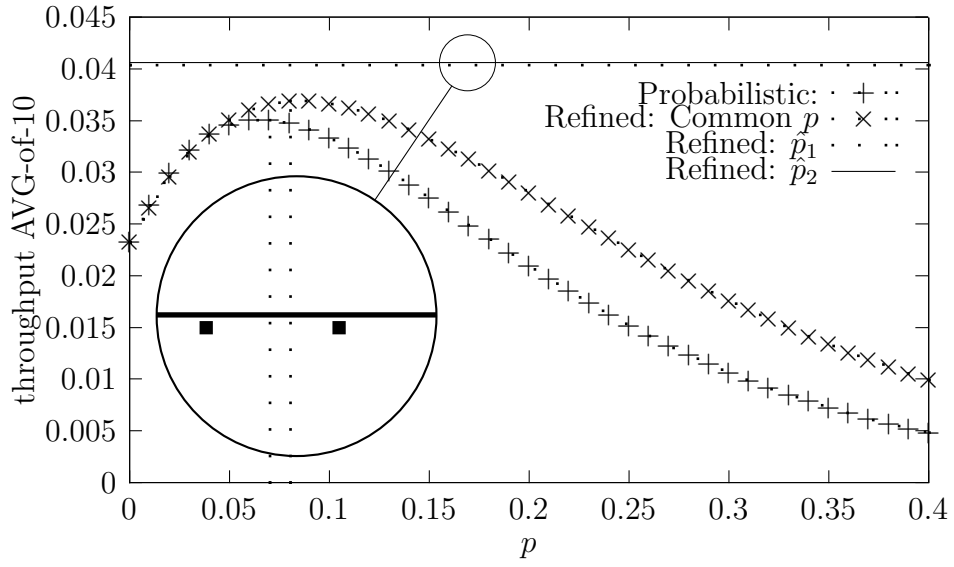


Figure D.5: Throughput as a function of the access probability p for the Soft Random Geometric Graph topology. The two vertical lines correspond to $p = 0.7$ and $p = 0.8$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput under common p , respectively. The two horizontal lines correspond to the individual access probability scenarios, $\hat{p}_1(u)$ and $\hat{p}_2(u)$. Confidence intervals are no larger than 3.91%.

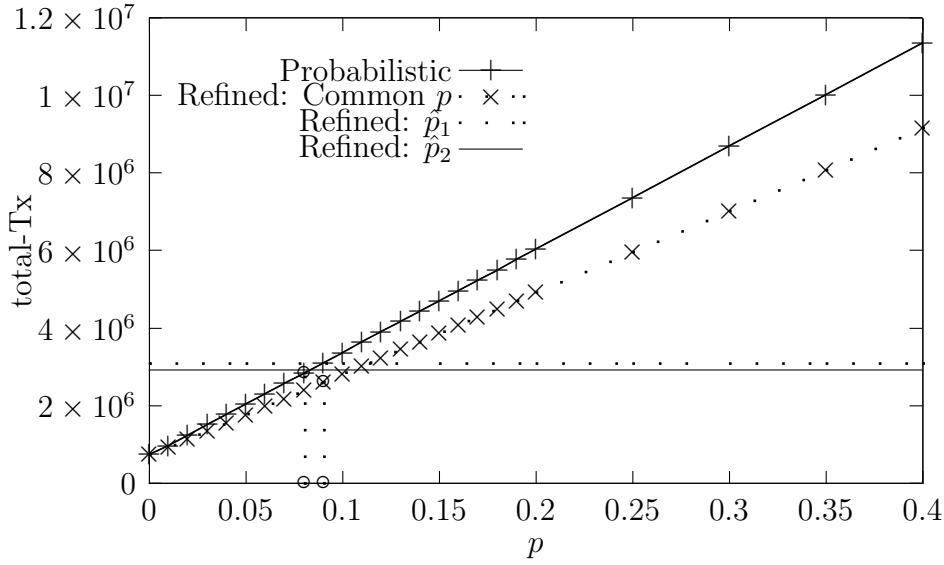


Figure D.6: The total number of transmissions as a function of the access probability p for the Random Geometric Graph topology. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput, respectively. Confidence intervals are no greater than 0.13%.

access probability cases, the total number of transmissions are comparable to those under the Probabilistic Policy when the maximum throughput is assumed. A better performance is also observed when using $\hat{p}_2$ compared to $\hat{p}_1$.

Fig. D.7 depicts the average number of successful transmissions per node per frame for the Random Geometric Graph topology during assigned or non-assigned time-slots separately. For the assigned time-slots and for the fixed access probability, it is observed from the depicted results that $p = 0.9$ corresponds to 19.94 successful transmissions per frame per node under the Refined Policy, which is about 45% better compared to the 13.68 successful transmissions under the Probabilistic Policy (for $p = 0.8$ where the maximum throughput is assumed). On the other hand, for the non-assigned time-slots, nodes under the Refined Policy succeed on 37.8 time-slots which are about 2% worse than under the Probabilistic Policy (38.5 successful transmissions on average). However, the increase of successful transmissions during the assigned time-slots outweighs the decrease of successes during the non-assigned

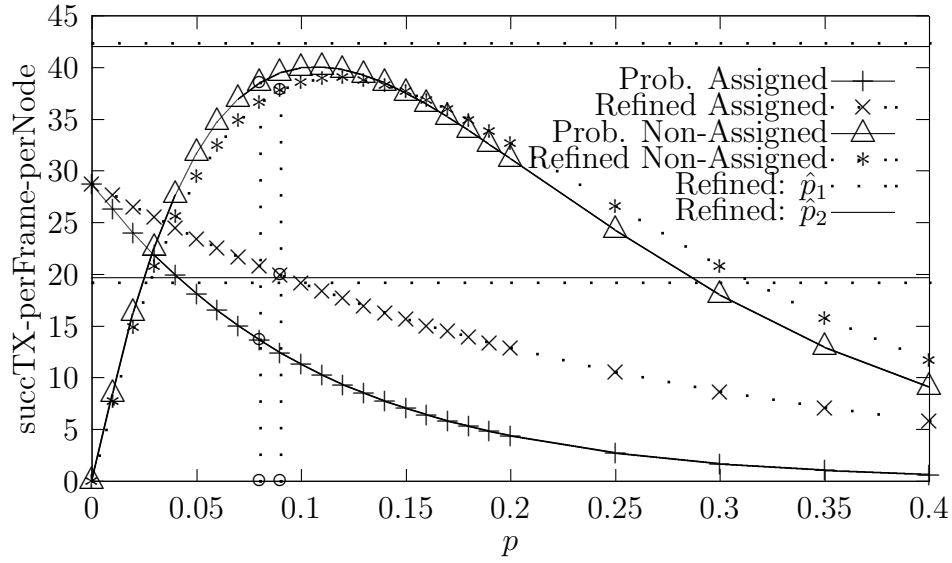


Figure D.7: Average number of successful transmissions for assigned and non-assigned time-slots per node per frame as a function of the access probability p for the Random Geometric Graph topology. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the Probabilistic Policy and the Refined Policy assume the maximum throughput, respectively. Confidence intervals are no greater than 3.5%.

time-slots. Regarding the individual access probability cases, it is observed that the successes during assigned time-slots are comparable to the Refined Policy case, where the highest throughput under the common access probability is achieved. At the same time, the successful transmissions during non-assigned time-slots are increased.

D.4.3 Simulation results for regular topologies

Fig. D.8 depicts throughput under the Probabilistic and the Refined Policies for an 18-regular graph topology. Similarly to the RGG and SRGG topology cases, the Refined Policy outperforms the Probabilistic Policy. The two horizontal lines correspond to the individual access probability cases ($\hat{p}_1$ and $\hat{p}_2$). Both throughput values corresponding to those cases match the throughput of two of the common access probability scenarios, which is to be expected since it is a regular graph

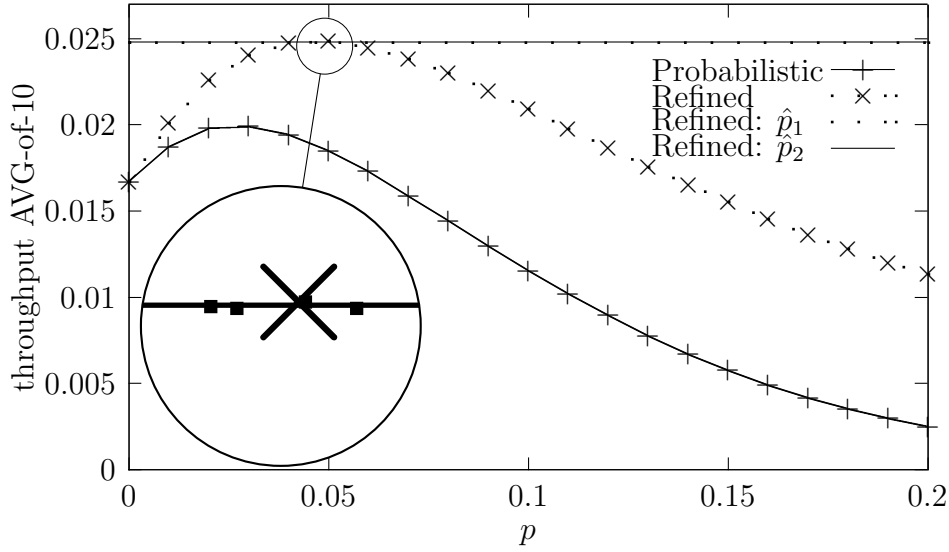


Figure D.8: Average throughput of ten networks for a 18-regular graph topology. The magnifying glass depicts the largest throughput value under common access probability, compared to both individual access probability values.

topology so all nodes calculate the same individual access probability value. It is observed that even though employing the individual probability, the maximum throughput, corresponding to a slightly higher probability value, is not assumed. However, the distance from the top is almost negligible. This difference, as already mentioned in Section D.3, can be attributed to the fact that some nodes that were expected to transmit probabilistically during some time-slots, do not transmit at all because, based on their own local information, they do not perceive those time-slots as free.

D.4.4 Simulation results for various RGG topologies

Figures D.9, D.10, D.11 and D.12 depict throughput of the Refined Policy for four RGG networks, created with different parameters. The fixed access probability scenarios are compared with the $\hat{p}_2$ individual access probability case. Furthermore, the analytical expression corresponding to the throughput calculation is evaluated here, as given in Equation D.6. Results from these simulations are used as input for

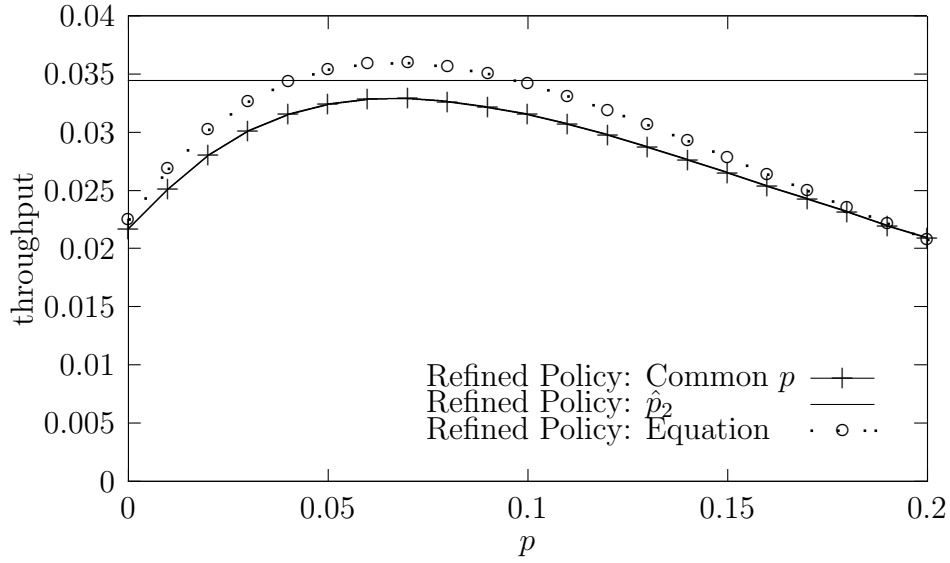


Figure D.9: Throughput evaluation for a RGG network topology with the following parameters: $N = 961$, $D = 25$, $k = 1$, $q = 31$.

Equation D.6.

Under all four scenarios, it is observed that the individual access probability calculation performs better in terms of throughput than the best common access probability scenario. Regarding the evaluation of the throughput analytical expression, it is observed that the numerical and the experimental results are close. For all four scenarios, it is also observed that the analytical expression results in larger values when p is close to the maximum. In contrast, as p increases, the analytical expression calculations decrease faster than the experimental results resulting in a lower value. This is attributed to the fact that the various average values used for the derivation of Equation D.6 introduce a deviation to the calculated values that eventually affect the overall performance.

Finally, two tables (D.2 and D.3) present results regarding those sets that are important for the derivation of the individual access probability for both cases. It can be observed that the standard deviation is relatively low, suggesting that if the individual values are substituted with their averages, the loss of accuracy will be low.

The results presented here suggest that the Refined Policy eventually avoids

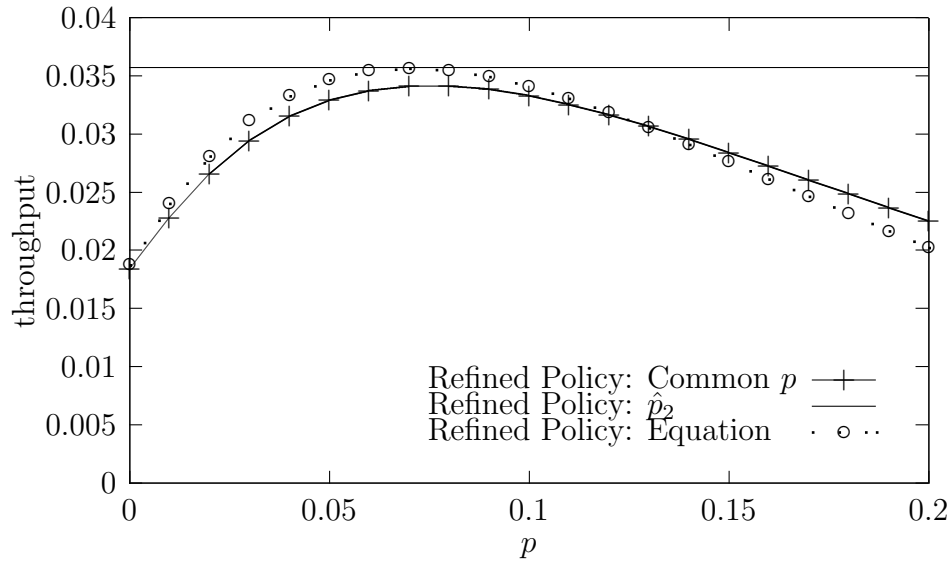


Figure D.10: Throughput evaluation for a RGG network topology with the following parameters: $N = 1681$, $D = 23$, $k = 1$, $q = 41$.

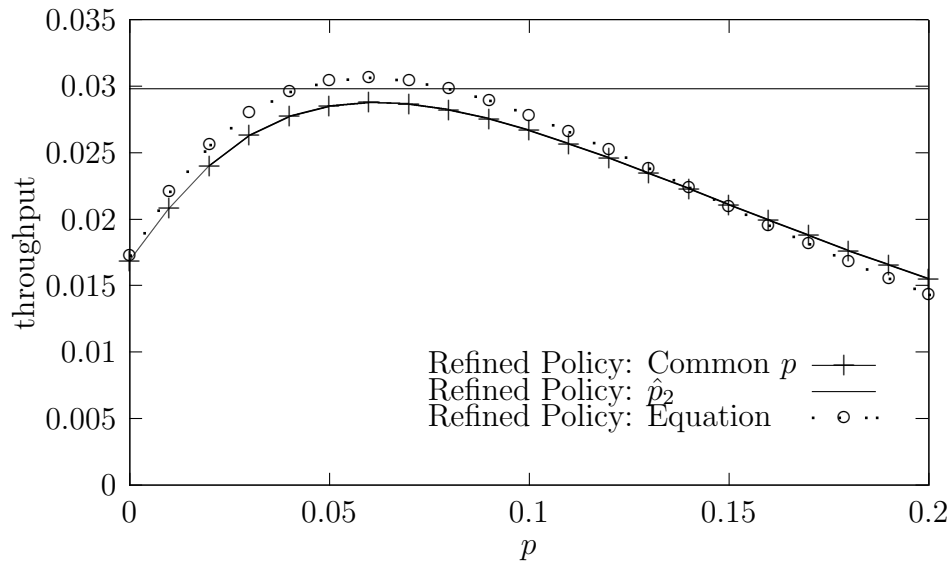


Figure D.11: Throughput evaluation for a RGG network topology with the following parameters: $N = 1849$, $D = 25$, $k = 1$, $q = 43$.

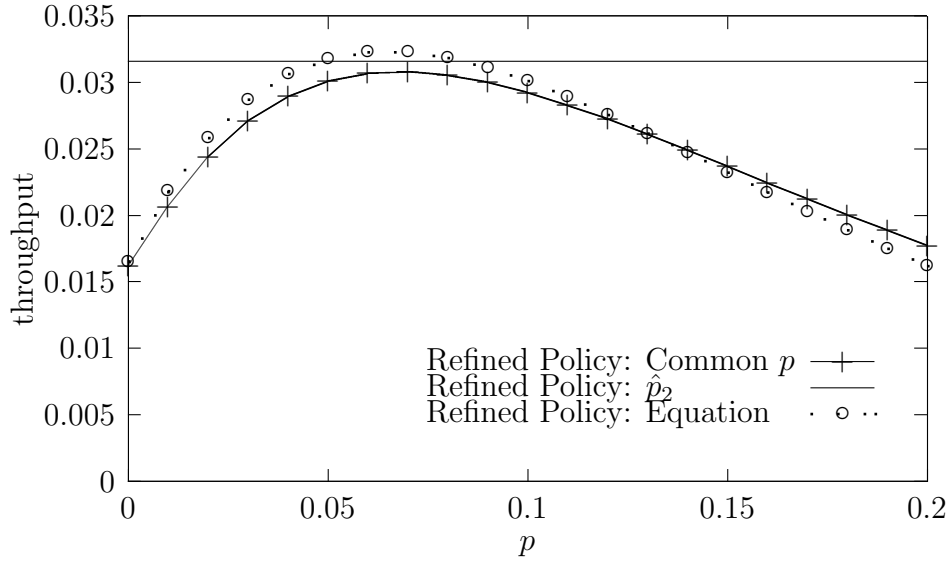


Figure D.12: Throughput evaluation for a RGG network topology with the following parameters: $N = 2209$, $D = 24$, $k = 1$, $q = 47$.

transmissions that would cause collisions. This allows other transmissions – that would otherwise be corrupted – to be successful and this, in turn, leads to an overall increase in system throughput and decreased energy consumption. Additionally, it is shown that calculating an individual value of the access probability in a distributed fashion is feasible and produces better results than the pre-assignment of a fixed access probability value common to all nodes.

D.5 Discussion and Conclusions

In this chapter, the Refined Policy is presented which is a TDMA topology-transparent policy extending the Deterministic and the Probabilistic Policies described earlier. The Refined Policy’s contribution is twofold: Firstly, a way is provided for utilizing the unused time-slots of the TDMA frame with the use of probabilistic transmissions and secondly, a way is introduced for calculating this transmission probability value in a decentralized fashion.

Regarding the unused time-slots utilization, the Refined Policy is based on the Probabilistic Policy under which, as described earlier, nodes are allowed to addi-

Set	Count	Min	Max	AVG	STD.DEV
$ S^{AF_{a \rightarrow b}} $		4,06	4,76	4,4	0,10
$ S^{FF_{a \rightarrow b}} $		16,43	16,54	16,49	0,02
$ AF_{a \rightarrow b} $		19	29	22,89	1,41
$ F_a $		799	820	809,8	3,25
$ FF_{a \rightarrow b} $		696	715	705,46	3,05

Table D.2: Example values for various sets in an 18-regular graph topology network with the following parameters: $N = 1000, D = 19, k = 1, q = 37$.

Set	Count	Min	Max	AVG	STD.DEV
$ S^{AF_{a \rightarrow b}} $		0,25	6,85	3,05	1,01
$ S^{FF_{a \rightarrow b}} $		1,9	15,1	8,71	2,26
$ AF_{a \rightarrow b} $		20	36	29,39	2,68
$ F_a $		783	1296	1047,61	92,60
$ FF_{a \rightarrow b} $		694	1261	949,58	93,31

Table D.3: Example values for various sets in a RGG network topology with the following parameters: $N = 1000, D = 19, k = 1, q = 37$.

tionally transmit during all their non-assigned time-slots with an access probability p . However, under the Refined Policy only a subset of those non-assigned time-slots is selected for probabilistic transmissions. This subset is derived by each node in a decentralized way. Each node utilizes information already contained inside the received messages (the transmitter's unique ID) to derive the set of time-slots that are non-assigned both to itself and to its 1-hop neighbors. This behavior is shown to increase system throughput when compared to that of the Probabilistic Policy's. This performance increase is attributed to the fact that those transmissions that did not take place (but they do under the Probabilistic Policy) had a very high chance of corrupting neighboring transmissions, since they would take place during some neighbor's assigned time-slot. This behavior is clearly demonstrated when a throughput comparison is made separately for the assigned and non-assigned time-

slots. It is shown that nodes under the Refined Policy achieve increased throughput during transmissions originating in their assigned time-slots. On the contrary, throughput in their non-assigned time-slots is decreased. This decrease is also to be expected, since the number of total transmissions during non-assigned time-slots is smaller under the Refined Policy. However, this decrease is outweighed by the increase observed during the assigned time-slots, resulting in the aforementioned general system throughput increase.

Additionally, it is observed that the total transmissions that took place under the Refined Policy are less than those under the Probabilistic Policy. Consequently, the aforementioned throughput increase was achieved while nodes performed fewer transmissions in total. This reduction can contribute to energy conservation.

The discussion until now assumes that nodes under both policies transmit with a common access probability value and the comparison between them was conducted for a range of values that are assumed to have been assigned to the nodes prior to the network operation. However, if the policy is to be used in a real network, a way for calculating and assigning a single probability value has to be implemented. This requirement introduces various problems, since it is obvious that a procedure has to be devised for both the calculation of the value and its assignment to the nodes afterwards. Such problems might include the gathering of information towards a centralized authority, which might be difficult in an ad hoc environment, or the implementation of a distributed algorithm, which might introduce high overhead especially in the case where nodes are mobile and the calculations have to be repeated at regular intervals.

To tackle those problems, the Refined Policy introduces the option of calculating in distributed fashion an individual access probability value for each node. This calculation is performed by each node individually and the only information required is its 1-hop neighbor count. Then, each node assumes that every other node in the network has the same neighbor count and based on this assumption proceeds to calculate a probability value that maximizes throughput under those network parameters. This calculation can be repeated whenever the node's neighbor count changes as no significant overhead is introduced.

The individual access probability method is evaluated in topologies including Random Geometric Graphs (thus the neighbor count per node will vary, contrary to the performed assumption) as well as K-regular graphs (thus the assumption made

by the nodes will match the simulation scenario). Under the RGG topologies, it is shown that the use of the individual access probability further improves throughput when compared to the aforementioned common access probability scenarios. Under the K-regular graph topologies, the individually calculated value is common for all nodes, thus it matches some common probability scenario, consequently no throughput improvement can be expected under such topology. However, simulation results demonstrate that the individually calculated probability value is very close the one that produces the maximum possible throughput when a common probability value is used.

In conclusion, the results presented in this chapter suggest that probabilistic approaches similar to those implemented in the Refined Policy are able to increase system performance in various ways. Consequently they might be suitable for various applications, especially when the objective is the utilization of unused time-slots in TDMA topology-transparent schemes like the Deterministic Policy.

Chapter E

The Fairness-Aware Policy

AN important factor for consideration when designing a MAC policy is the fair treatment of every node in the network. Fairness can be defined in various ways depending on the particular application. In the MAC layer, it is usually defined as the ability to equally distribute the medium access time among the nodes. However, this is a very generic definition, as the meaning of the word “equally” may also be defined according to the requirements of the particular application.

Traditional TDMA schemes are inherently fair because nodes operating under them are guaranteed to access the medium during their assigned time-slots. Under those schemes, nodes are usually assigned the same number of time-slots within a frame, consequently the medium is distributed “equally”, in the literal sense of this word. The Deterministic Policy may also be considered inherently fair because all nodes are assigned the same number of time-slots and are guaranteed a minimum number of successful transmissions. However, since collisions are allowed here, it cannot be expected that all nodes will successfully access the medium for “exactly” the same number of time-slots (as demonstrated in section B.2.2), so the definition of fairness for this policy has to consider the minimum guaranteed number of successes. Finally, the Probabilistic Policy can also be considered inherently fair because it assigns an “equal” access probability value to all nodes but it can be expected that nodes with less neighbors will be able to perform more successful transmissions as the medium is less congested in this area.

In this chapter, the Adaptive Policy [39] is revisited which extends the Proba-

bilistic Policy by adapting the value of the transmission probability during time-slots that a successful probabilistic transmission takes place. It will be shown that this behavior suffers from fairness issues, in the sense that some nodes experience very low throughput in favor of others. To tackle those issues, the *Fairness Aware Policy* is proposed in this section. Under this policy, nodes make use of a fairness evaluation metric as feedback and adapt their access probability value accordingly, with the purpose of achieving the maximum possible fairness among them.

E.1 Fairness Issues

Although the aforementioned adaptive policy achieves greater average throughput than both the Deterministic and the Probabilistic Policies, it also treats unfairly some of the nodes by not allowing them the same opportunities to access the wireless medium. The reason behind this unfair treatment is the fact that a problem similar to the hidden terminal problem exists. An example is suitable to give an insight to the problem before going to the formal definitions of the fairness metrics.

Let the example topology of Figure E.1 to be considered. Each node transmits data packets to its neighbor node towards node a and the network operates under full load (each node always has data to transmit). Under the adaptive policy, as soon as node b transmits a packet successfully to node a during a time-slot $i \notin \Omega_b$, then it will try in subsequent frames with probability one. If during the same time-slot node d transmits to node c , there will be a collision since node c also receives the transmission of node b towards node a . The transmission probability of node b for the particular time-slot should revert to its original value to allow node d to transmit successfully in some of the subsequent frames but this will never take place since there is no way for node b to become aware that its transmission interferes with node d 's transmission. Node b will always receive an ACK from node a and will continue transmitting with probability one during that particular time-slot at every consequent frame. Consequently node d is being treated “unfairly” in terms of channel allocation since there will be very few (if any) time-slots that it may successfully transmit.

Although the demonstrated problem corresponds to a very simple scenario, the above topology could well be part of a larger network where more nodes experience this unfair treatment.

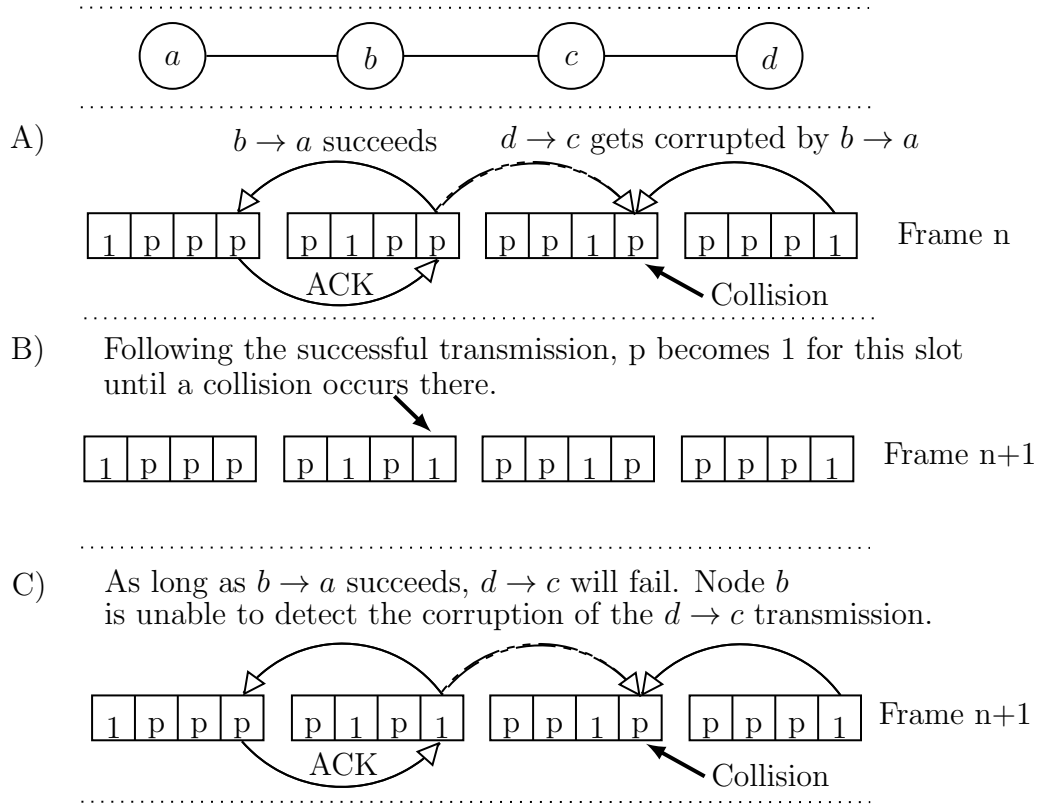


Figure E.1: Four nodes in a chain topology. The status of two consecutive frames of theirs under the adaptive policy is depicted underneath them, including the events that take place during the fourth time-slot. Nodes b , c and d transmit data packets to its neighbor node towards node a .

This problem does not appear under the Deterministic Policy because the algorithm responsible for the time-slot allocation ensures that each node will have at least one successful transmission per node. It also does not appear under the Probabilistic Policy since all nodes have exactly the same opportunity of transmitting during a non-assigned time-slot.

Motivated by this observation, a new policy is proposed in this chapter that takes into consideration the system fairness as well as the individual fairness of each node. Before presenting this new policy, the fairness evaluation metrics are described in the following section.

E.2 Fairness Evaluation Metrics

Among the numerous fairness metrics [142] Jain's index and envy are considered in this work and presented next.

E.2.1 The Jain's Index

The Jain's index [64] provides a simple centralized way of evaluating a system's fairness. It is defined as,

$$\mathcal{J}(\mathbf{X}) = \frac{[\sum_{\forall u} x_u]^2}{n \sum_{\forall u} x_u^2} \quad (\text{E.1})$$

where x_u is node's u resource allocation and $\mathbf{X}$ a vector of all allocations [64]. Later in the simulations section, the resource allocation will correspond to the total number of successful transmissions per node. The previous function produces a value within the $[0, \dots, 1]$ range. The higher this value the fairer the system. When $\mathcal{J}(\mathbf{X})$ is close to 0 this is an indication that the vast majority of individuals are treated unfairly in favor of a few. In contrast, when resources are allocated evenly among the individuals then it is the case that $\mathcal{J}(\mathbf{X}) = 1$.

E.2.2 The Envy Metric

The envy metric [70] has a distributed nature since it considers neighboring nodes for estimating their mutual envy. More specifically, a utility function $\mathcal{U}$ is defined that measures the impact of a current resource allocation x_u for node u by providing a value within the $[0, \dots, 1]$ range. When $\mathcal{U}(x_u) = 0$, this corresponds to the case

that node u did not transmit successfully not even once while $\mathcal{U}(x_u) = 1$ corresponds to the case that node u managed to transmit successfully at every time-slot.

Envy can be defined in various ways, which are thoroughly analyzed in [70] and [142] the ones considered here are given next.

- *Pairwise envy* : $\mathcal{E}_{uv}(\mathbf{X})$ for two nodes u and v and a given allocation $\mathbf{X}$ represents the amount of “envy” a node u “feels” for a node v for a resource allocation $\mathbf{X}$. Based on our previous definitions, the pairwise envy can be defined as,

$$\mathcal{E}_{uv}(\mathbf{X}) = \mathcal{U}(x_v) - \mathcal{U}(x_u) \quad (\text{E.2})$$

For the case of $\mathcal{E}_{uv}(\mathbf{X}) > 0$, node u is envious of v and the opposite is true when $\mathcal{E}_{uv}(\mathbf{X}) < 0$.

- *Individual envy*: $\mathcal{E}_u(\mathbf{X})$ of a node u represents the amount of envy that node u feels, compared to all its D_u neighbors at the same time, when the resource allocation is $\mathbf{X}$. Each node’s individual envy is the average of all its pairwise envies and it is defined as,

$$\mathcal{E}_u(\mathbf{X}) = \frac{1}{D_u - 1} \sum_{\forall v, v \neq u} \mathcal{E}_{uv}(\mathbf{X}) \quad (\text{E.3})$$

In a similar fashion as with pairwise envy, when $\mathcal{E}_u(\mathbf{X}) > 0$, node u is not satisfied with the resource allocation within its neighborhood and the opposite is true when $\mathcal{E}_u(\mathbf{X}) < 0$.

The envy metric will be used later as an integral part of the algorithm implemented in the proposed policy presented here. The result, as will be seen in subsection E.4.4, is the improvement of throughput to a point where fairness is not compromised. Since the envy metric can be distributively calculated based on information that is available in the nearby nodes, it does not add any significant overhead as would be the case with Jain’s index. Still, Jain’s index will also be used for evaluation purposes.

E.3 The Fairness-Aware TDMA MAC Policy

The main idea behind the proposed policy is to obtain feedback regarding fairness and exploit this information to adjust accordingly the value of transmission probability for each node. As already mentioned, the individual envy metric is employed as a fairness metric.

The first step under the proposed *Fairness-Aware Policy* is to determine the set of assigned time-slots Ω_u to each node u per frame as given by the Deterministic Policy. When data are available for transmission, then a transmission takes place for any time-slot $i \in \Omega_u$. When the time-slot $i \notin \Omega_u$, then a transmission takes place with probability p as long as there are data available for transmission.

Let $p_{\min}$ be the particular value of the transmission probability when no successful transmission has taken place before for a given time-slot $i \notin \Omega_u$ for a node u . Assume the event of a successful transmission at time-slot $i \notin \Omega_u$ for node u . Then, under the proposed policy, during the next frame, node u at time-slot $i \notin \Omega_u$ will transmit with probability $p_{\max}$. If a collision occurs, then the transmission probability becomes $p_{\min}$.

At the beginning of the system's operation $p_{\max} = 1$ but as time passes the value of $p_{\max}$ may be periodically modified taking values from within the $[p_{\min}, \dots, 1]$ range. This periodical adjustment of $p_{\max}$ throughout the network operation is the core of the proposed policy.

The next step is to adjust the value of the transmission probability p considering successful transmissions and fairness issues. In order to implement this step, each node is required to keep count of its own successful transmissions and pass this information within the header of every data packet it transmits. This extra field will be a small one, thus, adding negligible extra overhead to the overall system.

Whenever a particular node successfully receives a data packet, extracts this information from the header and stores it for future use, regardless of whether the intended receiver was itself or another node. This information is updated when a new packet is received from the same transmitter node. In the case of mobile network scenarios, the list of neighbor nodes may also be dynamically updated.

Given that the count of successful transmissions of each node is known to its neighbor nodes, the utility function of the envy metric ($\mathcal{U}$ and $\mathcal{E}$ for notation sim-

plicity), can be easily calculated for each node in the network as

$$\mathcal{U} = \frac{\text{successful transmissions until now}}{\text{total number of time-slots}}. \quad (\text{E.4})$$

Every node is now able to calculate its own pairwise envies by using the values of $\mathcal{U}$ in Equation (E.2). Then, with the use of Equation (E.3) the particular node's individual envy $\mathcal{E}$ is also calculated.

Given the $\mathcal{E}$ value, the following three cases are identified:

- ($\mathcal{E} > 0$): If the value of the calculated individual envy of a node is positive, this corresponds to the case the particular node has been treated unfairly until now compared to its neighbors. Consequently this node may increase its p_{max} (and adjust all corresponding time-slots), provided that $p_{max} \leq 1$.
- ($\mathcal{E} < 0$): when the individual envy is negative, this corresponds to the case that the particular node has benefited from the current time-slot allocation compared to its neighbors. Consequently it should decrease p_{max} (and adjust all corresponding time-slots) to allow its neighbors to increase their successful transmissions, provided that $p_{max} \geq p_{min}$.
- ($\mathcal{E} = 0$): p_{max} remains unchanged.

The increase/decrease of the p_{max} value will take place by adding or subtracting an arbitrarily predefined constant value c to its current value. This method should suffice for the needs of the present work, however a more optimal method of modifying p_{max} may exist and will be considered in future works.

As already mentioned, the proposed policy relies on local information and adapts whenever a successful transmission takes place and given the individual envy metric. Its throughput and fairness is evaluated against the other policies in the following section using simulation results.

E.4 Performance Evaluation

A program has been developed in the OMNET++ simulation platform [140] for the evaluation of the proposed fairness-aware policy, compared against the three topology-transparent policies (i.e. the deterministic policy, the probabilistic policy and the adaptive policy). The value for the increment constant $c = 0.1$.

The network size is set to $N = 1000$ nodes. The maximum node degree is $D = 19$. The application of the Chlamtac-Faragó algorithm to this type of network results in $k = 1$ and $q = 37$. Nodes' clocks are assumed to be perfectly synchronized and the wireless channel is considered ideal. Re-transmissions occur only after collisions. Ten different networks are randomly created that correspond to the above parameters. All networks are connected random geometric graphs, communication range is 0.054 for every node and node 0 is always selected as the node that all data packets will be transferred to over a shortest path tree. The duration of each simulation is 20 frames. The simulation scenarios will run at each one of the above networks and the average of the resulting values will be used for evaluating the MAC policies.

E.4.1 Evaluation Metrics

The evaluation metrics that are considered are (i) throughput; (ii) network fairness (Jain's index); (iii) node fairness (individual envy); (iv) the maximum number of consecutive re-transmissions.

Throughput is defined as the number of successful transmissions per node per time-slot,

$$\text{throughput} = \frac{\text{total successful transmissions}}{\text{total nodes} \times \text{total time-slots}}.$$

Network fairness is evaluated by calculating the Jain's index at the end of the simulation. The wireless medium is not shared among all nodes so depending on the topology it is expected that some nodes will have chance of less collisions than others.

Fairness per node is evaluated by using the individual envy metric. During each simulation this metric is calculated at the end of every frame to provide feedback to the fairness-aware policy. However, only the particular value at the end of the simulation is used for evaluation.

The maximum number of consecutive re-transmissions is considered here as a metric that is closely related to the delay seen by a node. Large numbers of consecutive re-transmissions correspond to increased delay due to the consecutive collision events that are the reason for the re-transmissions.

Finally, Pearson's correlation coefficient will be used to investigate whether there is any sort of linear association between an individual node's fairness level and its corresponding delay.

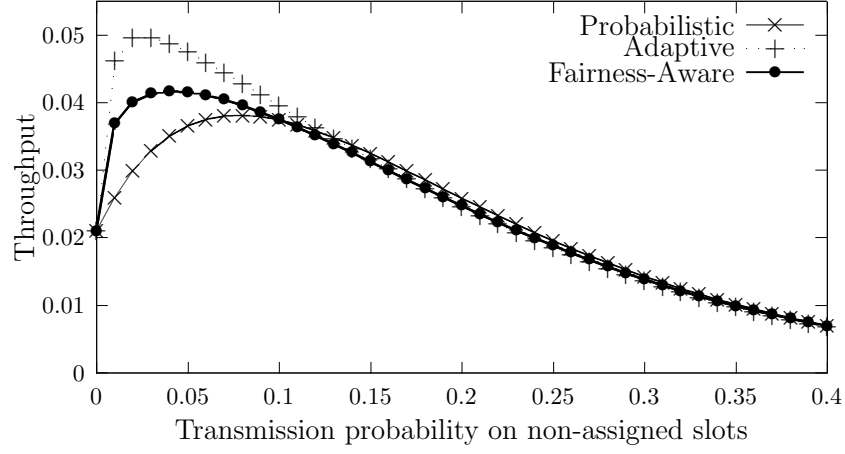


Figure E.2: Throughput as a function of the transmission probability. The upper and lower bounds of 95% confidence interval do not exceed 3.29% of the average values

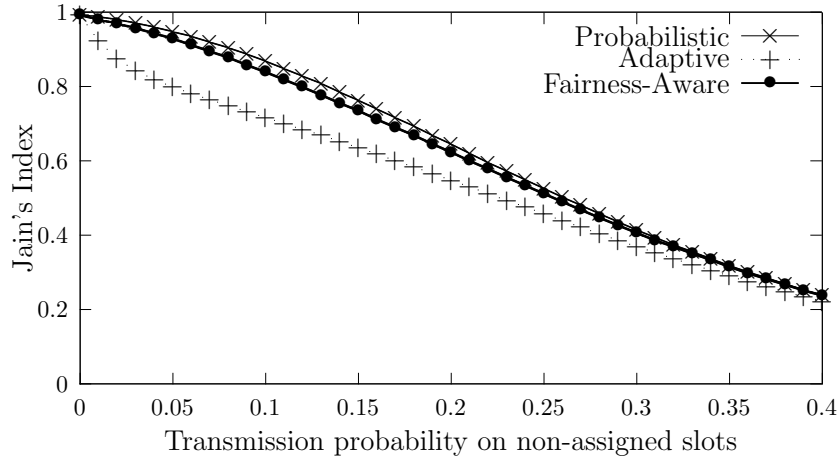


Figure E.3: Jain's index as a function of transmission probability. The upper and lower bounds of 95% confidence interval are below 1% of the average values when transmission probability is within ± 0.03 of the value which achieves maximum throughput for each policy.

E.4.2 Throughput Evaluation

The average throughput of the ten networks is depicted in Figure E.2 as a function of the transmission probability p . The throughput value of the deterministic policy can be seen when $p = 0$. This is the case where the nodes transmit only during the time-slots that were assigned on them by the algorithm. For any other value of $0 < p \leq 0.4$, throughput corresponding to the Probabilistic, Adaptive and Fairness-Aware Policies is depicted.

It can be observed that throughput under all three non-deterministic policies is greater than that under the Deterministic Policy when $0 < p \lesssim 0.23$. Furthermore, the Adaptive Policy achieves the highest throughput value, assuming its maximum value at $p = 0.03$ (136% increase when compared to the Deterministic Policy) while the Probabilistic Policy assumes its maximum value at $p = 0.08$ (81% increase). Throughput under the proposed Fairness-Aware Policy lies between them, and a throughput improvement by 98% is observed against the Deterministic Policy at $p = 0.04$.

E.4.3 Network Fairness

In Figure E.3, Jain's Index is depicted for all four policies as a function of the transmission probability p (the Deterministic Policy corresponds to $p = 0$). As expected, the fairest scenario is the one where $p = 0$ (Deterministic Policy) since all nodes have the same opportunities to transmit. However, the rate of success for each node is determined, as described in section B.2.2, by the specific polynomial group allocated to every neighborhood. Consequently, although all nodes are allocated the same number of time-slots, the number of successful transmissions differs among them, leading to a Jain's index value slightly lower than 1.

For the case of $p > 0$, it is observed (and confirmed as expected) that the Adaptive Policy is the least fair one, even though throughput under this policy is greater than that under the others. The best policy in terms of fairness is the Probabilistic Policy since nodes are allowed to transmit with the same probability during non-assigned time-slots. An interesting observation is that the proposed Fairness-Aware policy is slightly inferior to the Probabilistic Policy in terms of fairness. Note that throughput is larger under the Fairness-Aware Policy when compared against the Probabilistic Policy. Thus, it appears from the macroscopic view of the (overall)

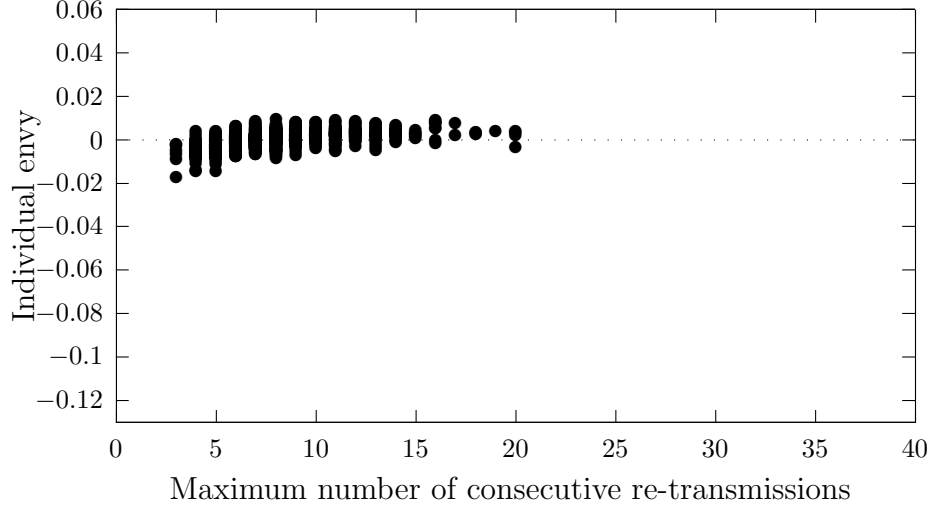


Figure E.4: Individual envy per node as a function of maximum number of consecutive re-transmissions under the probabilistic policy. Pearson's coefficient $r = 0.5194$

network fairness that the proposed policy is preferred against the Adaptive Policy in terms of fairness.

E.4.4 Fairness and Maximum Number of Re-transmissions per Node

Figures E.4, E.5 and E.6 depict each node's individual envy value for one arbitrarily selected network out of the ten that were created and for $p = 0.03$, in conjunction with the maximum number of re-transmissions per node. Individual envy was calculated with the use of equation (E.3). The particular value of the transmission probability $p = 0.03$ is the one that the adaptive policy assumes maximum throughput.

It is observed that under the Probabilistic Policy (Figure E.4) the individual envy values for the majority of nodes are concentrated within the $[-0.0075, 0.0075]$ range. Only a few nodes are treated more favorably having their individual envy values close to -0.015 . The most unfairly treated nodes have individual envy values concentrated around 0.01. The maximum number of re-transmissions does not exceed 20. A

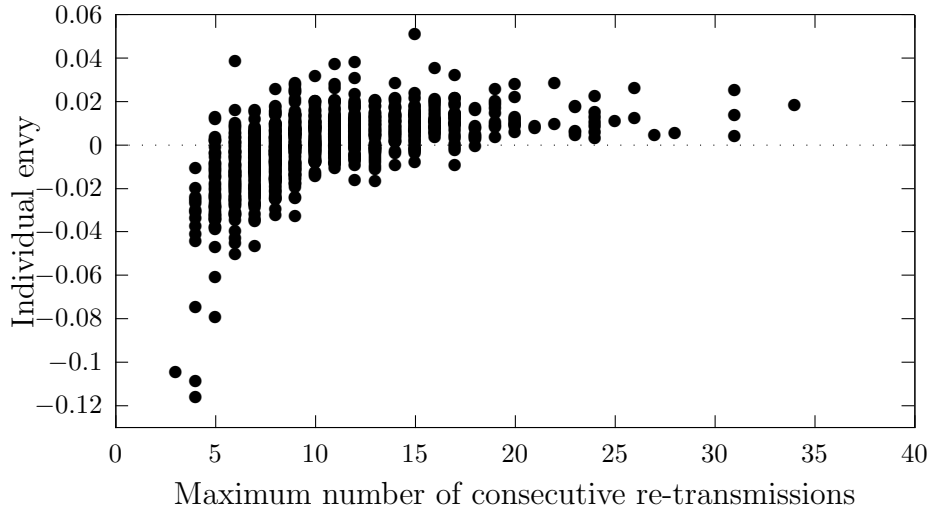


Figure E.5: Individual envy per node as a function of maximum number of consecutive re-transmissions under the adaptive policy. Pearson's coefficient $r = 0.5380$

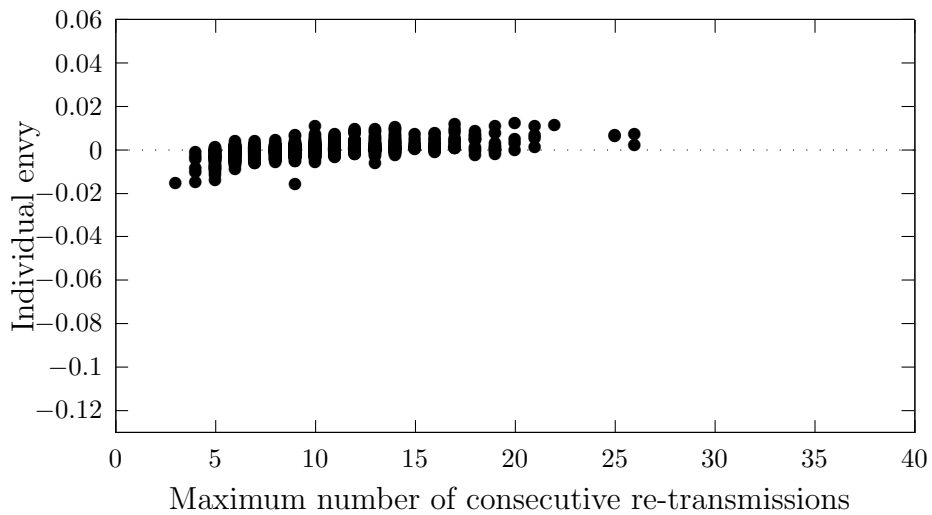


Figure E.6: Individual envy per node as a function of maximum number of consecutive re-transmissions under the fairness-aware policy. Pearson's coefficient $r = 0.5394$

moderate correlation between unfairness and delay is also observed, as the nodes with the higher number of consecutive re-transmissions tend to be unfairly treated, while the opposite holds true for the nodes with small number of consecutive re-transmissions.

Under the Adaptive Policy, as depicted in Figure E.5, it is observed that the individual envy values for the majority of the nodes lies between -0.02 and 0.02 . This is a 100% increase compared to the Probabilistic Policy. When looking at the edge values one can observe that the increase is even larger since there are some extremely favorably treated nodes of individual envy about -0.12 and the most unfavorably treated nodes concentrate around 0.04 . These results confirm the claim that the Adaptive Policy treats several nodes unfairly while others are more privileged. Again, as under the Probabilistic Policy, there seems to be a moderate positive correlation between fairness and delay.

It is interesting to observe that under the Fairness-Aware policy, the obtained results are close to those under the Probabilistic Policy. In particular, the individual envy value for the majority of the nodes lies within the $[-0.005, 0.005]$ range and the edge values just exceed the $[-0.015, 0.01]$ range. Thus, it can be concluded that the proposed policy, compared to the Probabilistic, achieves roughly the same levels of individual fairness and numbers of consecutive re-transmissions. A moderate positive correlation between fairness and delay is observable here too.

E.4.5 A Fairness Evaluation of the Refined Policy

In this section, the Refined Policy as presented in chapter D is revisited and evaluated with respect to fairness. Additionally, a comparison between the Fairness-Aware and the Refined Policy is conducted. The comparison of the two policies proposed in this thesis is interesting as they both extend the Deterministic and the Probabilistic Policy and they both improve on their predecessors' performance. However, in order to achieve their goals, they follow very different approaches.

Figure E.7 depicts throughput performance of the Fairness-Aware Policy compared to the Refined Policy. For the latter, both the common access and the individual access probability cases are considered. It can be observed that the common probability case of the Refined Policy performs better from the Fairness-Aware Policy in terms of their assumed maximum throughput value, although their difference

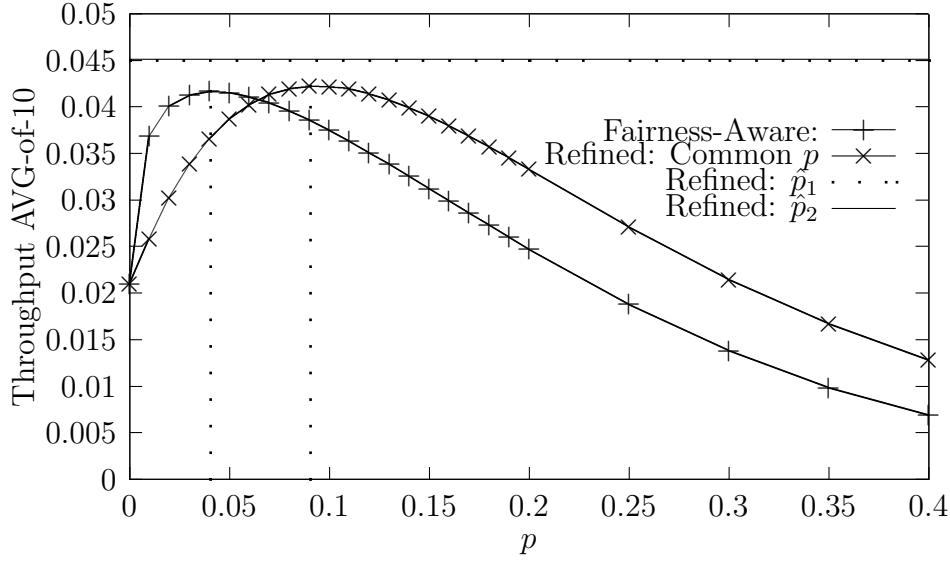


Figure E.7: Throughput of the Fairness-Aware Policy in comparison to the Refined Policy.

can be considered negligible. Their main difference lies in the value of the access probability that this maximum value is assumed. The Fairness-Aware Policy assumes its maximum throughput value when $p = 0.4$ while the Refined Policy assumes its maximum throughput value when $p = 0.9$. The depicted vertical lines correspond to those two cases. When the individual access probability cases are considered, throughput performance is increased, as can be observed by the two horizontal lines and as was already presented in the corresponding chapter where the Refined Policy was described.

In figure E.7 the two policies are compared in terms of total transmissions. It can be observed that the Refined Policy performs better when both policies operate under the same common access probability value. However, when only the cases where each policy assumes its maximum throughput are compared, it can be seen that the Fairness-Aware Policy transmits fewer messages than the Refined Policy. Note that when the Refined Policy was compared to the Probabilistic Policy in the corresponding chapter (figure D.6), the former was transmitting fewer packets even when only the cases where they assumed their maximum throughput were considered. The individual access probability cases transmit even more messages

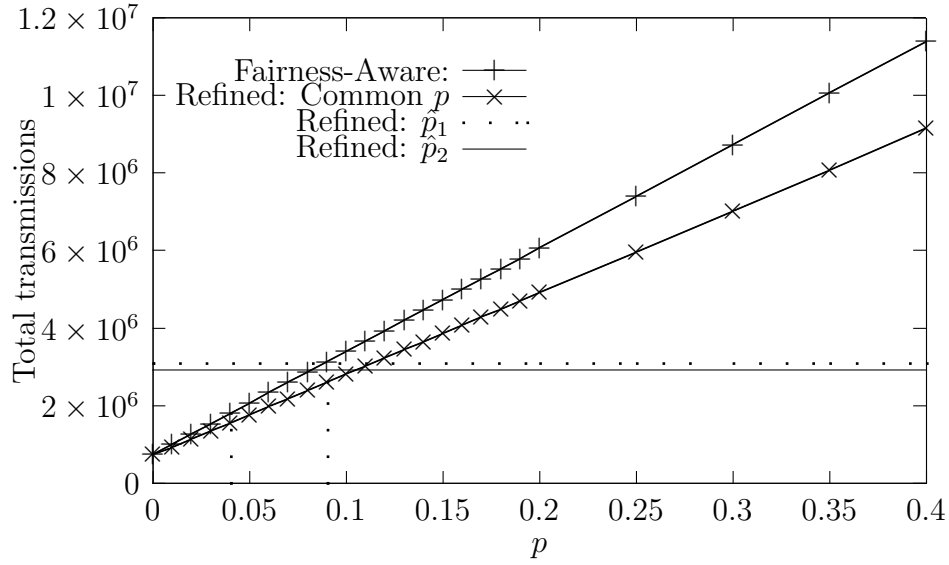


Figure E.8: Total transmissions of the Fairness-Aware Policy in comparison to the Refined Policy.

but at an increased throughput performance as already mentioned.

Figure E.9 depicts the individual envy for each node of a network operating under the Refined Policy and for the p_1 access probability case. Note that this is the same network that was used for figures E.4, E.5 and E.6. It can be observed that the majority of nodes are concentrated within the $(-0.02...0.02)$ interval in terms of individual envy and within the $(5...25)$ interval in terms of maximum number of consecutive re-transmissions. There are many nodes that were treated favorably when compared to the rest. Furthermore, some nodes demonstrate increased number of re-transmissions (more than 25). The depicted figure resembles the one depicted in figure E.5 which corresponds to the Adaptive Policy. However an interesting observation can be made here. Under the Adaptive Policy, the nodes that demonstrate the worst performance in terms of maximum re-transmissions, at the same time show a positive envy value, meaning that they consider themselves to have been treated unfairly when compared to their neighbors. Under the Refined Policy, those nodes have a negative envy value, meaning that they believe to have benefited from the current medium allocation when compared to their neighbors. Furthermore, the nodes that under the Refined Policy have benefited most, do not seem to perform

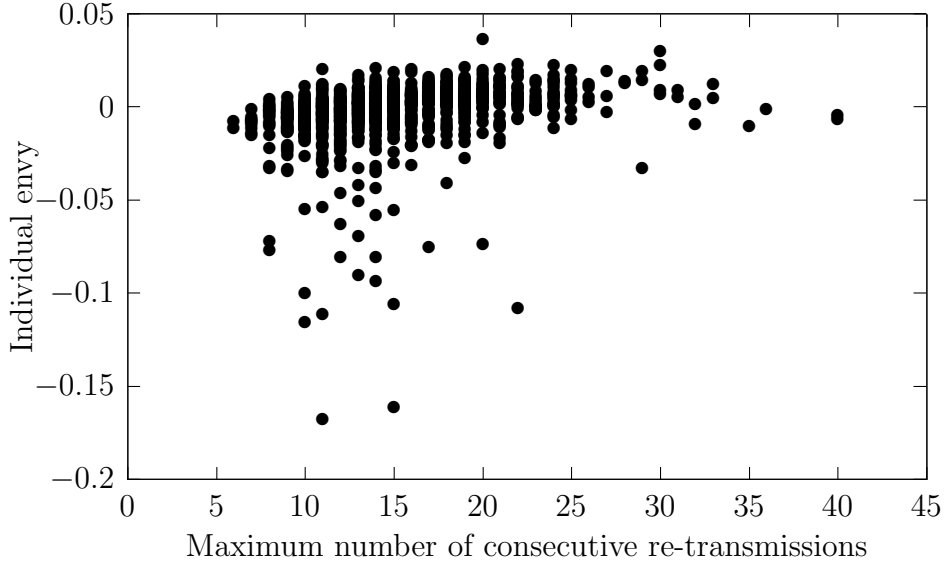


Figure E.9: Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with the individual access probability $\hat{p}_1$ case. Pearson's coefficient $r = 0.27$.

much better in terms of delay when compared to the rest as has been the case with the corresponding nodes under the Adaptive Policy. Consequently, it can be concluded that there is no correlation among the individual envy each node calculates and its performance in terms of delay. This can also be derived from the fact that the Pearson's correlation coefficient for those two variables is $r = 0.27$, a value which implies that there is negligible correlation between them.

Figure E.10 depicts the individual envy for each node of the previously used network when it operates under the Refined Policy with the use of the $\hat{p}_2$ access probability. Similar conclusions can be drawn to those of figure E.9. However, it may additionally be observed that the envy values corresponding to the nodes that benefited most are slightly larger (implying that the benefit was smaller). Similar observation can be made for the nodes that demonstrated higher delay, as those values have been slightly reduced as well. Those observations imply that the use of the individual access probability $\hat{p}_2$, when compared to the use of $\hat{p}_1$ might provide a higher degree of fairness while at the same time providing slightly increased throughput.

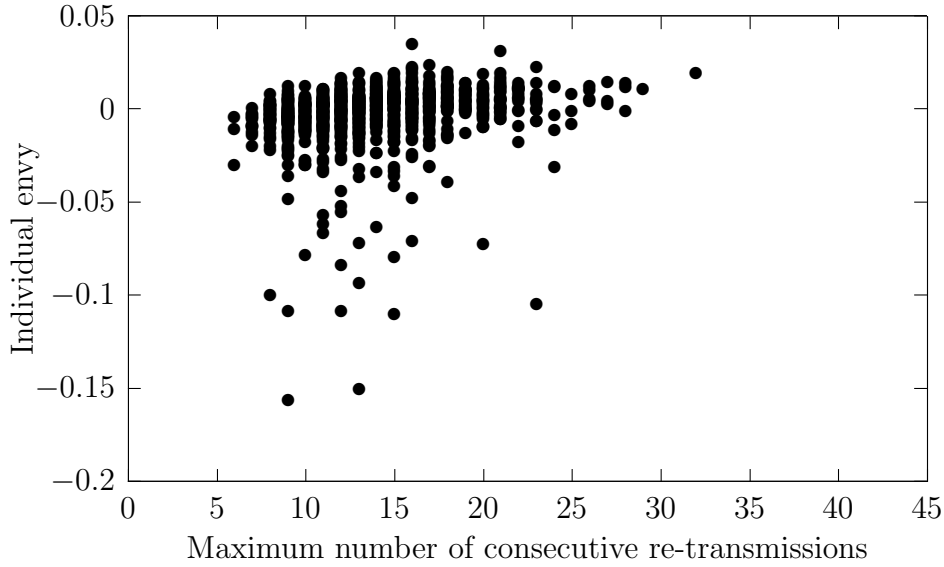


Figure E.10: Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with the individual access probability $\hat{p}_2$ case. Pearson's coefficient $r = 0.22$.

A final conclusion which can also be drawn by studying figures E.9 and E.10 is that both depicted policies do not treat the nodes fairly. This conclusion becomes more evident if those figures are compared with figure E.4 which depicts the fairness evaluation of the Probabilistic Policy. However, this unfairness is to be expected because since under the Refined Policy (when it operates using either $\hat{p}_1$ or $\hat{p}_2$) nodes assume various values for their transmission probability in non assigned time-slots, based on their neighbor count. Consequently, it is a logical expectation that nodes with few neighbors will transmit more frequently than nodes with more neighbors and will also achieve more successful transmissions since the transmission medium is likely to be less congested in their local neighborhood. This can be confirmed in figures E.11 and E.12 where each node's individual envy is depicted with respect to its number of neighbors. It can be observed that the nodes that have benefited most are the ones with only one neighbor. It is also obvious that a correlation exists between those two variables.

Figure E.13 depicts the individual envy for the nodes of the same network that was also used in figures E.4, E.5 and E.6 but here it operates under the Refined Policy

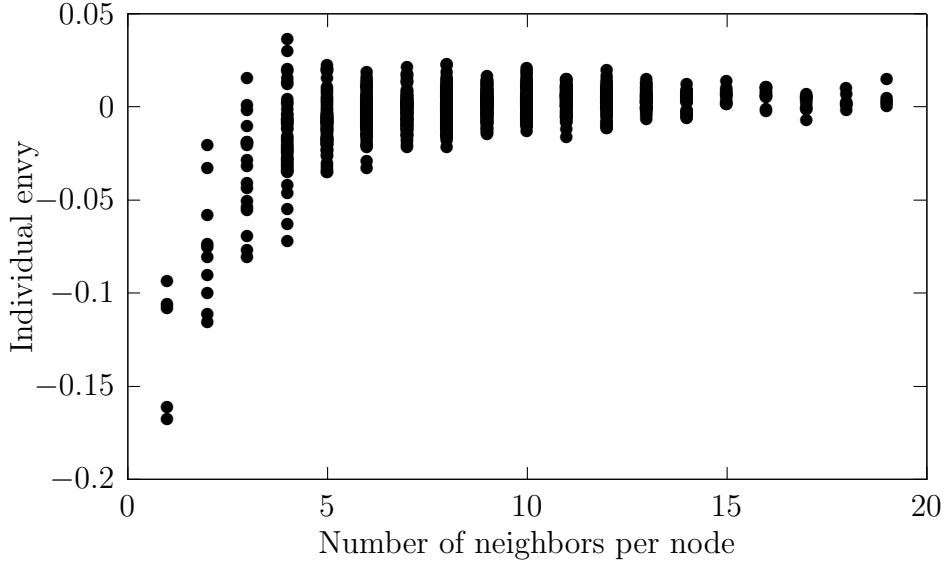


Figure E.11: Individual envy per node as a function of the number of neighbors per node under the Refined Policy operating with the individual access probability $\hat{p}_1$ case.

with common access probability. Its value is $p = 0.03$ as was also the case with the aforementioned policies during their evaluation. It can be observed that the policy's performance with respect to fairness as well as to delay is better than the other three policies' performance. However, under the current access probability value, throughput performance of the Refined Policy is lower than that of the Fairness-Aware Policy but comparable to that of the Probabilistic Policy.

Figure E.14 depicts the individual envy for a regular graph network with $K = 18$ operating under the Refined Policy and for both individual envy cases ($\hat{p}_1$ and $\hat{p}_2$). It can be observed that the individual envy value for all nodes is close to zero, meaning that all nodes feel that the resource allocation was fair. This was an expected result, since under this topology all nodes have exactly the same number of neighbors and they will also transmit under the same access probability p value. The differences in terms maximum consecutive re-transmissions can be attributed to the fact that, as mentioned earlier in section B.2.2, different combinations of polynomials produce different numbers of successful transmissions.

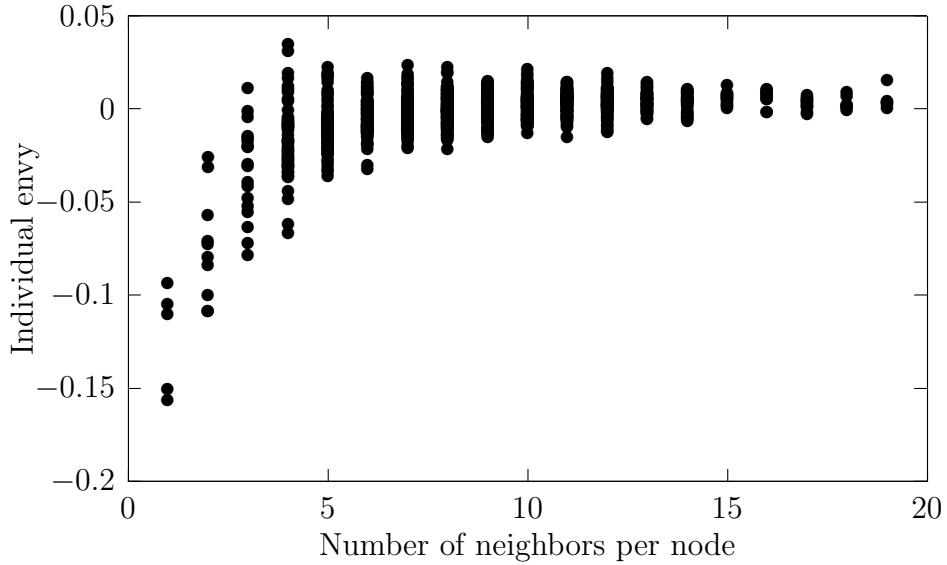


Figure E.12: Individual envy per node as a function of the number of neighbors per node under the Refined Policy operating with the individual access probability $\hat{p}_2$ case.

E.5 Discussion and Conclusions

In this chapter, another TDMA topology-transparent MAC policy is introduced, the Fairness-Aware Policy. This policy, similarly to the Refined Policy (introduced earlier in chapter D) and the Probabilistic and Adaptive Policies (which it extends) tries to increase throughput performance by allowing probabilistic transmissions in non-assigned time-slots. The value of the transmission probability is adjusted dynamically based on a feedback mechanism that considers whether the transmission medium has been allocated fairly among the nodes.

An important matter for consideration is how fairness can be defined and how it is quantified so as comparisons based on certain values are possible. For the purposes of evaluating the policies considered here, fairness is defined as the ability of each considered policy to provide an equal number of successful transmissions to the nodes. Consequently, based on this definition, the quantification of fairness relies simply on counting the number of successful transmissions of each node.

Two already existing fairness metrics are presented and used for evaluation. The

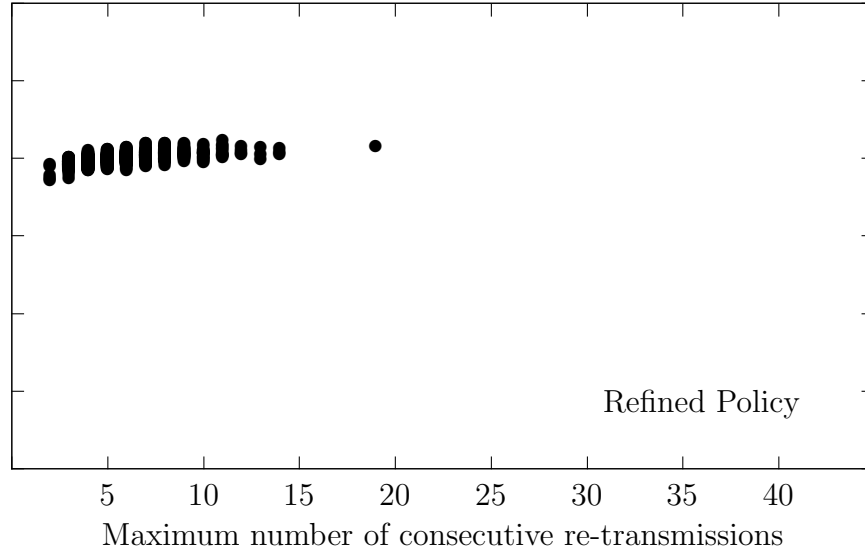


Figure E.13: Individual envy per node as a function of maximum number of consecutive re-transmissions under the Refined Policy operating with common access probability $p = 0.03$

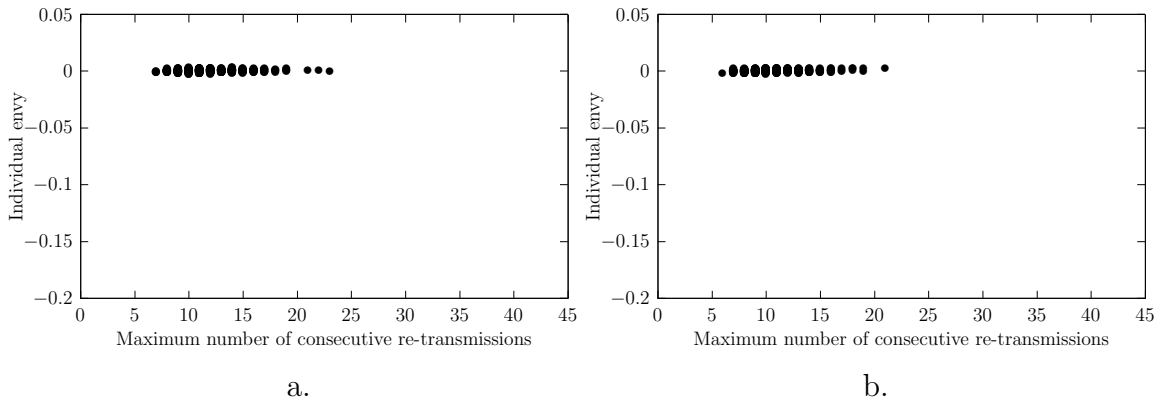


Figure E.14: Individual envy per node as a function of maximum number of consecutive re-transmissions for a K-18 regular graph network operating under the Refined Policy with common access probability $p = 0.03$

Jain's index requires global information and evaluates the total network fairness in a centralized fashion. The envy metric can be applied distributively so it was used by each node in the feedback mechanism that allows the dynamic adjustment of the transmission probability in non-assigned time-slots.

The introduced policy was compared against the Deterministic, Probabilistic, Adaptive and Refined Policies in terms of fairness, throughput, maximum consecutive re-transmissions and total number of transmissions. Simulation results show that the Fairness-Aware Policy, while not being able to achieve system throughput as high as the Adaptive Policy, it improves it when compared to the Deterministic and Probabilistic Policies and is only slightly inferior to the Refined Policy, when the latter operates with a common access probability value for all nodes. This improvement appears when the transmission probability on non-assigned time-slots (p) lies between a particular range of values. Under all the probabilistic policies, a peak throughput value is also observed for some value of p , different for each policy.

Under the Adaptive Policy it is obvious that some nodes are allocated too many time-slots so that their counterparts suffer from reduced performance both in terms of throughput and delay. Under the proposed policy, a node becomes aware to the fact that it has overused the medium and refrains from transmitting, thus allowing its neighboring nodes to have more frequent access to the medium. The opposite holds true for the unfairly treated nodes as they gradually increase their transmission probability to get increased access to the medium until they are satisfied.

When the Fairness-Aware Policy was compared to the Refined Policy, some interesting observations were made. When nodes under the Refined Policy operate with a common probability, the peak throughput for both policies is comparable. However, the Fairness-Aware Policy achieves its peak throughput on a lower probability value than the Refined Policy does. This fact seems to lead to a reduced number of total transmissions for the Fairness-Aware Policy. Another interesting observation is the fact that the Refined Policy, when using individual probability values for the nodes, seems to treat them unfairly and to a degree that is comparable to the Adaptive Policy's treatment. However the difference here is that the unfair treatment in terms of throughput under the Refined Policy does not seem to correlate with delay increase, as was the case under the Adaptive Policy. A correlation does exist though, between throughput and the number of neighbors. However this correlation is to be expected since the Refined Policy calculates higher individual probability

values for the nodes that have lower neighbor count. Consequently, nodes with fewer neighbors transmit more often in their non-assigned time-slots.

Based on the observed unfairness of the Refined Policy, an argument can be made whether the envy metric as defined here and used for feedback in the Fairness-Aware Policy is suitable for the evaluation of the Refined Policy. Since the latter is a policy that intentionally allows nodes to increase their total transmissions with respect to their neighbor count, perhaps a different definition is required for the envy metric if this policy is to be evaluated in terms of fairness.

In conclusion, the Fairness-Aware Policy demonstrated the potential of using a fairness metric as feedback mechanism that contributes to the improvement of system throughput to a point that the network fairness is not compromised considerably.

Chapter F

Low-cost Device Implementation of a Topology-Transparent Policy

SOME particular types of IoT networks consist of a large number of low-powered and low-cost devices. Those devices are usually of low computational capabilities as well. For such a network to be viable, power consumption of each node must be a primary concern. In such environment, the use of a TDMA MAC policy can be considered as an option because of its inherent power efficiency.

In this chapter, an implementation of the TiMAC protocol (as described in chapter C) in low-cost devices is presented. Even though the implementation is limited by synchronization issues and a small number of nodes, the results demonstrate the potential for employing topology-transparent policies on IoT networks consisting of low-cost devices.

F.1 The Proposed System

A network consisting of low-cost devices is assumed to play the role of the IoT system. Each device is a wireless node of the considered network and certain specifications regarding node operation need to be taken into consideration in order to implement the previously described TiMAC policy. The particular information along with various implementation issues (e.g., TDMA synchronization) is presented next. More specifically, the elements comprising the low-cost devices (nodes) are given in F.1.1, the types of messages being exchanged among the nodes are described in F.1.2,

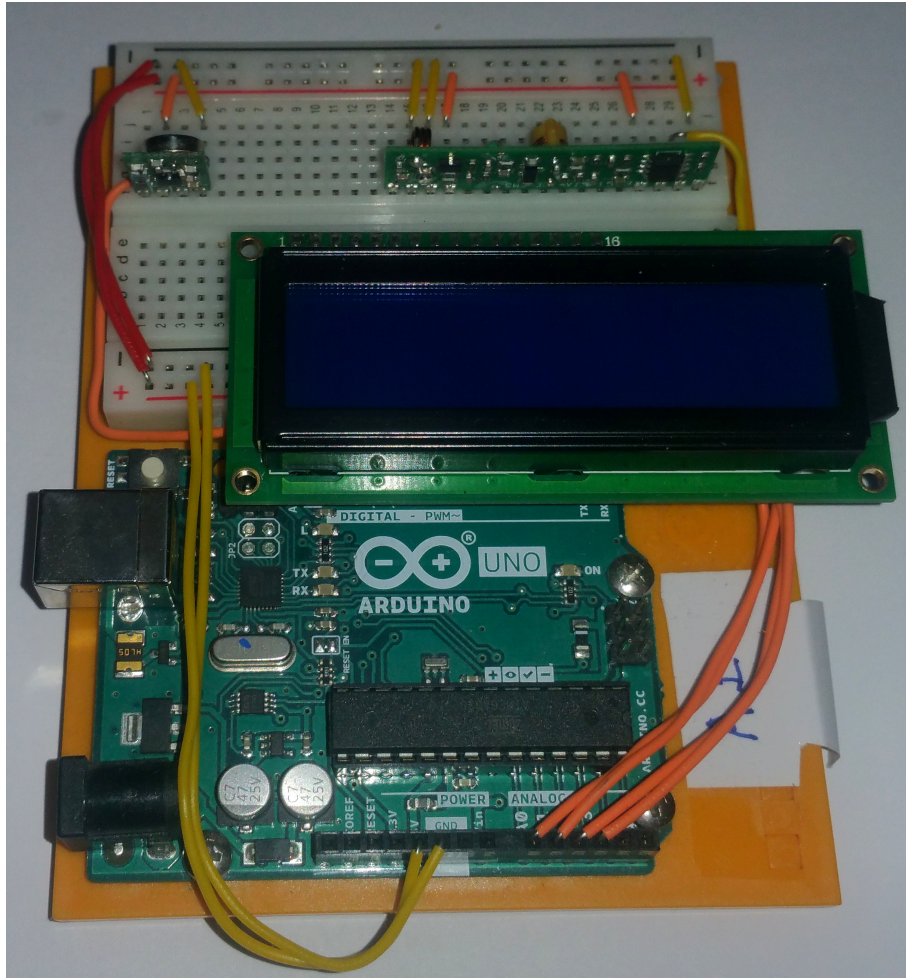


Figure F.1: A device of the considered system enhanced with an LCD screen.

TDMA parameters are presented in F.1.3, and synchronization issues are given in F.1.4.

F.1.1 Low-cost devices

As already mentioned, each device has to be low-cost and in this sense, industrial motes cannot be used because of their high cost. To achieve the low-cost goal, each node has been assembled using three essential elements. The first element is the core part of the node and is represented by an Arduino prototyping platform [143]. The rest of the elements are two RF modules operating at 433 MHz and are used

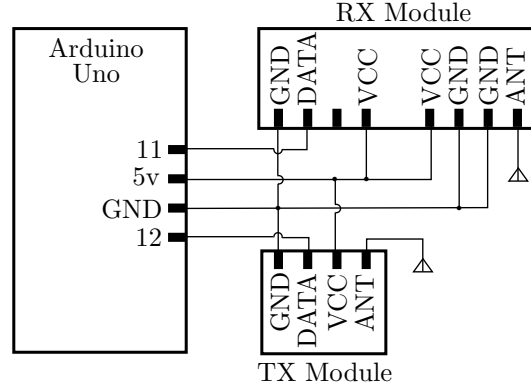


Figure F.2: The wiring between the Arduino and the RF modules that implements the device for both transmission (i.e., Tx-module data connected to pin 12) and reception (i.e., Rx-module data connected to pin 12). The antenna (ANT) along with the power supply pins (i.e., GND and VCC) are also depicted.

for transmission and reception purposes. In Fig. F.1, one of the nodes comprising the system is shown. All three mentioned elements are installed, alongside with an LCD screen for experiment monitoring and debugging purposes.

Regarding the Arduino prototyping platform, it is an open-source and low-cost electronics platform, easy to use, and capable of hosting various components (e.g., the RF modules considered in this work). There are plenty of Arduino board designs utilizing a variety of microprocessors and controllers. The particular board used for this work is the Arduino Uno Rev. 3. The latter is a board that is built on top of the ATMEL ATMEGA328 micro-controller with a clock speed of 16MHz and 2KB of SRAM [144].

As for the wireless communication part of the devices, it is handled by short-range RF modules operating in the license-free *Industrial, Scientific and Medical* (ISM) Band of 433.050 - 434.790 MHz. This particular band is free licensed to users for amateur and radio-location services [145]. Two different components are used to realize transmission (Tx) and reception (Rx), i.e., TWS-BS-V1.0.3 [146] and RWS-371-V1.0.3 [147], respectively. As already mentioned, these modules co-operate with Arduino and the wiring applied to them is schematically illustrated in Fig. F.2.

F.1.2 Message types

For the implementation of the TDMA protocol, two types of messages are exchanged among the network nodes of the considered low-cost IoT system. The group of messages that belong to the first type of messages are the **SYNC** messages. **SYNC** messages are transmitted by all network nodes at the beginning of each frame, for time synchronization purposes. The payload of **SYNC** messages “carries” the time remaining until the first time-slot begins. The second type of messages contains the **DATA** messages. By the time a network node has data ready for transmission, it constructs a **DATA** message that contains the data to be sent. The next step is to transmit the **DATA** message during the particular node’s time-slot. The existence of these two distinct message types is necessary for the smooth operation of the TDMA protocol. At the beginning of each frame, all nodes exchange and process **SYNC** messages in order to achieve synchronization of the receiver’s TDMA clock timer. **DATA** messages, carrying the valuable information nodes are supposed to send, are transmitted by the network nodes during the particular time-slots that have been assigned to them.

F.1.3 TDMA parameters

On the one hand, low-cost devices and the elements comprising them ensure a low price for the final system. On the other hand, several limitations regarding frame timing parameters have to be taken into account when implementing the TDMA protocol on the selected ISM Band (of 433.050 - 434.790 MHz) using low-cost devices. More specifically, such limitations are: (i). nodes’ internal clock may deviate significantly [148]; (ii). the interference on the selected band may be high [149, 150]; and (iii). the low-cost transmitter’s accuracy and receiver’s sensitivity may be reduced.

In order to tackle the effects and drawbacks of the above limitations, some countermeasures are taken. For avoiding collisions occurring due to the clock drifts, each time-slot (ts_i) of the TDMA frame is set to last for a considerably long period (i.e., 500ms), whereas a 300ms long guard time (t_g) is introduced between them for the same reason. For achieving the synchronization needed, at the beginning of each frame, nodes are allowed to get synchronized during a time period of 2000ms (st). At the end of the frame, one more guard period, the frame guard period, is consid-

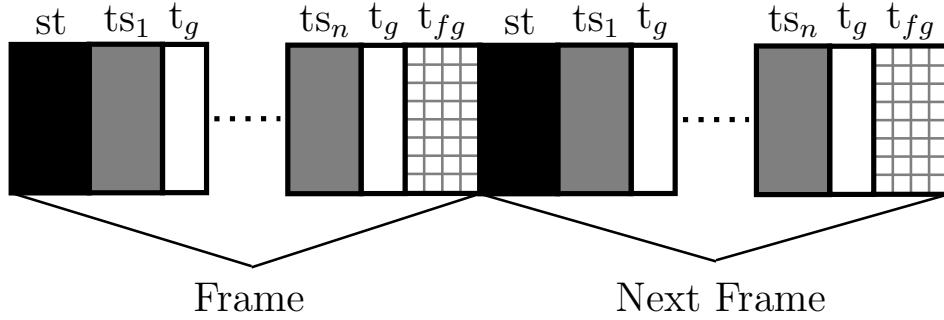


Figure F.3: The TDMA frame of the implemented MAC protocol. Each time-slot (ts_i) ends with the guard period (t_g). The synchronization time (st) along with the frame guard period (t_{fg}) are also depicted.

ered lasting 500ms (t_{fg}), thus allowing for further node's operations (e.g., sensing, message processing) to take place. The complete TDMA frame of the implemented policy is depicted in Fig. F.3.

F.1.4 Synchronization

A significant factor in TDMA environments is the nodes' awareness of the time that a frame begins. In order to fulfill the above requirement in multi-hop environments, a (multi-hop) decentralized clock synchronization mechanism has to be implemented. Timestamping techniques that have been extensively employed in the literature by several proposed synchronization algorithms (e.g., [151, 152, 153]) are employed here. Moreover, in the current work, the considered synchronization mechanism has to take into account that the focus is on the implementation of TiMAC on low-cost devices; thus, considering the drawbacks the low-cost nature results to. In this sense, a long enough time period of 2000ms is considered for nodes to synchronize their clocks. During this time period, starting at the beginning of each frame, nodes synchronize their clocks by transmitting the previously described *SYNC* messages. The latter process goes as follows: a reference node transmits a *SYNC* message to its neighbor nodes, thus informing them about the time remaining until the first time-slot of the frame starts. Subsequently, every node that receives this message for the first time adjusts its clock accordingly and transmits a new *SYNC* message to its neighbor nodes.

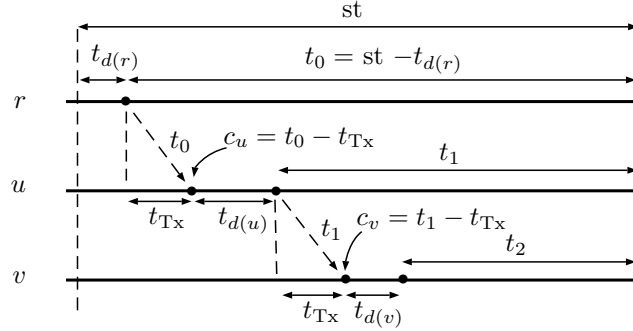


Figure F.4: Illustration of the synchronization mechanism within a synchronization period (st), among nodes r , u and v connected in a chain topology. Nodes wait for a certain amount of time (i.e., t_{dr} , t_{du} and t_{dv} respectively) before transmitting the time remaining until the first time-slot (i.e., t_0 , t_1 and t_2 respectively). The internal clocks c_u , c_v along with the transmission time t_{tx} are also depicted.

Fig. F.4 depicts the considered synchronization mechanism between the selected reference node (r), and nodes u and v , connected in chain topology (i.e., r - u - v). In the example depicted, at the beginning of the synchronization period (st), the reference node r waits for a certain time interval t_{dr} and then transmits its clock $t_0 = st - t_{dr}$ to node u . When u receives the message, it subtracts the transmission time from t_0 and changes its clock accordingly (i.e., $c_u = t_0 - t_{tx}$). Subsequently, node u waits for a certain time interval (i.e., t_{du}) before transmitting its clock (i.e., t_1) to node v . Following the same procedure and by the time node v receives the message, it (i). changes its clock (i.e., $c_u = t_1 - t_{tx}$); (ii). waits for a certain amount of time (i.e., t_{dv}); and (iii). transmits its clock to the next-in-line node (if any). Apparently, node u may also receive node's v *SYNC* message, but since one has already been received, this one will be ignored.

F.2 Experimental Methodology & Results

A full graph topology is considered here for the experimental setup, consisting of five nodes. The considered network is assumed as part of a larger IoT network of maximum $N = 25$ nodes where the maximum number of neighbors is $D = 4$. Taking

the above into consideration, the five nodes were set up in a full graph topology so as to simulate the maximum possible neighborhood of the assumed network. As a result, each node has exactly four neighbors, while collisions are expected to occur. The expectation regarding the performance of TiMAC is to accomplish the “at least one transmission per node per frame” goal, i.e., at least one transmission free of collisions. Note that transmissions may be unsuccessful for various reasons. For example, there might be interference in the 433Mhz band, since the selected band is an ISM one and several devices placed near to the system’s devices may also use it during the experiment. For avoiding as many such cases as possible, special care was taken to conduct the experiments in isolated areas (e.g., the basement of the premises of the University campus).

F.2.1 Methodology

As already mentioned, TiMAC is based on TDMA and in this sense, its implementation is also based on TDMA. Considering the values deriving by the experimental system setup (i.e., $N = 25$ nodes and maximum number of neighbors $D = 4$), the corresponding values for k (i.e., $k = 1$) and q (i.e., $q = 5$) are extracted [37]. As a result, first-degree polynomials are going to be used for the time-slot allocation due to $k = 1$, and the length of the TDMA frame will be set at $q^2 = 25$, divided into five subframes of $q = 5$ time-slots each. Then, each node is randomly assigned a first-degree polynomial with coefficients from $GF(5)$ and according to the latter polynomial, the particular time-slot during which each node is allowed to transmit within each sub-frame is derived. Eventually, every node is allowed to transmit in five time-slots per frame.

Eleven different sets of polynomials are considered here, corresponding to the eleven different scenarios developed for the particular system. Consequently, different time-slots were assigned to each node per scenario and the obtained results are the summation of transmissions of 100 frames. Note that increased traffic conditions are assumed for the experimental setup, and therefore each node has always data ready for transmission during every time-slot. As for the receivers of transmitted packets, for each node, one of its neighbors is arbitrarily selected as the destination of the transmitted packets. The latter selection of receivers remains unchanged throughout the experiments.

The first set of polynomials is chosen in order to create a collision-free time-slot allocation scenario, such that each node transmits packets in different time-slots than that of its neighbors. The rest of the (ten) polynomial sets are created randomly.

The main parameter under investigation is the *throughput* value each polynomial set (i.e., scenario) results to. The obtained throughput is derived as the fraction of the average successful transmissions (i.e., total successful transmissions over the number of nodes) over the number of total time-slots i.e.,

$$\text{throughput} = \frac{\text{total successful transmissions}}{\text{total nodes} \times \text{total time-slots}}$$

During the period of 100 frames, each node is eligible for transmission for up to 500 time-slots whereas, the number of total time-slots equals 2500. Consequently, the maximum network throughput is given by,

$$\text{capacity} = \frac{500}{2500} = 0.2$$

Throughput as large as capacity is not expected to be achieved due to various reasons like the channel interference, the transmitter's accuracy and the receiver's sensitivity, etc., as already mentioned. On the other hand, TiMAC guarantees that at least one successful transmission per node per frame will take place. Consequently, the minimum network throughput is given by,

$$\text{minimum throughput} = \frac{100}{2500} = 0.04$$

F.2.2 Results

In Fig. F.5, the derived values of throughput for the eleven polynomial sets are depicted. It is observed here that in all cases, throughput is higher than the minimum value guaranteed by the TiMAC policy (i.e., 0.04). In addition, it is clear that the first polynomial set (scenario) results in the highest value of throughput; however, it is smaller than the maximum value (i.e., 0.2). The latter result is expected since, on the one hand, the particular set of polynomials leads to a collision-free time-slot allocation. On the other hand, the channel interference, transmitter's accuracy, and receiver's sensitivity may provoke unsuccessful transmissions.

Figure F.6 depicts the average successful transmissions per frame per node for the eleven polynomial sets. The particular results confirm the TiMAC policy's lower

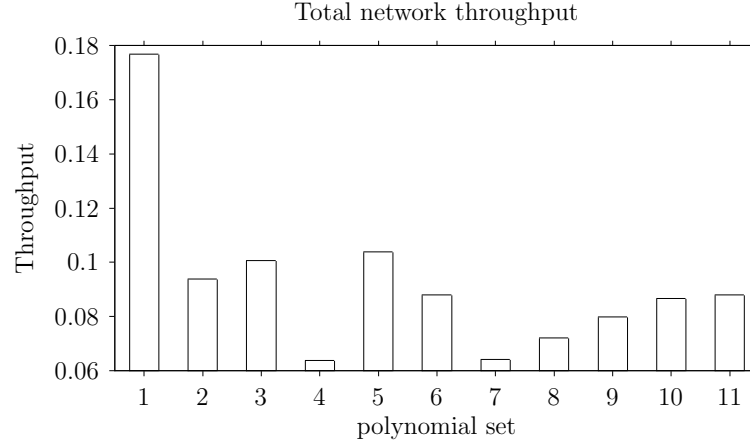


Figure F.5: Throughput corresponding to various polynomial sets. In all cases, the throughput lays between the expected maximum (i.e., 0.2) and minimum (i.e., 0.04) values.

bound of one successful transmission per frame per node. For the first polynomial set, it is observed that the successful transmissions are significantly more than the successful transmissions in the other ten scenarios. However, they are less than the maximum theoretically expected value of five, which is the number of successful transmissions per node per frame in cases where no packets are lost for the duration of the 100 frames.

The particular polynomials used in each set are listed in Table F.1. Although the network topology remains unchanged throughout the experimental phase, each set leads to different number of successful transmissions.

The successful transmissions per polynomial set are listed in Table F.2. Each set's sum of successful transmissions was used to derive the aforementioned throughput values.

F.3 Discussion and Conclusions

In this chapter, the TiMAC protocol, as presented in chapter C, was implemented in a small IoT network consisting of low-cost devices based on Arduino and 433 MHz RF modules. A decentralized method was used for synchronizing the nodes' clocks

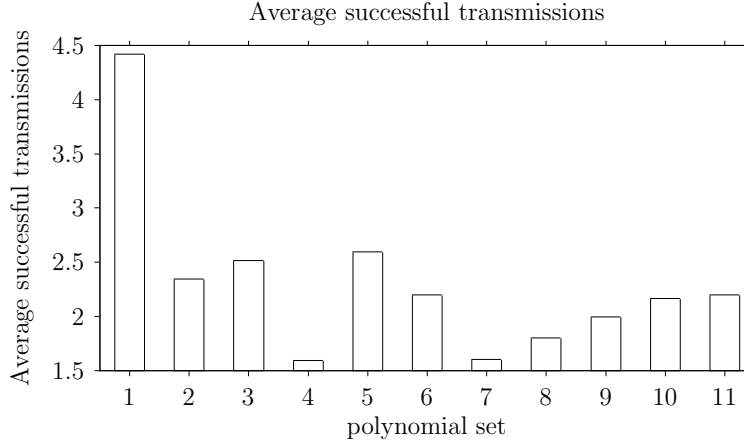


Figure F.6: Average number of successful transmissions per frame per node corresponding to various polynomial sets. In all cases, the number of successful transmissions is between the expected maximum (i.e., 5) and minimum (i.e., 1) values.

Polynomial Set	1	2	3	4	5	6	7	8	9	10	11
Node A	0x+0	1x+2	0x+1	0x+4	1x+0	0x+1	0x+3	0x+1	0x+2	0x+1	2x+1
Node B	0x+1	1x+3	0x+4	1x+1	1x+3	0x+4	1x+0	0x+2	0x+3	2x+0	2x+4
Node C	0x+2	2x+0	2x+0	1x+2	1x+4	2x+2	2x+4	0x+4	2x+4	2x+3	3x+0
Node D	0x+3	2x+2	2x+2	2x+0	3x+3	3x+3	3x+1	1x+0	3x+2	2x+4	3x+4
Node E	0x+4	3x+0	2x+3	3x+2	4x+4	4x+4	4x+4	4x+1	4x+1	4x+1	4x+2

Table F.1: The particular polynomial sets used in the experiments.

as required from the underlying TDMA policy. Experiments were conducted in a full graph topology network under increased network traffic load.

The conducted experiments confirm in practice the theoretical expectations from TiMAC as all of the results were within the expected boundaries in terms of throughput and successful transmissions per frame. The decentralized synchronization method used here also proved to be successful. At the same time, the fact that a particular experimental setup was close to the theoretical maximum expected values, suggest that the proposed policy can be improved if unique characteristics of particular polynomial sets are taken into account before assigning them to network nodes.

In conclusion, the experimental results presented in this chapter suggest that

Polynomial Set	1	2	3	4	5	6	7	8	9	10	11
Node A	495	203	101	100	301	200	100	300	298	98	202
Node B	423	399	200	101	300	199	102	200	201	194	300
Node C	500	193	258	398	400	300	200	206	200	400	198
Node D	396	275	302	99	198	200	200	97	198	195	200
Node E	396	102	398	99	99	200	200	99	102	195	200
Total	2210	1172	1259	797	1298	1099	802	902	999	1082	1100

Table F.2: Successful transmissions per node for each polynomial set.

TDMA topology transparent policies could be considered when designing an IoT system, as they offer a means of node deployment without the usual considerations of traditional TDMA schemes (physical location combined with particular time-slot assignment), which could prove to be easier due to the nature of this type of networks and still could meet the strict time constraints of various delay-sensitive applications.

Chapter G

Conclusions and Future Work

IN this thesis, existing topology-transparent TDMA policies were revisited and studied and new ones were proposed which improve on the previous ones in various aspects.

G.1 Summary and Conclusions

Initially, the Deterministic Policy is revisited which essentially implements Chlamtac and Faragò's original idea on topology-transparent TDMA scheduling. This policy is incorporated in the TiMAC protocol which is compared against VeMAC, a well established protocol for Vehicular Ad hoc Networks. The results show that both protocols perform similarly in terms of throughput but TiMAC achieves lower delays. Consequently, TiMAC and other similar topology-transparent policies may be a suitable candidate when designing MAC protocols for safety applications in Vehicular Ad hoc Networks.

The next revisited policy is the Probabilistic Policy, which extends the Deterministic Policy by allowing nodes to additionally transmit in all their non-assigned time-slots but under a pre-defined and common to all nodes access probability p . In this way, throughput is increased but at the cost of an increased number of transmissions and message collisions. The Refined Policy is proposed which extends the Probabilistic Policy by making the nodes aware of their neighbors' assigned time-slots. This knowledge allows nodes to refrain from certain probabilistic transmissions that are very likely to cause collisions with neighboring nodes' transmissions. It is

shown that this behavior, when compared to the Probabilistic Policy, leads to increased throughput while at the same time fewer total transmissions take place. Additionally, the concept of the individual access probability is introduced. Instead of calculating and pre-assigning a common access probability value to all nodes prior to the network operation as under the Probabilistic Policy, under the Refined Policy this value is calculated individually by each node and while the network operates. This addition to the Refined Policy is shown to increase its throughput even more, while at the same time eliminating the need of calculating and assigning a common probability value in a centralized way.

The last policy revisited in this thesis is the Adaptive Policy which further extends the Probabilistic Policy. Under this policy, nodes are able to adapt their transmission probability in certain time-slots. Specifically, whenever a successful transmission takes place in a non-assigned time-slot, the transmitter node adapts the access probability value to 1 for this time-slot. The original value is restored whenever a collision is detected in this time-slot. Although under the Adaptive Policy throughput performance is greatly increased when compared to the Probabilistic Policy, the problem is that the transmitter node very often fails to detect message collisions that would trigger the restoration of the original access probability value. This leads to unfair treatment of some nodes with respect to medium access. To tackle with this problem, the Fairness-Aware Policy is introduced. Under this policy, each node is able to obtain information about how fairly its neighbors have been treated until this particular moment and adjust its access probability value accordingly. Under the Fairness-Aware Policy, throughput performance is improved when compared to the Probabilistic Policy without compromising fairness.

Finally, an implementation of the TiMAC protocol in low-cost devices is presented. Those devices are comprised of the well-known Arduino electronic prototyping platform and inexpensive transceivers which operate in the 433MHz ISM Band. Despite the problems that are posed by the physical medium, the protocol managed to perform as expected, demonstrating the potential of using a TDMA topology-transparent policy in IoT environments.

G.2 Future Work Directions

The results presented in this thesis highlight the potential of using topology-transparent TDMA policies in IoT environments. However, there are still problems to be solved if those policies are to be implemented in a real-world scenarios.

The ideas presented and evaluated here assume an ideal physical medium. However, in a real-world implementation, packets may be lost due to channel errors. This means that the Deterministic Policy's minimum guaranteed successful transmissions per frame may not be achievable. As high throughput performance is not the purpose of the Deterministic Policy, it is interesting to be investigated whether a probabilistic scheme like those proposed here can be used in such way that, instead of improving throughput, tries to make up for the packets lost due to channel errors. However, the use of a probabilistic scheme is in itself reason enough for questioning the guaranteed transmissions offered by the Deterministic Policy, since due to the probabilistic transmissions taking place in every slot, no transmission is guaranteed. Consequently, another interesting topic for investigation is whether the introduced increase in performance under a probabilistic scheme makes up for the possible loss of determinism in terms of guaranteed successful transmissions per frame.

Further research with respect to the physical medium should consider the use of modern technologies like smart antennas and full-duplex communication. Multiple channels could also be considered as the policies proposed here are designed for single channel operation.

In chapter B.2.2 it was shown that the number of successful transmissions per frame for a node depends on the particular polynomials that have been assigned to its neighborhood. Consequently, it might be worth investigating whether this attribute can be exploited in clustering techniques, where each cluster is assigned a set of polynomials that ensure a minimum number of collisions among them.

Vehicular ad hoc networking is an application where the implementation of TDMA topology-transparent policies may be promising due to the fact that topology may change at a very fast rate. Consequently, future work could include enhancements that take into account specific characteristics of vehicular environments like specific vehicle movement patterns.

Regarding the ideas presented in the two policies proposed in this thesis, they both follow different paths in order to achieve their goals. Consequently, it is pos-

sible that a combination of their ideas in a new policy may be feasible. Specifically for the Fairness-Aware Policy, different definitions of fairness that consider additional characteristics can be considered and implemented as feedback mechanisms. Such characteristics may include the number of neighbors per node, the successful transmissions during some of the latest frames only or the delay of the transmitted messages. The aforementioned loss of determinism may also be incorporated in a definition for fairness. Additional experimentation can be conducted for fine-tuning the access probability value's adjustment. For example, different increment values (not necessarily constant) can be considered, as well as the boundaries of its minimum and maximum values. Furthermore, mobility scenarios should be considered for evaluating the policy's performance.

Similar experimentation with the access probability value's boundaries may be considered for the calculated value of the individual access probability. For example, it was shown in chapter E.4.5 that nodes with one or two neighbors are allowed to transmit very often due to the calculation of a large value for their access probability. It is interesting to investigate how the overall system performance will be affected if the access probability is bounded by a maximum value. Furthermore, similarly to the Fairness-Aware Policy, mobility scenarios should be considered.

Regarding the implementation of TiMAC in low-cost devices, future work should experiment with larger networks so that the policy may be tested in multi-hop environment. Additionally, every policy considered in this thesis may also be worth experimenting in a similar low-cost device scenario.

Bibliography

- [1] M. Alioto, *Enabling the Internet of Things: from integrated circuits to integrated systems*. Springer, 2017.
- [2] Q. Vu Khanh, V. Hoai Nam, L. Dao, A. Le, and G. Jeon, “Wireless communication technologies for iot in 5g: Vision, applications, and challenges,” *Wireless Communications and Mobile Computing*, vol. 2022, pp. 1–12, 02 2022.
- [3] T. hoon Kim, C. Ramos, and S. Mohammed, “Smart city and iot,” *Future Generation Computer Systems*, vol. 76, pp. 159–162, 2017.
- [4] H. Uddin, M. Gibson, G. A. Safdar, T. Kalsoom, N. Ramzan, M. Ur-Rehman, and M. A. Imran, “Iot for 5g/b5g applications in smart homes, smart cities, wearables and connected cars,” in *2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pp. 1–5, 2019.
- [5] B. Jan, H. Farman, M. Khan, M. Talha, and I. U. Din, “Designing a smart transportation system: An internet of things and big data approach,” *IEEE Wireless Communications*, vol. 26, no. 4, pp. 73–79, 2019.
- [6] O. Friha, M. A. Ferrag, L. Shu, L. Maglaras, and X. Wang, “Internet of things for the future of smart agriculture: A comprehensive survey of emerging technologies,” *IEEE/CAA Journal of Automatica Sinica*, vol. 8, no. 4, pp. 718–752, 2021.
- [7] M. H. Bithi, F. Faisal, A. Karim, S. Azam, B. Shanmugam, and R. Lakshmananthan, “Modern tree plantation system based on iot,” in *2020 Fourth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)*, pp. 25–29, 2020.

- [8] D. Soni and A. Makwana, "A survey on mqtt: a protocol of internet of things (iot)," in *International conference on telecommunication, power analysis and computing techniques (ICTPACT-2017)*, vol. 20, pp. 173–177, 2017.
- [9] V. Thoutam, "Physical design, origins and applications of iot," *Journal of Multidisciplinary Cases (JMC) ISSN 2799-0990*, vol. 1, pp. 26–33, Sep. 2021.
- [10] J. Shah, J. Kothari, and N. Doshi, "A survey of smart city infrastructure via case study on new york," *Procedia Computer Science*, vol. 160, pp. 702–705, 2019. The 10th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2019) / The 9th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2019) / Affiliated Workshops.
- [11] K. T. Kadhim, A. M. Alsahlany, S. M. Wadi, and H. T. Kadhum, "An overview of patients health status monitoring system based on internet of things (iot)," *Wireless Personal Communications*, vol. 114, no. 3, pp. 2235–2262, 2020.
- [12] H. H. Nguyen, F. Mirza, M. A. Naeem, and M. Nguyen, "A review on iot healthcare monitoring applications and a vision for transforming sensor data into real-time clinical feedback," in *2017 IEEE 21st International Conference on Computer Supported Cooperative Work in Design (CSCWD)*, pp. 257–262, 2017.
- [13] K. R. Karthikeyan, E. Dharan Babu, S. Ranjith, and S. Arunkumar, "Smart pill dispenser for aged patients," in *2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, pp. 1–5, 2021.
- [14] M. Kamruzzaman, N. I. Sarkar, J. Gutierrez, and S. K. Ray, "A study of iot-based post-disaster management," in *2017 International Conference on Information Networking (ICOIN)*, pp. 406–410, 2017.
- [15] K. Mehta, S. Sharma, and D. Mishra, "Internet-of-things enabled forest fire detection system," in *2021 Fifth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)*, pp. 20–23, 2021.

- [16] D. C. Tranca, D. Rosner, R. Curatu, A. Surpateanu, M. Mocanu, E. Pardau, and A. V. Palacean, "Industrial wsn node extension and measurement systems for air, water and environmental monitoring: Iot enabled environment monitoring using ni wsn nodes," in *2017 16th RoEduNet Conference: Networking in Education and Research (RoEduNet)*, pp. 1–6, 2017.
- [17] L. Shu, Y. Chen, Z. Sun, F. Tong, and M. Mukherjee, "Detecting the dangerous area of toxic gases with wireless sensor networks," *IEEE Transactions on Emerging Topics in Computing*, vol. 8, no. 1, pp. 137–147, 2020.
- [18] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular ad hoc network," *Journal of network and computer applications*, vol. 37, pp. 380–392, 2014.
- [19] J. Thota, N. F. Abdullah, A. Doufexi, and S. Armour, "V2v for vehicular safety applications," *IEEE transactions on intelligent transportation systems*, vol. 21, no. 6, pp. 2571–2585, 2019.
- [20] M. Conti and S. Giordano, "Multihop ad hoc networking: The theory," *IEEE Communications Magazine*, vol. 45, no. 4, pp. 78–86, 2007.
- [21] R. Ramanathan and J. Redi, "A brief overview of ad hoc networks: challenges and directions," *IEEE communications Magazine*, vol. 40, no. 5, pp. 20–22, 2002.
- [22] M. Ilyas, *The handbook of ad hoc wireless networks*. CRC press, 2017.
- [23] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Communications surveys & tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014.
- [24] E. Jovanov, D. Raskovic, J. Price, A. Krishnamurthy, J. Chapman, and A. Moore, "Patient monitoring using personal area networks of wireless intelligent sensors," *Biomedical Sciences Instrumentation*, vol. 37, pp. 373–378, 2001.
- [25] M. J. N. Mahi, S. Chaki, S. Ahmed, M. Biswas, S. Kaiser, M. S. Islam, M. Sookhak, A. Barros, and M. Whaiduzzaman, "A review on vanet research: Perspective of recent emerging technologies," *IEEE Access*, 2022.

- [26] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, “ADHOC MAC: New MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services,” *Wireless Networks*, vol. 10, no. 4, pp. 359–366, 2004.
- [27] A. Boukerche, B. Turgut, N. Aydin, M. Z. Ahmad, L. Bölöni, and D. Turgut, “Routing protocols in ad hoc networks: A survey,” *Computer networks*, vol. 55, no. 13, pp. 3032–3080, 2011.
- [28] Z. Wei, L. Yue-hui, and J. Wei-ping, “A study on mac sublayer of obu in etc system,” in *2010 International Conference on Computer Application and System Modeling (ICCASM 2010)*, vol. 13, pp. V13–338, IEEE, 2010.
- [29] M. Hadded, P. Mühlethaler, A. Laouiti, R. Zagrouba, and L. A. Saïdane, “TDMA-based MAC protocols for vehicular ad hoc networks: A survey, qualitative analysis, and open research issues,” *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, pp. 2461–2492, 2015.
- [30] R. Stanica, E. Chaput, and A.-L. Beylot, “Comparison of csma and tdma for a heartbeat vanet application,” in *2010 IEEE International Conference on Communications*, pp. 1–5, 2010.
- [31] S. Gobriel, D. Mosse, and R. Cleric, “Tdma-asap: Sensor network tdma scheduling with adaptive slot-stealing and parallelism,” in *2009 29th IEEE International Conference on Distributed Computing Systems*, pp. 458–465, 2009.
- [32] S. C. Ergen and P. Varaiya, “Tdma scheduling algorithms for wireless sensor networks,” *Wireless networks*, vol. 16, pp. 985–997, 2010.
- [33] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, “Energy-efficient low duty cycle mac protocol for wireless body area networks,” *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 915–925, 2009.
- [34] J. G. Andrews, S. Weber, and M. Haenggi, “Ad hoc networks: To spread or not to spread? [ad hoc and sensor networks],” *IEEE Communications Magazine*, vol. 45, no. 12, pp. 84–91, 2007.

- [35] Z. Cai, M. Lu, and C. N. Georghiades, "Topology-transparent time division multiple access broadcast scheduling in multihop packet radio networks," *IEEE Transactions on vehicular technology*, vol. 52, no. 4, pp. 970–984, 2003.
- [36] F. Wang, P. Zeng, and H. Yu, "Slot time synchronization for tdma-based ad hoc networks," in *2008 International Symposium on Computer Science and Computational Technology*, vol. 2, pp. 544–548, 2008.
- [37] I. Chlamtac and A. Faragó, "Making transmission schedules immune to topology changes in multi-hop packet radio networks," *IEEE/ACM Trans. Netw.*, vol. 2, no. 1, pp. 23–29, 1994.
- [38] K. Oikonomou and I. Stavrakakis, "Analysis of a Probabilistic Topology-Unaware TDMA MAC Policy for Ad Hoc Networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, pp. 1286–1300, September 2004.
- [39] K. Oikonomou and I. Stavrakakis, "An adaptive time-spread multiple-access policy for wireless sensor networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2007, 05 2007.
- [40] H. A. Omar, W. Zhuang, and L. Li, "VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 1724–1736, Sept 2013.
- [41] S. Cao and V. C. Lee, "A novel adaptive TDMA-based MAC protocol for VANETs," *IEEE Communications Letters*, vol. 22, no. 3, pp. 614–617, 2018.
- [42] W.-D. Yang, P. Li, Y. Liu, and H.-S. Zhu, "Adaptive TDMA slot assignment protocol for vehicular ad-hoc networks," *The Journal of China Universities of Posts and Telecommunications*, vol. 20, no. 1, pp. 11 – 25, 2013.
- [43] R. Zou, Z. Liu, L. Zhang, and M. Kamil, "A near collision free reservation based mac protocol for VANETs," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1538–1543, April 2014.
- [44] H. Yu, Z. He, and K. Niu, "STDMA for vehicle-to-vehicle communication in a highway scenario," in *2013 5th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, pp. 133–138, Oct 2013.

- [45] F. Yu and S. Biswas, “A self reorganizing MAC protocol for inter-vehicle data transfer applications in vehicular ad hoc networks,” in *Proceedings - 10th International Conference on Information Technology, ICIT 2007*, pp. 110–115, 2007.
- [46] F. Yu and S. Biswas, “Self-configuring TDMA protocols for enhancing vehicle safety with DSRC based vehicle-to-vehicle communications,” *IEEE journal on selected areas in communications*, vol. 25, no. 8, 2007.
- [47] H. A. Omar, W. Zhuang, and L. Li, “VeMAC: A novel multichannel MAC protocol for vehicular ad hoc networks,” in *Computer Communications Workshops (INFOCOM WKSHPS), 2011 IEEE Conference on*, pp. 413–418, IEEE, 2011.
- [48] W. Yang, W. Liu, P. Li, and L. Sun, “TDMA-based control channel access for IEEE 802.11 p in VANETs,” *International Journal of Distributed Sensor Networks*, vol. 10, no. 8, p. 579791, 2014.
- [49] “IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications amendment 6: Wireless access in vehicular environments,” *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, pp. 1–51, July 2010.
- [50] W. Li, J.-B. Wei, and S. Wang, “An evolutionary time spread multiple access protocol for ad hoc networks,” in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, pp. 1781–1785, IEEE, 2008.
- [51] J. Xie and C. Li, “Weight clustering based TDMA-MAC scheme in VANET,” *Automatika*, vol. 57, no. 1, pp. 252–260, 2016.
- [52] F. Han, D. Miyamoto, and Y. Wakahara, “Rtob: A TDMA-based MAC protocol to achieve high reliability of one-hop broadcast in VANET,” in *Pervasive Computing and Communication Workshops (PerCom Workshops), 2015 IEEE International Conference on*, pp. 87–92, IEEE, 2015.

- [53] V. Nguyen, D. N. M. Dang, S. Jang, and C. S. Hong, “e-VeMAC: an enhanced vehicular MAC protocol to mitigate the exposed terminal problem,” in *Network Operations and Management Symposium (APNOMS), 2014 16th Asia-Pacific*, pp. 1–4, IEEE, 2014.
- [54] M. Hadded, R. Zagrouba, A. Laouiti, P. Muhlethaler, and L. A. Saidane, “An adaptive TDMA slot assignment strategy in vehicular ad hoc networks,” *Journal of Machine to Machine Communications*, vol. 1, no. 2, pp. 175–194, 2014.
- [55] X. Jiang and D. H. Du, “PTMAC: A prediction-based TDMA MAC protocol for reducing packet collisions in VANET,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 11, pp. 9209–9223, 2016.
- [56] T. Wang, X. Wang, X. Tian, and X. Gan, “HD-MAC: A throughput enhancing TDMA-based protocol in high dynamic environments,” in *Mobile Ad-Hoc and Sensor Networks (MSN), 2016 12th International Conference on*, pp. 105–109, IEEE, 2016.
- [57] I. F. M. Zain, A. Awang, and A. Laouiti, “Hybrid MAC protocols in VANET: a survey,” in *Vehicular Ad-Hoc Networks for Smart Cities*, pp. 3–14, Springer, 2017.
- [58] N. Gupta, A. Prakash, and R. Tripathi, “Medium access control protocols for safety applications in vehicular ad-hoc network: A classification and comprehensive survey,” *Vehicular Communications*, vol. 2, no. 4, pp. 223–237, 2015.
- [59] N. Torabi and B. S. Ghahfarokhi, “Survey of medium access control schemes for inter-vehicle communications,” *Computers & Electrical Engineering*, 2017.
- [60] A. Sgora, D. J. Vergados, and D. D. Vergados, “A survey of TDMA scheduling schemes in wireless multihop networks,” *ACM Computing Surveys (CSUR)*, vol. 47, no. 3, p. 53, 2015.
- [61] S. Huaizhou, R. V. Prasad, E. Onur, and I. Niemegeers, “Fairness in wireless networks: Issues, measures and challenges,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, pp. 5–24, 2013.

- [62] Y. Zhou and H. Sethu, "On the relationship between absolute and relative fairness bounds," *IEEE Communications Letters*, vol. 6, no. 1, pp. 37–39, 2002.
- [63] M. Siddik, S. S. Moni, M. S. Alam, W. A. Johnson, *et al.*, "Safe-mac: Speed aware fairness enabled mac protocol for vehicular ad-hoc networks," *Sensors*, vol. 19, no. 10, p. 2405, 2019.
- [64] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination," *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, 1984.
- [65] C. E. Shannon, "A mathematical theory of communication," *Bell system technical journal*, vol. 27, no. 3, pp. 379–423, 1948.
- [66] M. Uchida and J. Kurose, "An information-theoretic characterization of weighted alpha-proportional fairness," in *IEEE INFOCOM 2009*, pp. 1053–1061, IEEE, 2009.
- [67] T. Lan, D. Kao, M. Chiang, and A. Sabharwal, *An axiomatic theory of fairness in network resource allocation*. IEEE, 2010.
- [68] B. Radunovic and J.-Y. Le Boudec, "A unified framework for max-min and min-max fairness with applications," *IEEE/ACM Transactions on networking*, vol. 15, no. 5, pp. 1073–1083, 2007.
- [69] F. Kelly, "Charging and rate control for elastic traffic," *European transactions on Telecommunications*, vol. 8, no. 1, pp. 33–37, 1997.
- [70] L. G. Boiney, "When efficient is insufficient: Fairness in decisions affecting a group," *Management Science*, vol. 41, no. 9, pp. 1523–1537, 1995.
- [71] J. Sangiamwong, K. Tsukamoto, and S. Komaki, "Frequency channel blocking scheme in mesh-topology millimeter-wave broad-band entrance networks," *IEEE transactions on microwave theory and techniques*, vol. 53, no. 12, pp. 3723–3730, 2005.

- [72] M. Dianati, X. Shen, and S. Naik, "A new fairness index for radio resource allocation in wireless networks," in *IEEE Wireless Communications and Networking Conference, 2005*, vol. 2, pp. 712–717, IEEE, 2005.
- [73] Q.-V. Pham and W.-J. Hwang, "Fairness-aware spectral and energy efficiency in spectrum-sharing wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10207–10219, 2017.
- [74] L. Zheng, D. W. Cai, and C. W. Tan, "Max-min fairness rate control in wireless networks: Optimality and algorithms by perron-frobenius theory," *IEEE Transactions on Mobile Computing*, vol. 17, no. 1, pp. 127–140, 2017.
- [75] Q. Liu, K.-C. Leung, V. O. Li, Z. Zhao, G. Yang, and L. Cui, "Fairness and high-throughput scheduling for multihop wireless ad hoc networks," *Ad Hoc Networks*, vol. 52, pp. 195–206, 2016.
- [76] S. S. Kalamkar, J. P. Jeyaraj, A. Banerjee, and K. Rajawat, "Resource allocation and fairness in wireless powered cooperative cognitive radio networks," *IEEE Transactions on Communications*, vol. 64, no. 8, pp. 3246–3261, 2016.
- [77] S. Bi, Y. Zeng, and R. Zhang, "Wireless powered communication networks: An overview," *IEEE Wireless Communications*, vol. 23, no. 2, pp. 10–18, 2016.
- [78] C. Guo, B. Liao, L. Huang, Q. Li, and X. Lin, "Convexity of fairness-aware resource allocation in wireless powered communication networks," *IEEE Communications Letters*, vol. 20, no. 3, pp. 474–477, 2016.
- [79] C. Guo, B. Liao, L. Huang, X. Lin, and J. Zhang, "On convexity of fairness-aware energy-efficient power allocation in spectrum-sharing networks," *IEEE Communications Letters*, vol. 20, no. 3, pp. 534–537, 2015.
- [80] A. Thudugalage, S. Atapattu, and J. Evans, "Beamformer design for wireless energy transfer with fairness," in *2016 IEEE International Conference on Communications (ICC)*, pp. 1–6, IEEE, 2016.
- [81] S. Singh, M. Geraseminko, S.-p. Yeh, N. Himayat, and S. Talwar, "Proportional fair traffic splitting and aggregation in heterogeneous wireless networks," *IEEE Communications Letters*, vol. 20, no. 5, pp. 1010–1013, 2016.

- [82] M. Ghorbanzadeh, A. Abdelhadi, and C. Clancy, "A utility proportional fairness radio resource block allocation in cellular networks," in *2015 International Conference on Computing, Networking and Communications (ICNC)*, pp. 499–504, IEEE, 2015.
- [83] L. Sanabria-Russo, J. Barcelo, B. Bellalta, and F. Gringoli, "A high efficiency mac protocol for wlans: Providing fairness in dense scenarios," *IEEE/ACM Transactions on Networking*, vol. 25, no. 1, pp. 492–505, 2016.
- [84] J. Barcelo, B. Bellalta, C. Cano, and M. Oliver, "Learning-beb: Avoiding collisions in wlans," *Carrier Sense Multiple Access with Enhanced Collision Avoidance*, p. 23, 2009.
- [85] A. Li and G. Han, "A fairness-based mac protocol for 5g cognitive radio ad hoc networks," *Journal of Network and Computer Applications*, vol. 111, pp. 28–34, 2018.
- [86] J. Lei, J. Tao, J. Huang, and Y. Xia, "A differentiated reservation mac protocol for achieving fairness and efficiency in multi-rate ieee 802.11 wlans," *IEEE Access*, vol. 7, pp. 12133–12145, 2019.
- [87] F. Chen, B. Li, M. Yang, Z. Yan, and X. Zuo, "Fairness oriented mac protocol for the next generation wlan," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, IEEE, 2017.
- [88] R. Diamant, P. Casari, and M. Zorzi, "A tdma-based mac protocol exploiting the near-far effect in underwater acoustic networks," in *OCEANS 2016-Shanghai*, pp. 1–5, IEEE, 2016.
- [89] S. Lmai, M. Chitre, C. Laot, and S. Houcke, "Throughput-efficient super-tdma mac transmission schedules in ad hoc linear underwater acoustic networks," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 1, pp. 156–174, 2016.
- [90] A. Lindgren, A. Doria, and O. Schelén, "Probabilistic routing in intermittently connected networks," *ACM SIGMOBILE mobile computing and communications review*, vol. 7, no. 3, pp. 19–20, 2003.

- [91] D. G. Reina, S. Toral, P. Johnson, and F. Barrero, "A survey on probabilistic broadcast schemes for wireless ad hoc networks," *Ad Hoc Networks*, vol. 25, pp. 263–292, 2015.
- [92] Y. Sasson, D. Cavin, and A. Schiper, "Probabilistic broadcast for flooding in wireless mobile ad hoc networks," in *2003 IEEE Wireless Communications and Networking, 2003. WCNC 2003.*, vol. 2, pp. 1124–1130, IEEE, 2003.
- [93] G. Koufoudakis, K. Oikonomou, and G. Tsoumanis, "Adapting probabilistic flooding in energy harvesting wireless sensor networks," *Journal of Sensor and Actuator Networks*, vol. 7, no. 3, p. 39, 2018.
- [94] M. Rahmati and D. Pompili, "Probabilistic spatially-divided multiple access in underwater acoustic sparse networks," *IEEE Transactions on Mobile Computing*, vol. 19, no. 2, pp. 405–418, 2018.
- [95] X. Zeng, M. Yu, and D. Wang, "A new probabilistic multi-hop broadcast protocol for vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 12, pp. 12165–12176, 2018.
- [96] L. Liu, C. Chen, T. Qiu, M. Zhang, S. Li, and B. Zhou, "A data dissemination scheme based on clustering and probabilistic broadcasting in vanets," *Vehicular Communications*, vol. 13, pp. 78–88, 2018.
- [97] A. Srivastava, A. Prakash, and R. Tripathi, "Fuzzy-based beaconless probabilistic broadcasting for information dissemination in urban vanet," *Ad Hoc Networks*, vol. 108, p. 102285, 2020.
- [98] F. Maliqi, F. Bassi, P. Duhamel, and I. Limani, "A probabilistic harq protocol for demodulate-and-forward relaying networks," *IEEE Transactions on Wireless Communications*, vol. 18, no. 3, pp. 1623–1636, 2019.
- [99] W. Liu, K. Nakauchi, and Y. Shoji, "A neighbor-based probabilistic broadcast protocol for data dissemination in mobile iot networks," *IEEE Access*, vol. 6, pp. 12260–12268, 2018.
- [100] S.-Y. Chen, T.-F. Huang, K. C.-J. Lin, Y.-W. P. Hong, and A. Sabharwal, "Probabilistic medium access control for full-duplex networks with half-duplex

- clients,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2627–2640, 2017.
- [101] F. Gandino, R. Ferrero, B. Montrucchio, and M. Rebaudengo, “Probabilistic dcs: An rfid reader-to-reader anti-collision protocol,” *Journal of Network and Computer Applications*, vol. 34, no. 3, pp. 821–832, 2011.
- [102] J. Waldrop, D. W. Engels, and S. E. Sarma, “Colorwave: A mac for rfid reader networks,” in *2003 IEEE Wireless Communications and Networking, 2003. WCNC 2003.*, vol. 3, pp. 1701–1704, IEEE, 2003.
- [103] R. Ferrero, F. Gandino, B. Montrucchio, and M. Rebaudengo, “Improving colorwave with the probabilistic approach for reader-to-reader anti-collision tdma protocols,” *Wireless networks*, vol. 20, no. 3, pp. 397–409, 2014.
- [104] Q. Ye and W. Zhuang, “Token-based adaptive mac for a two-hop internet-of-things enabled manet,” *IEEE Internet of Things Journal*, vol. 4, no. 5, pp. 1739–1753, 2017.
- [105] J. Hu, W. Lyu, S. Zhong, and J. Huang, “Motion prediction based tdma protocol in vanets,” *Electronics*, vol. 9, no. 11, p. 1792, 2020.
- [106] J.-H. Ju and V. Li, “An optimal topology-transparent scheduling method in multihop packet radio networks,” *IEEE/ACM Transactions on Networking*, vol. 6, no. 3, pp. 298–306, 1998.
- [107] J.-H. Ju and V. Li, “Tdma scheduling design of multihop packet radio networks based on latin squares,” *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1345–1352, 1999.
- [108] C. J. Colbourn, V. R. Syrotiuk, and A. C. H. Ling, “Steiner systems for topology-transparent access control in manets,” in *Ad-Hoc, Mobile, and Wireless Networks* (S. Pierre, M. Barbeau, and E. Kranakis, eds.), (Berlin, Heidelberg), pp. 247–258, Springer Berlin Heidelberg, 2003.
- [109] C. Xu, Y.-J. Xu, Z. Wang, and H. Luo, “A topology-transparent mac scheduling algorithm with guaranteed qos for multihop wireless network,” *Journal of Control Theory and Applications*, vol. 9, pp. 106–114, 02 2011.

- [110] Y.-S. Su, "Topology-transparent scheduling via the chinese remainder theorem," *IEEE/ACM Transactions on Networking*, vol. 23, no. 5, pp. 1416–1429, 2015.
- [111] M. Qiao, H. Zhao, L. Zhou, C. Zhu, and S. Huang, "Topology-transparent scheduling based on reinforcement learning in self-organized wireless networks," *IEEE Access*, vol. 6, pp. 20221–20230, 2018.
- [112] H. Xiao and G. Xiao, "A framework of topology-transparent scheduling based on polynomial ring," *IEEE Wireless Communications Letters*, vol. 8, no. 3, pp. 829–832, 2019.
- [113] D. Dash and D. K. Sanyal, "Mimo-ttr+: A novel topology-transparent scheduling scheme for mimo wireless networks," in *2020 International Conference on COMmunication Systems NETworkS (COMSNETS)*, pp. 547–550, 2020.
- [114] L. Deng, F. Liu, Y. Zhang, and W. S. Wong, "Delay-constrained topology-transparent distributed scheduling for manets," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 1, pp. 1083–1088, 2021.
- [115] U. N. Kar, D. Dash, D. K. Sanyal, D. Guha, and S. Chattopadhyay, "A survey of topology-transparent scheduling schemes in multi-hop packet radio networks," *IEEE Communications Surveys Tutorials*, vol. 19, no. 4, pp. 2026–2049, 2017.
- [116] W. Zhu, "Tdma frame synchronization of mobile stations using a radio clock signal for short range communications," in *Vehicular Technology Conference, 1994 IEEE 44th*, pp. 1878–1882, IEEE, 1994.
- [117] M. A. Lombardi, L. M. Nelson, A. N. Novick, and V. S. Zhang, "Time and frequency measurements using the global positioning system," *Cal Lab: International Journal of Metrology*, vol. 8, no. 3, pp. 26–33, 2001.
- [118] Y.-H. Yoon and Y.-B. Ko, "Ctmac: A cooperative TDMA MAC in vehicular ad hoc networks," in *Information and Communication Technology Convergence (ICTC), 2017 International Conference on*, pp. 772–774, IEEE, 2017.

- [119] K. F. Hasan, Y. Feng, and Y.-C. Tian, “GNSS time synchronization in vehicular ad-hoc networks: Benefits and feasibility,” *IEEE Transactions on Intelligent Transportation Systems*, 2018.
- [120] P. Mumford, “Relative timing characteristics of the one pulse per second (1PPS) output pulse of three GPS receivers,” in *6th International Symposium on Satellite Navigation Technology Including Mobile Positioning and Location Services*, 2003.
- [121] S. Bharati and W. Zhuang, *System Model*, pp. 21–24. Cham: Springer International Publishing, 2018.
- [122] W. Ding, J. Wang, Y. Li, P. Mumford, and C. Rizos, “Time synchronization error and calibration in integrated GPS/INS systems,” *ETRI journal*, vol. 30, no. 1, pp. 59–67, 2008.
- [123] W. Franz, H. Hartenstein, and M. Mauve, *Inter-vehicle-communications Based on Ad Hoc Networking Principles: The FleetNet Project*. Universitätsverlag Karlsruhe Karlsruhe, 2005.
- [124] K. Sjöberg, E. Uhlemann, and E. G. Ström, “Delay and interference comparison of CSMA and self-organizing TDMA when used in VANETs,” in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pp. 1488–1493, IEEE, 2011.
- [125] I. T. Union, “Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band.” https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1371-5-201402-I!!PDF-E.pdf, 2014. Online; accessed 03 May 2018.
- [126] V. Dragonas, K. Oikonomou, and I. Stavrakakis, “A topology-independent tdma mac policy for safety applications in vehicular networks,” in *The 1st International Balkan Conference on Communications and Networking (BalkanCom 2017)*, 2017.
- [127] V. Dragonas, K. Oikonomou, K. Giannakis, and I. Stavrakakis, “A disjoint frame topology-independent tdma mac policy for safety applications in vehicular networks,” *Ad Hoc Networks*, vol. 79, pp. 43–52, 2018.

- [128] V. Dragonas, G. Tsoumanis, and K. Oikonomou, “A refined topology-independent probabilistic tdma mac policy for ad hoc networks,” in *2021 International Balkan Conference on Communications and Networking (BalkanCom)*, pp. 61–65, IEEE, 2021.
- [129] V. Dragonas, G. Tsoumanis, and K. Oikonomou, “A probabilistic refined policy for topology-independent medium access control in ad hoc network environments,” *ITU Journal on Future and Evolving Technologies*, vol. 3, pp. 483–497, 2022.
- [130] V. Dragonas, D. Kallergis, G. Tsoumanis, and K. Oikonomou, “On utilizing unused slots in topology-transparent tdma mac policies for ad hoc networks,” in *2022 Global Information Infrastructure and Networking Symposium (GIIS)*, pp. 57–61, IEEE, 2022.
- [131] V. Dragonas, G. Tsoumanis, G. Koufoudakis, A. Papamichail, K. Oikonomou, and I. Stavrakakis, “A fairness-aware topology independent tdma mac policy in time constrained wireless ad hoc networks,” *Computer Networks*, vol. 171, p. 107157, 2020.
- [132] A. Papamichail, V. Dragonas, G. Koufoudakis, K. Oikonomou, G. Tsoumanis, and I. Stavrakakis, “Low-cost device implementation of a topology independent mac (timac) policy,” in *Third International Balkan Conference on Communications and Networking*, 2019.
- [133] G. Tsoumanis, A. Papamichail, V. Dragonas, G. Koufoudakis, C. T. Angelis, and K. Oikonomou, “Implementation of a topology independent mac (timac) policy on a low-cost iot system,” *Future Internet*, vol. 12, no. 5, p. 86, 2020.
- [134] I. Stewart, *Galois Theory, Third Edition*. Chapman Hall/CRC Mathematics Series, Taylor & Francis, 2003.
- [135] Z. Wan, *Lectures on Finite Fields and Galois Rings*. Lectures on Finite Fields and Galois Rings, World Scientific, 2003.
- [136] R. M. de Moraes, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, “On mobility-capacity-delay trade-off in wireless ad hoc networks,” in *Modeling, Analysis, and Simulation of Computer and Telecommunications Systems*,

2004. (*MASCOTS 2004*). *Proceedings. The IEEE Computer Society's 12th Annual International Symposium on*, pp. 12–19, Oct 2004.
- [137] S. A. Jafar, “Too much mobility limits the capacity of wireless ad-hoc networks,” in *Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE*, vol. 6, pp. 3436–3440 Vol.6, Nov 2004.
 - [138] M. Grossglauser and D. N. C. Tse, “Mobility increases the capacity of ad hoc wireless networks,” *IEEE/ACM Trans. Netw.*, vol. 10, pp. 477–486, Aug. 2002.
 - [139] A. Ebner, H. Rohling, R. Halfmann, and M. Lott, “Synchronization in ad hoc networks based on UTRA TDD,” in *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 4, pp. 1650–1654 vol.4, Sept 2002.
 - [140] A. Varga and R. Hornig, “An overview of the OMNeT++ simulation environment,” in *1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops*, pp. 1–10, March 2008.
 - [141] M. Penrose, *Random geometric graphs*, vol. 5. OUP Oxford, 2003.
 - [142] H. SHI, R. V. Prasad, E. Onur, and I. G. M. M. Niemegeers, “Fairness in wireless networks: issues, measures and challenges,” *IEEE Communications Surveys Tutorials*, vol. 16, pp. 5–24, First 2014.
 - [143] M. Banzi and M. Shiloh, *Getting started with Arduino: the open source electronics prototyping platform*. Maker Media, Inc., 2014.
 - [144] Arduino LLC, *Arduino*, 9 2010. Rev3.
 - [145] International Telecommunication Union (ITU), “Radio Regulations.” <https://www.itu.int/pub/R-REG-RR-2016>, 2016.
 - [146] WENSHING ELECTRONICS CO.,LTD, *Wireless Hi Power Transmitter Module (RF ASK)*, 10 2010. v1.0.3.
 - [147] WENSHING ELECTRONICS CO.,LTD, *Wireless Hi Sensitivity Receiver Module (RF ASK)*, 12 2008. v1.0.3.

- [148] C. Guo, J. Shen, Y. Sun, and N. Ying, “Rb particle filter time synchronization algorithm based on the dpm model,” *Sensors*, vol. 15, no. 9, pp. 22249–22265, 2015.
- [149] “Ieee recommended practice for powering and grounding electronic equipment,” *IEEE Std 1100-2005 (Revision of IEEE Std 1100-1999)*, pp. 1–703, May 2006.
- [150] D. Robinson, T. A. Wysocki, V. W. Smith, and K. Popovski, “Background radio frequency interference measurements for wireless devices in the electricity supply industry,” 2005.
- [151] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, “The flooding time synchronization protocol,” in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 39–49, ACM, 2004.
- [152] S. Ganeriwal, R. Kumar, and M. B. Srivastava, “Timing-sync protocol for sensor networks,” in *Proceedings of the 1st international conference on Embedded networked sensor systems*, pp. 138–149, ACM, 2003.
- [153] K. Skiadopoulos, A. Tsipis, K. Giannakis, G. Koufoudakis, E. Christopoulou, K. Oikonomou, G. Kormentzas, and I. Stavrakakis, “Synchronization of data measurements in wireless sensor networks for iot applications,” *Ad Hoc Networks*, 2019.
- [154] A. Varga, “Omnet++,” in *Modeling and tools for network simulation*, pp. 35–59, Springer, 2010.

Appendices

Appendix I

Comparison Figures - Fairness

This section contains ten figures that correspond to the ten different networks that were used throughout the experimental phase for the fairness evaluation of the policies in comparison (Probabilistic Policy, Adaptive Policy, Fairness-Aware Policy, Refined Policy). Each figure is split into four subfigures with each one of them corresponding to one of the aforementioned policies.

All ten networks are comprised of 1000 nodes which are placed according to a connected random geometric graph topology. The access probability value during non-assigned time-slots for all policies is common to all nodes and is $p = 0.03$. Note that for the Fairness-Aware Policy this value corresponds to the p_{min} parameter.

Each subfigure contains 1000 points, each point corresponding to one of the 1000 network nodes. Each point depicts the individual envy of the corresponding node as a function of its maximum number of consecutive re-transmissions.

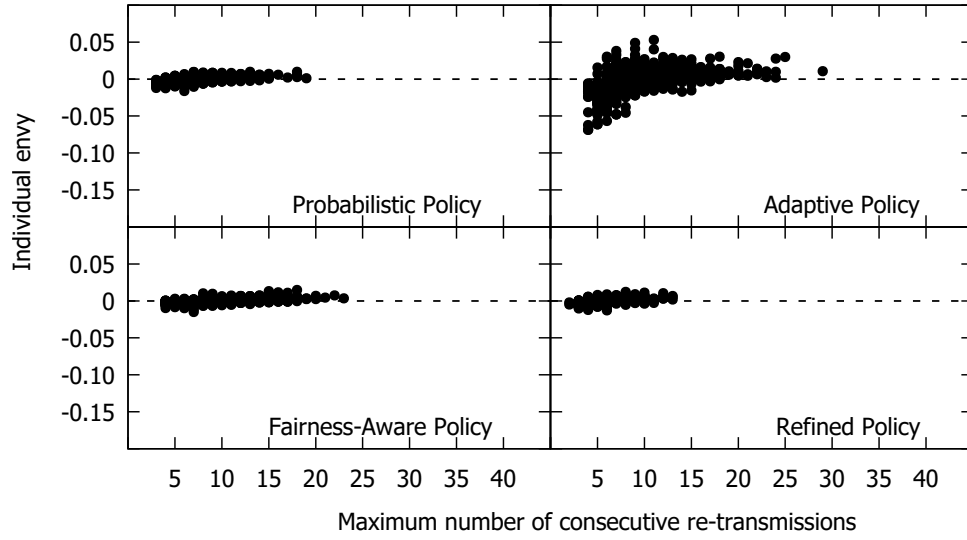


Figure I.1: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 53)

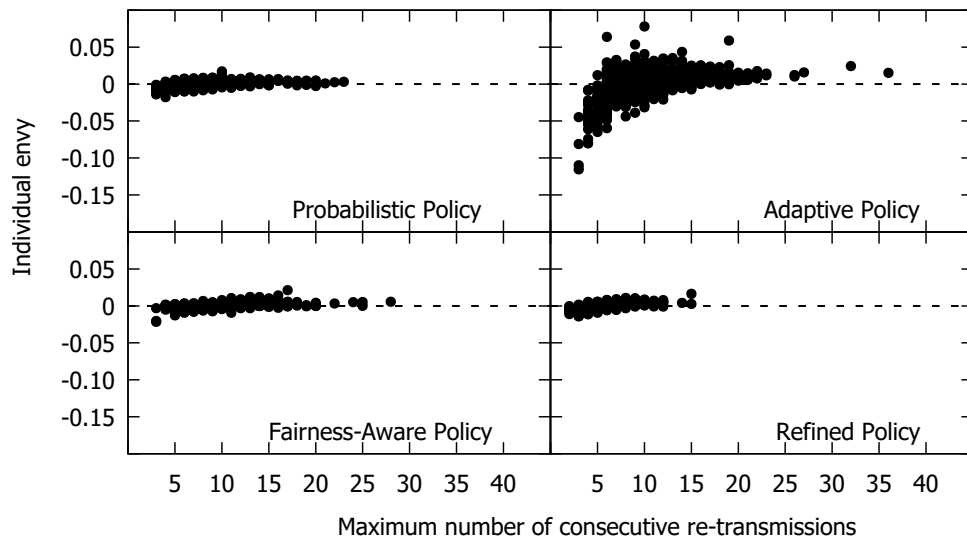


Figure I.2: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 253)

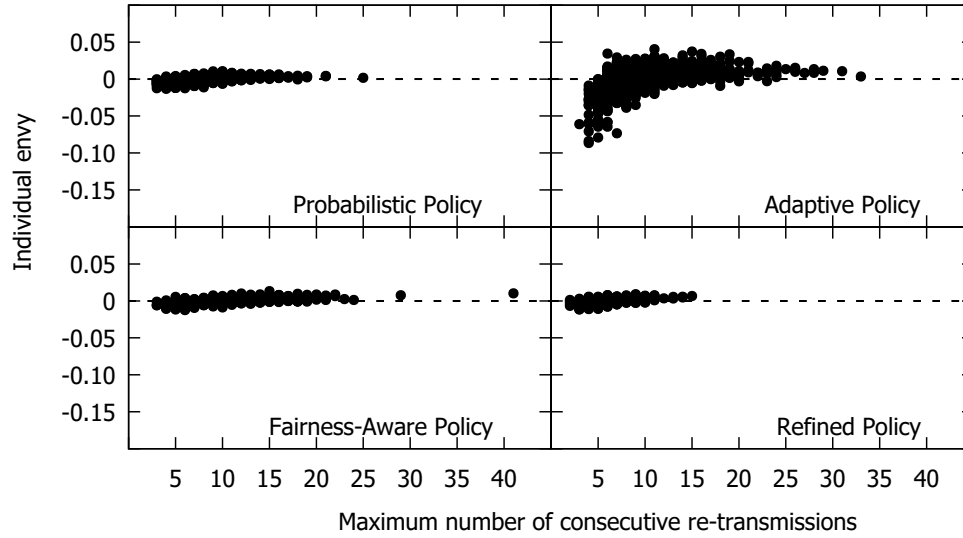


Figure I.3: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 266)

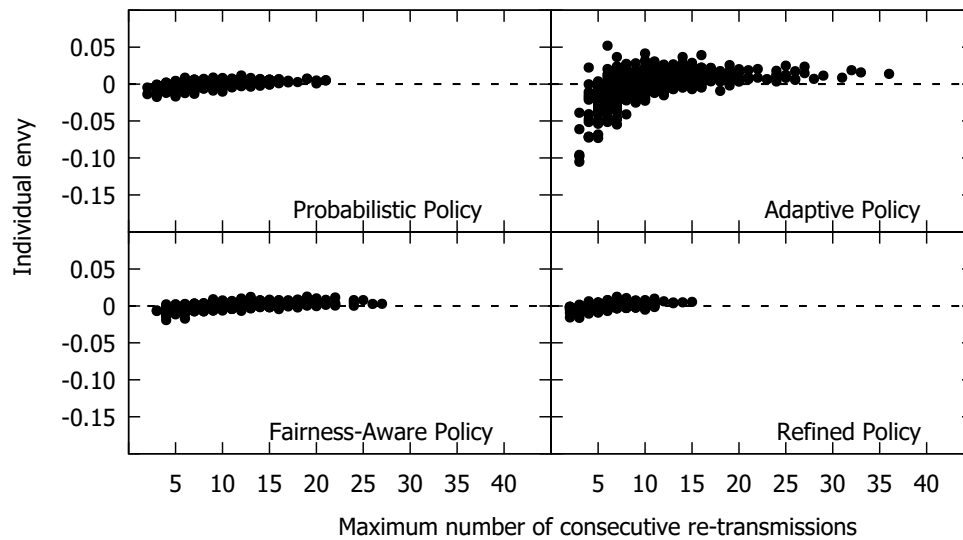


Figure I.4: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 271)

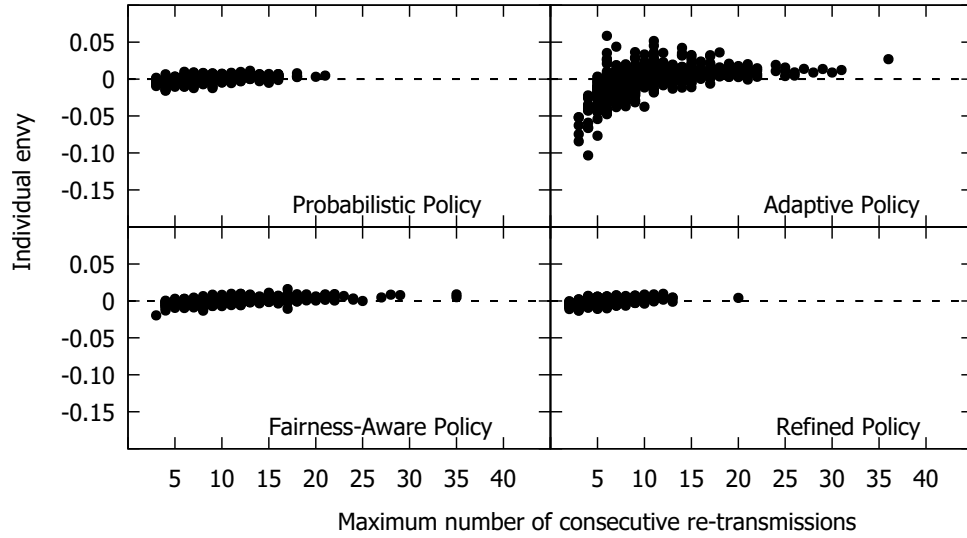


Figure I.5: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 310)

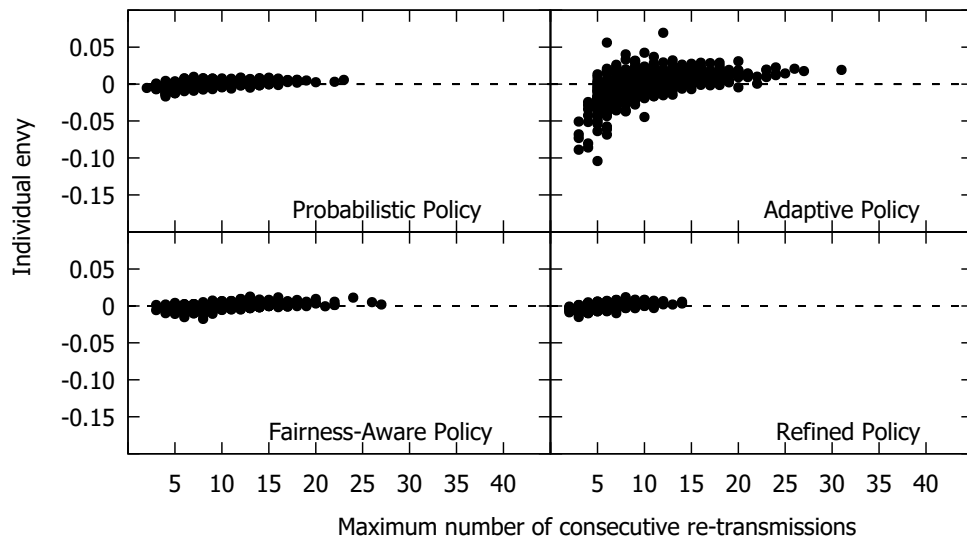


Figure I.6: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 450)

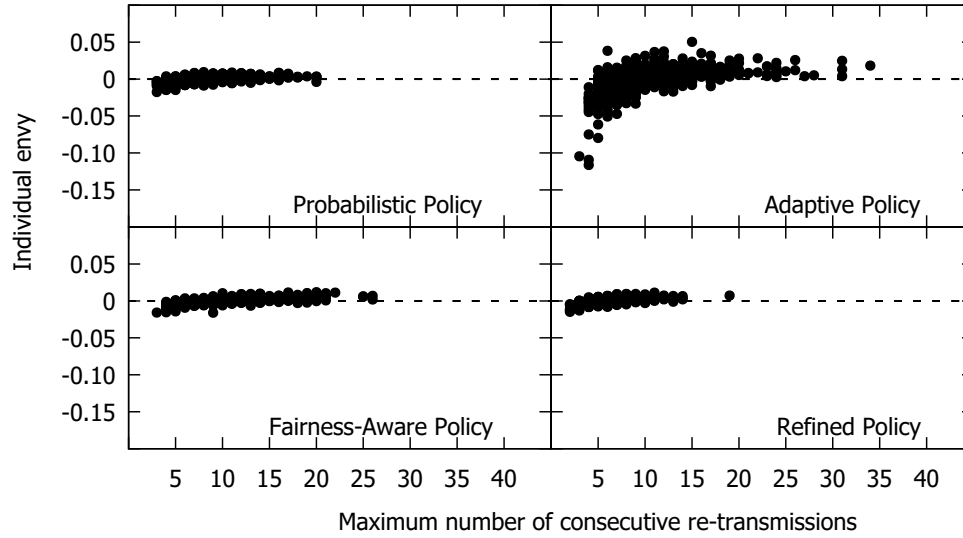


Figure I.7: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 662)

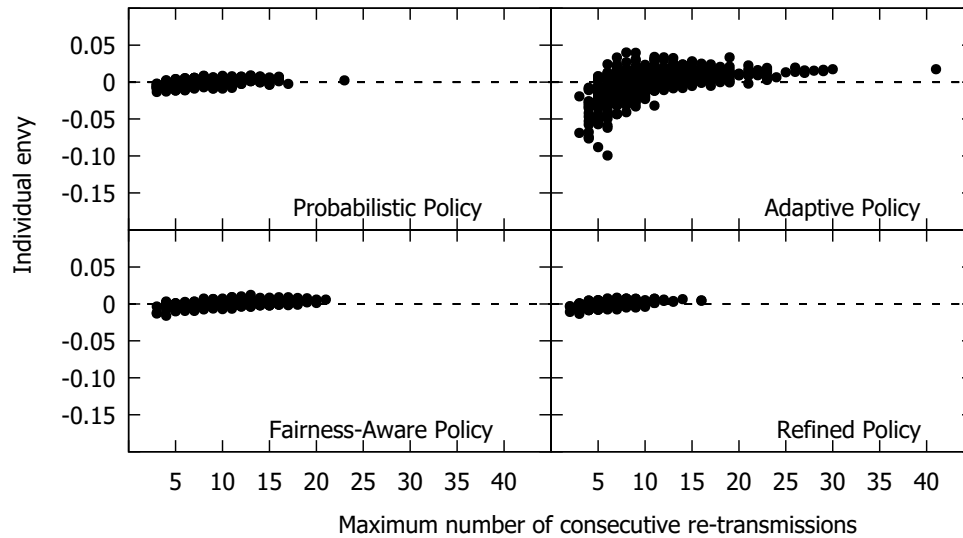


Figure I.8: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 795)

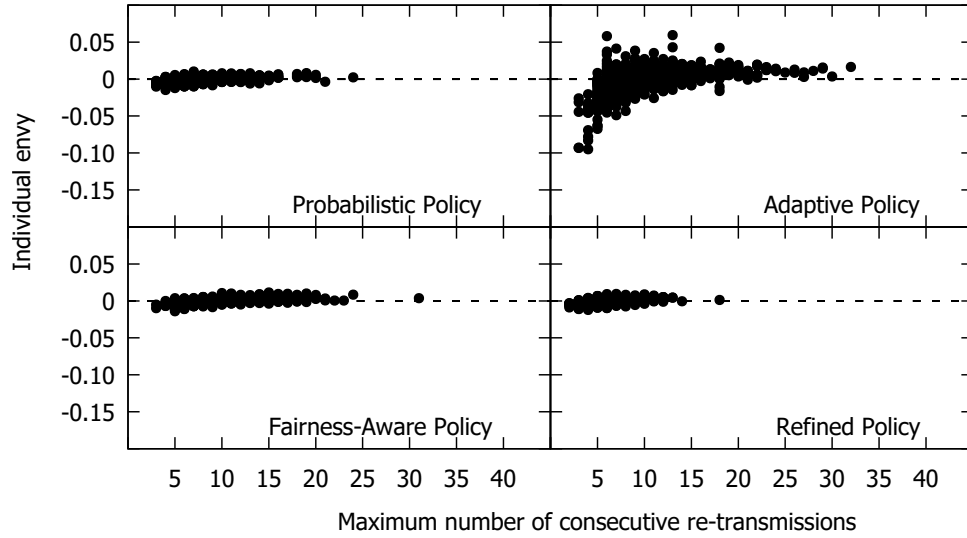


Figure I.9: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 803)

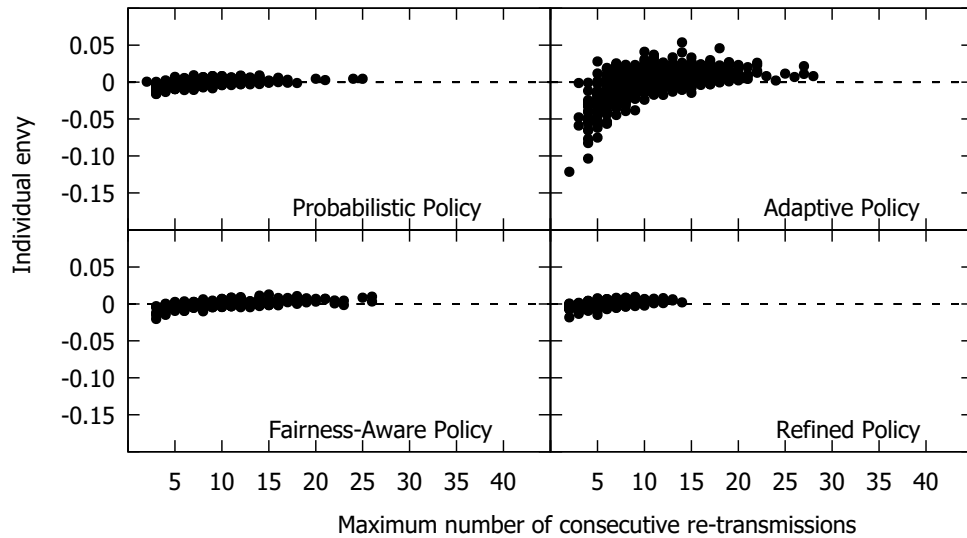


Figure I.10: Individual Envy as a function of the maximum number of consecutive re-transmissions (Network ID: 893)

Appendix II

The OMNeT++ Discrete Event Simulator

The simulation results presented in this thesis were conducted with the use of the OMNeT++ Simulator [140][154]. Their developers describe it as “an extensible, modular, component-based C++ simulation library and framework which also includes an integrated development and a graphical runtime environment” [154]. Its Integrated Development Environment (IDE) is based on the well known Eclipse IDE. OMNeT++ is distributed under the Academic Public License. Its current version is 6.0.1 and is freely available from its website (omnetpp.org).

An OMNeT++ simulation is comprised of modules. A module may represent either a complete network node or a node’s component that performs a specific function. Multiple modules that perform distinct functions can be hierarchically grouped into more complex modules that represent a complete network node. The hierarchically lower modules are called *simple modules*. Those are the ones that implement every possible action that may be taken by a network node. Simple modules can be grouped into *compound modules*. Multiple compound modules can also be grouped into one compound module as well. Compound modules do not implement any functionality, their sole purpose is to group simple modules together.

The hierarchically higher modules are the simulated network’s nodes, thus a *network object* has to be created that will incorporate them and organize them according to any desirable topology. Various parameters can be defined within the network object, for example the real network’s physical area boundaries can be set

if they are relevant to the simulation scenario. Naturally, a number of nodes has to be created within the network and connections have to be established among them so as a network topology can be formed.

The usual way of creating a network topology is to connect nodes with other nodes through *gates*. Gates represent the input and output interfaces of modules. A node's single gate may only be connected to a single gate of another node but each node may have multiple gates or gate arrays. Then two specific nodes are able to communicate through the *channel* that is created between their corresponding connected gates. A node that wishes to communicate with a neighboring node has to create a *message object* and submit it to its output gate that is connected with the neighbor's corresponding input gate. Then, the message is automatically delivered to the recipient node. If a delay has been set (either through the corresponding channel parameter or within the message itself) then the message will be held and delivered at the appropriate time.

The simulation environment maintains a queuing system, the *Future Event Set (FES)*, with the purpose of organizing the delivery of messages. Those are delivered sequentially, according to the order in which they were positioned in the queue. Each message submitted for delivery is put in the FES. Each message's position there is determined by a timestamp called the *arrival time*. Specifically, messages that are scheduled to arrive earlier to their destination are given priority over others. If the arrival times match, then they are prioritized according to a first-come first-serve policy. It is possible to manipulate the priority among messages with identical arrival times by setting a *scheduling priority*.

When a message is delivered to its destination, an event occurs in the recipient object. This event triggers the automatic execution of a specific function in this object. This function is initially blank but its purpose is to be overridden and rewritten by the simulation designer in such way that it will act according to the information contained in the message.

The elapsed time during the simulation (*simulation time*) is not related in any way to the real time as it is normally perceived. The current simulation time essentially is the arrival time of the currently processed message. It does not matter how large is the difference between the arrival times of two consecutive messages. When the processing of the first message ends, the simulator will not wait until the corresponding time interval has passed but instead will instantly start process-

ing the next message and the simulation time will be set at the appropriate value. Consequently, the real time duration of a simulation will not match the simulation time as those depend on the total number of events, on how much processing work is required for each event and on the processing power of the hardware that runs the simulations. It is usual that the real time required for the completion of the simulation is much more than the time interval that corresponds to the simulated scenario, especially when the network contains hundreds of nodes.

A simulation project consists of various types of files. The main types are described below:

- Ned files: This type of files is used for creating the network topology. “Ned” stands for “network description”. As their name implies, they are exclusively used to describe the various network elements. Each network environment and each different network node type corresponds to a ned file. This file is essentially a class definition and based on this class, as is the case with any object oriented language, multiple objects can be created. In similar fashion, multiple networks may be defined, each one corresponding to its own ned file. The programming language used in these files is called the NED language which was built for this purpose by the OMNeT++ creators. Its syntax is similar to the C++ language.
- C++ files: These include the usual header and cpp files that are widely used in the C++ language. Those files are exclusively used for implementing the various actions that might take place upon the arrival of a new message to a node, thus their purpose is to define the behavior of the network nodes. As expected, the C++ language is used here. As mentioned earlier, the nodes’ behavior is implemented exclusively in simple modules as compound modules are only used for grouping simple modules together and network modules contain the description of the network topology with no functionality included. Consequently, C++ files are only supported for simple modules.
- Ini files: These, as their name implies, are files that contain initialization parameters. The syntax here follows its own rules but it is usually just a matter of assigning values to variables defined in the ned files. Their use is optional, because the initialization parameters can be set directly into the corresponding

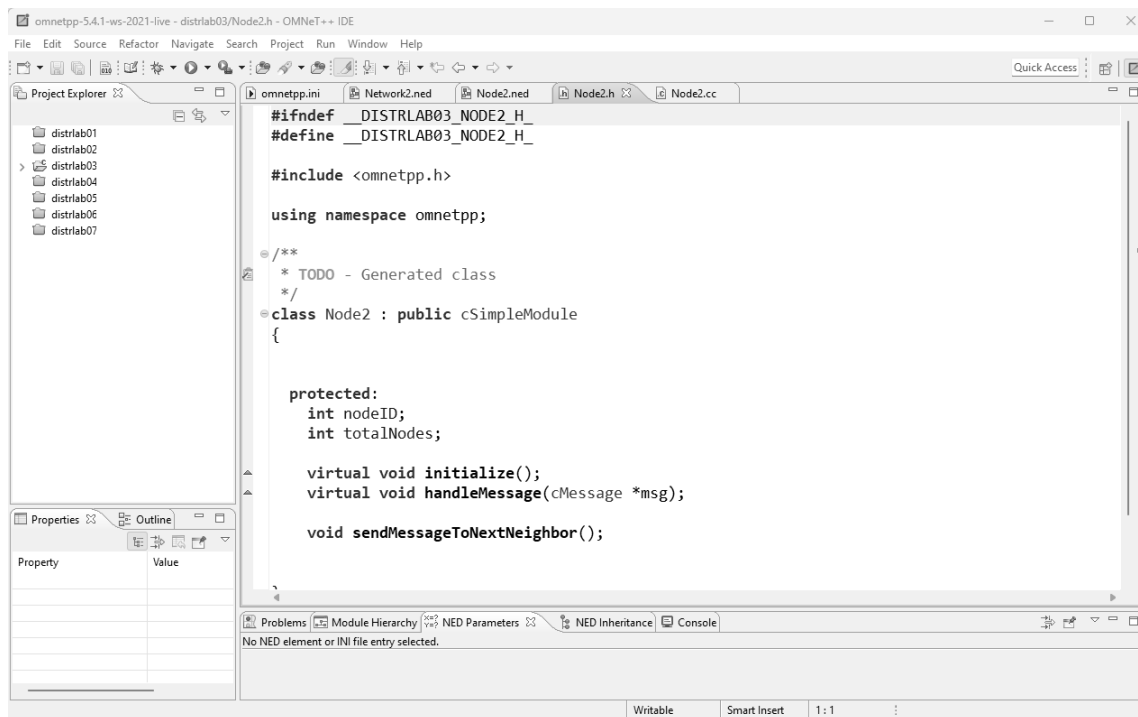


Figure II.1: The OMNeT++ Integrated Development Environment.

ned file, however, their use provides a centralized way of assigning parameters to multiple ned files and additionally allows for the execution of multiple simulation runs where each run has been initialized with a different set of values.

When a new simple module is created, the simulation environment automatically creates its corresponding ned, header and cpp files. Initially, the contents of those files are based on a very basic template. The simulation designer has to edit them and add the parameters and functionality that are needed for the specific simulation scenario. When a new compound module or network is created, only the corresponding ned file is provided, as no functionality can be defined here.

Figure II.1 depicts the main window of the IDE. The project explorer, where multiple projects may exist at the same time, can be found on the left side of the window. As can also be seen, the element that occupies most of the available space is the editor and this is where the ned, ini, cpp and header files are created and edited.

In the editor window of figure II.1, a typical C++ class declaration for a class

with name “Node2” is depicted. This is a basic example of a class that has been created by the simulation designer with the purpose of creating multiple network nodes that are based on this class. It extends the “cSimpleModule” class. The extension of “cSimpleModule” is the standard procedure when creating a simple module for the network. The extension of this class provides two essential methods that are also depicted in this figure. Those methods are meant to be overridden by the simulation designer and they are described in more detail below:

- `initialize()`: This method is automatically executed when the object is created. Its purpose, as its name implies, is to initialize the object’s variables with suitable values.
- `handleMessage(cMessage *msg)`: This method is automatically executed when the object receives a message. The received message is passed as an argument to the “msg” pointer. Most of the coding is usually done within this method. The standard procedure is to check the contents of the message and perform an action accordingly. Consequently, it is very common that this method contains multiple “if...then” statements that take care of every different type of received message.

The careful implementation of the two aforementioned classes is essential for any simulation scenario. Countless additional classes and methods exist which are all documented in the OMNeT++ Simulation Manual which is freely accessible from the OMNeT++ website.

Figure II.2 depicts the window that monitors the progress of the currently running simulation scenario. An example scenario is depicted that corresponds to a full-graph topology. On the left side of the window, elements containing information about the various modules can be found. On the bottom side, information about the events that take place during the simulation is depicted. On the top side, buttons implementing (among others) the “start”, “pause”, “stop” and “accelerate” actions are available that allow for controlling the simulation scenario as desired.

After the simulation has been set up, it can be run either with the use of a Graphical User Interface (GUI) (like the one depicted in figure II.2) or in command line mode. The use of a GUI allows for visual inspection while the simulation is running and is useful for debugging purposes. However, it will add considerable

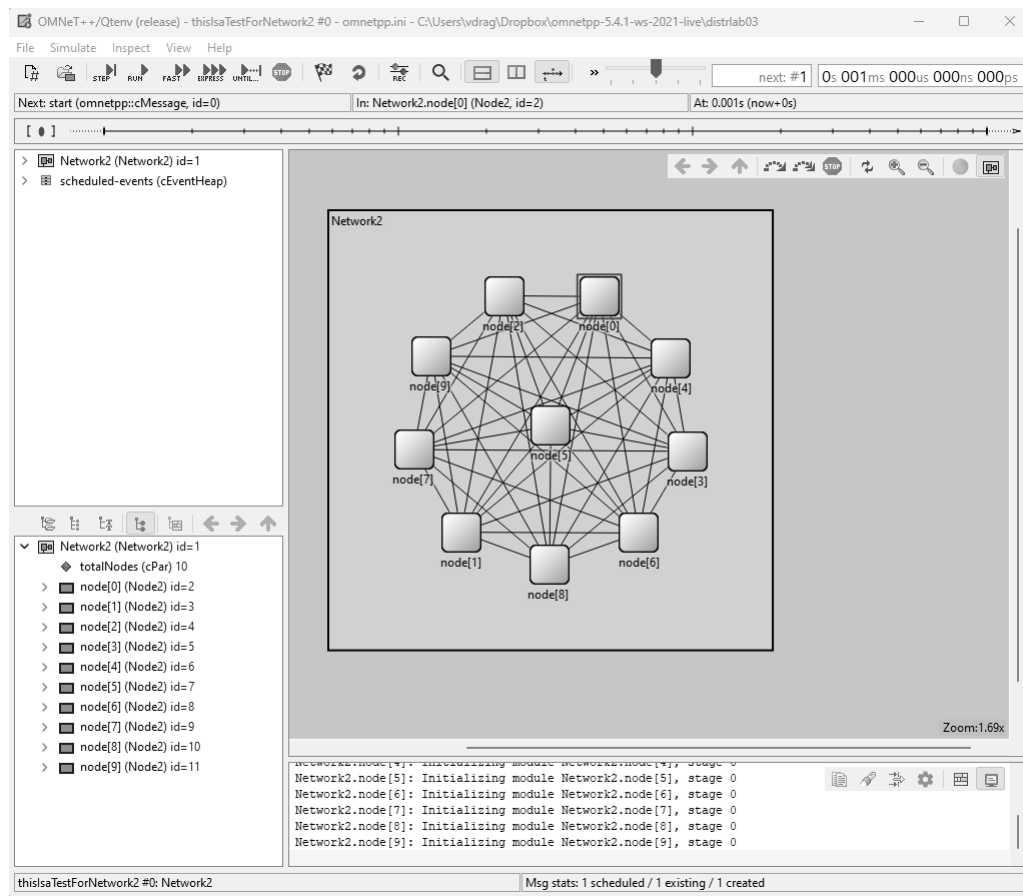


Figure II.2: The OMNeT++ Graphical Runtime Environment.

overhead if the simulation contains a large number of modules and performs computationally intensive tasks. Therefore, when the simulation scenario has been tested with a small number of nodes and it has been confirmed that it will execute as expected, the GUI can be disabled and the simulation can be run under a text based environment which allows for greatly decreased execution times.

After the simulation scenario has been completed successfully, OMNeT++ provides various tools for gathering the simulation results. Alternatively, the designers may write their own methods for exporting the results in plain text files, using any desired custom format which will allow data processing under any 3rd party software that may be required.

Appendix III

Publication Table

Refereed Journals

- V. Dragonas, G. Tsoumanis, and K. Oikonomou, “A probabilistic refined policy for topology-independent medium access control in ad hoc network environments,” *ITU Journal on Future and Evolving Technologies*, vol. 3, pp. 483-497, 2022.
- G. Tsoumanis, A. Papamichail, V. Dragonas, G. Koufoudakis, C. T. Angelis, and K. Oikonomou, “Implementation of a topology independent mac (timac) policy on a low-cost iot system,” *Future Internet*, vol. 12, no. 5, p. 86, 2020.
- V. Dragonas, G. Tsoumanis, G. Koufoudakis, A. Papamichail, K. Oikonomou, and I. Stavrakakis, “A fairness-aware topology independent tdma mac policy in time constrained wireless ad hoc networks,” *Computer Networks*, vol. 171, p. 107157, 2020.
- V. Dragonas, K. Oikonomou, K. Giannakis, and I. Stavrakakis, “A disjoint frame topology-independent tdma mac policy for safety applications in vehicular networks,” *Ad Hoc Networks*, vol. 79, pp. 43-52, 2018.

Refereed Conferences

- V. Dragonas, D. Kallergis, G. Tsoumanis, and K. Oikonomou, “On utilizing unused slots in topology-transparent tdma mac policies for ad hoc networks,” in *2022 Global Information Infrastructure and Networking Symposium (GIIS)*, pp. 57-61, IEEE, 2022.

- V. Dragonas, G. Tsoumanis, and K. Oikonomou, “A refined topology independent probabilistic tdma mac policy for ad hoc networks,” in 2021 International Balkan Conference on Communications and Networking (BalkanCom), pp. 61-65, IEEE, 2021.
- A. Papamichail, V. Dragonas, G. Koufoudakis, K. Oikonomou, G. Tsoumanis, and I. Stavrakakis, “Low-cost device implementation of a topology independent mac (timac) policy” in Third International Balkan Conference on Communications and Networking, 2019.
- V. Dragonas, K. Oikonomou, I. Stavrakakis, “A topology-independent tdma mac policy for safety applications in vehicular networks,” in The 1st International Balkan Conference on Communications and Networking (BalkanCom 2017), 2017.

Appendix IV

Glossary

Access Probability	The probability value under which a node may transmit in a non-assigned slot
Ad Hoc Network	A network that is built spontaneously, allowing nodes to communicate with each other without the existence of typical network infrastructure devices
Body Area Network	A Body Area Network is a network where the nodes are devices that are worn or carried by a person
Channel Access Scheme	A method which allows multiple nodes to share the same communication channel
Complete Graph	A graph in which every vertex is directly connected to any other vertex by an edge
Frame	A specified interval which is repeated over time and in which a node is accessing the medium with a specific method or pattern
Internet of Things	The Internet paradigm under which everyday objects are interconnected with each other
Medium Access Control	Network data transfer policy that determines how data are transmitted between two or more network nodes through a common transmission medium

Mobile Ad hoc Network	An ad hoc network comprised of mobile nodes
Personal Area Network	A network which extends the connectivity of a Body Area Network so that its devices can communicate with devices a few meters away
Random Geometric Graph	A graph that is comprised of uniformly distributed vertices that connect with any other vertex only if their <i>euclidean distance</i> r is smaller than a predefined value
Regular Graph	A graph in which all vertices have the same number of neighbors
Soft Random Geometric Graph	A graph that is comprised of uniformly distributed vertices that connect with any other vertex under a <i>connectivity probability</i> $p(r) = e^{-(r/r_c)^\gamma}$, where r_c is <i>the connectivity radius</i> of each node, r is the particular pair's <i>euclidean distance</i> and γ is a constant related to the particular environment
Subframe	A time interval that corresponds to one portion of a frame which is assumed to be split into multiple portions of equal duration
Throughput	A number that represents the ability of a system to successfully transmit messages or data packets in a given time interval
Topology-Transparent policy	A policy that remains unaffected from changes in topology
Transmission Delay	The time interval between the creation of a message in a transmitter node and its successful reception from the receiver node
Vehicular Ad hoc Network	A mobile ad hoc network where the nodes are vehicles

Wide Area Network	A Local Area Network that covers an area of a few hundred meters.
Wireless Local Area Network	A Local Area Network where its nodes are connected wirelessly, either with network infrastructure devices or in ad hoc fashion

Appendix V

Notations

q	Order of a Galois field
$GF(q)$	A Galois field of order q
k	Degree of a polynomial with Galois field coefficients
Ω_u	Set of node u 's assigned time-slots
$f_u(x)$	Node u 's Galois field polynomial
s	A subframe of the Deterministic Policy's frame
N	The number of total nodes in the network
D	The number of maximum neighbors per node in the network
L	Frame length
$ \bar{S} $	Average number of neighbors in the network
$ \bar{S} /D$	Topology density under the probabilistic policy

p	Access probability
F_u	The set of time-slots that have not been assigned either to the transmitting node u or any of its neighbor nodes
$u \rightarrow v$	A transmission from node u to node v
$AA_{u \rightarrow v}$	The set of time-slots that are assigned to node u as well as to at least one of its 1-hop or 2-hop neighbors, which can corrupt the transmission $u \rightarrow v$
$AF_{u \rightarrow v}$	The set of time-slots that are assigned to node u and are not assigned to any node that can corrupt the transmission $u \rightarrow v$
$FA_{u \rightarrow v}$	The set of time-slots that node u perceives as free but are also assigned to one or more neighbors able corrupt the transmission $u \rightarrow v$
$FF_{u \rightarrow v}$	The set of time-slots that node u perceives as free and are not assigned to any node able to corrupt the transmission $u \rightarrow v$
$S_{u \rightarrow v}^{2hop}$	The set of nodes that are 2-hop neighbors to node u and are able to corrupt transmission $u \rightarrow v$
$S_{u \rightarrow v}^{2hop}$	The set of nodes that are 2-hop neighbors to node u and are able to corrupt transmission $u \rightarrow v$
$S_i^{AF_{u \rightarrow v}}$	The set of nodes that may corrupt transmission $u \rightarrow v$ during time-slot $i \in AF_{u \rightarrow v}$
$ S^{AF_{u \rightarrow v}} $	The average number of nodes that may corrupt transmission $u \rightarrow v$ for all time-slots in $AF_{u \rightarrow v}$ set
$ S^{AF} $	The average number of $ S^{AF_{u \rightarrow v}} $ for all considered transmissions
$S_i^{FF_{u \rightarrow v}}$	The set of nodes that may corrupt transmission $u \rightarrow v$ during time-slot $i \in FF_{u \rightarrow v}$
$ S^{FF_{u \rightarrow v}} $	The average number of nodes that may corrupt transmission $u \rightarrow v$ for all time-slots in $FF_{u \rightarrow v}$ set
$ S^{FF} $	The average number of $ S^{FF_{u \rightarrow v}} $ for all considered transmissions

$P_{R,i,u \rightarrow v}$	Throughput for a particular time-slot i and a particular transmission $u \rightarrow v$ under the Refined Policy
$P_{R,u \rightarrow v}$	Throughput for transmission $u \rightarrow v$ for all time-slots under the Refined Policy
P_R	System throughput for the Refined Policy
$P_{i,u \rightarrow v}$	Throughput for a particular transmission $u \rightarrow v$ and for a time-slot i perceived as free by node u under the Refined Policy
$\hat{p}_1(u)$	The individual access probability of node u for the complete graph case under the Refined Policy
$\hat{p}_2(i, u)$	The access probability of node u for a particular time-slot i for the K-regular graph case under the Refined Policy
$\hat{p}_2(u)$	The individual access probability of node u for the K-regular graph case under the Refined Policy
$\mathbf{X}$	A vector of the resource allocation of all nodes in a network
$\mathcal{J}(\mathbf{X})$	Jain's index for the resource allocation $\mathbf{X}$
x_u	Current resource allocation for node u
$\mathcal{U}$	Utility function for envy evaluation
$\mathcal{U}(x_u)$	Utility function for envy evaluation for resource allocation x_u
$\mathcal{E}_{uv}(\mathbf{X})$	Pairwise envy between node u and node v
$\mathcal{E}_u(\mathbf{X})$	Individual envy of node u
$p_{\min}$	The value of the access probability when no successful transmission has taken place before for a given time-slot $i \notin \Omega_u$ for a node u under the Fairness-Aware Policy

$p_{\max}$	The value of the access probability after a successful transmission has taken place before for a given time-slot $i \notin \Omega_u$ for a node u under the Fairness-Aware Policy
$\mathcal{E}$	A simplified notation for $\mathcal{E}_u(\mathbf{X})$

Appendix VI

Abbreviations

BAN	Body Area Network
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
FES	Future Event Set
FDMA	Frequency Division Multiple Access
GPS	Global Positioning System
GUI	Graphical User Interface
GRAND	Galois RAdio Network Design
IDE	Integrated Development Environment
IoT	Internet of Things
MAC	Medium Access Control

MANET	Mobile Ad hoc NETwork
PAN	Personal Area Network
RG	Random Geometric Graph
SRGG	Soft Random Geometric Graph
TDMA	Time Division Multiple Access
VANET	Vehicular Ad hoc NETwork
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

Appendix VII

Index

- Access probability, 17
- Ad hoc network, 3
- Adaptive Policy, 32
- Arduino, 106
- Body Area Network, 3
- Carrier Sense Multiple Access, 5
- Channel access scheme, 5
- Code Division Multiple Access, 6
- Complete graph, 65
- Delay, 5
- Deterministic Policy, 23
- Energy consumption, 5
- Envy, 86
- Fairness, 10
- Fairness Aware Policy, 84
- Frame, 6
- Frequency Division Multiple Access, 6
- Galois field theory, 22
- Global Positioning System, 7
- GRAND algorithm, 25
- Individual access probability, 65
- Individual envy, 87
- Internet Of Things, 1
- Jain's index, 86
- Medium Access Control, 4
- Mobile ad hoc network, 1
- Pairwise envy, 87
- Personal Area Network, 3
- Probabilistic Policy, 32
- Random Geometric Graph, 70
- Regular graph, 65
- Soft Random Geometric Graph, 70
- Subframe, 24
- Synchronization, 5
- Throughput, 4
- TiMAC, 35
- Time Division Multiple Access, 6

Time-slot, 6

Topology-transparent, 7

Vehicular ad hoc network, 3

VeMAC, 35

Wide Area Network, 3

Wireless Local Area Network, 3

Wireless Sensor Network, 2