A PROBABILISTIC REFINED POLICY FOR TOPOLOGY-INDEPENDENT MEDIUM ACCESS CONTROL IN AD HOC NETWORK ENVIRONMENTS

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Abstract – *Modern network environments are starting to engulf billions of different interconnected devices that support a wide range of applications. Depending on the case, these environments range from static (e.g., wireless sensors) to highly dynamic (e.g., vehicular networks) with respect to topology changes and have different constraints for throughput, time delay, energy consumption etc. Supporting such applications in a topology-varying ad hoc environment is a challenging task. Thus, TDMA-based MAC policies are revisited here and a new policy, i.e., the refined policy is proposed, which builds and improves on the topology-independent policies that appear in the literature. In particular, an individual access probability is introduced that is distributively calculated by each node to access time slots that may result to collisions, but if not then unused network resources will be utilized, thus, increasing throughput. The key idea under the refined policy is to identify and refrain from transmitting during slots that collisions are likely to appear. An analytical expression for the individual access probability is also derived here. It is also shown through simulation experiments that energy consumption is also reduced in addition to throughput incremented under the proposed policy.*

Keywords – Ad hoc, Galois fields, refined policy, TDMA, MAC, topology-independent

1. INTRODUCTION

The emerging modern network environments are large-scale and of diverse characteristics. For example, billions of IoT (Internet of Things) devices are already in operation supporting a variety of everyday life applications [1]. Examples of these applications include (but are not limited to) healthcare [2], vehicular networking [3], disaster management [4], military applications [5], etc. These devices are expected either to connect to a network infrastructure or to communicate directly with each other [6] (e.g., vehicle-to-vehicle communication [7]).

Considering these highly dynamic modern ad hoc environments, the effectiveness of Medium Access Control (MAC) policies is a key aspect and it is expected that TDMA-based ones will provide improved throughput, safety applications [8] and reduced energy consumption [9], [10]. Note that TDMA-based MAC policies are more promising when energy efficiency is a primary concern [11], [12] or when low transmission delay is necessary [8].

Compared to CSMA-based MAC policies [13], TDMA-based ones introduce a certain overhead. Apart from synchronizing nodes [14], in case of topology changes, slot re-allocation may be required which is a resource-consuming process [15]. Topology-independent MAC policies are revisited here to tackle the latter problem, to inherently adapt to topology changes. More specifically, a new policy, i.e., the *Refined Policy*, is proposed that both builds and improves on the topology-independent policies that appear in the literature. The work presented here is an improvement of an earlier version [16].

The seminal paper by Chlamtac and Faragó [17] introduced the *Deterministic Policy* that allowed nodes to transmit during a specific subset of time slots within the frame. Time slots were *assigned* (i.e., allowed to transmit) per node utilizing properties of finite Galois fields under no assumption about the underlying topology (considering only upper bounds of network size and node degree). It was shown that under *heavy traffic* conditions (i.e., all nodes always have data packets available for transmission), there exists at least one successful transmission per frame for each node [17]. To improve on the reduced throughput under the deterministic policy [18], a probabilistic one (i.e., the *Probabilistic Policy*) was proposed in [19] that allowed transmission during time slots not assigned (to be referred to as *non-assigned* hereafter) under the deterministic policy according to a fixed *access probability*, common for all network nodes.

Although throughput increases under the probabilistic policy, compared to the deterministic policy for specific access probability values, the number of transmissions also increases. This also leads to increased transmission collisions. As shown in this paper, nodes may refrain from transmitting during the previously mentioned unassigned time slots that would have resulted in transmission collisions. This motivated the introduction of the *Refined Policy* that bridges the gap between the deterministic policy (that prohibits transmission to unassigned time slots) and the probabilistic policy (that permits transmission to unassigned time slots according to the access probability).

Under the refined policy, each node becomes aware of its neighbors' assigned time slot scheduling as part of the initialization process, thus not introducing any extra overhead (e.g., without integrating any additional information within the transmitted messages). This allows for two improvements that are incorporated in the proposed policy. The first is that it transmits during its assigned time slots (as under the deterministic policy) and a *refined* subset of the unassigned ones. The second is that, unlike the fixed and common to all nodes value of the access probability, each node calculates its *individual access probability* for transmitting during the previously mentioned refined unassigned time slots. Two cases concerning the individual access probability are considered: based on information gathered from one-hop and two-hop neighbor nodes, respectively.

In this paper, the proposed refined policy is studied and analytical expressions concerning throughput are provided. In addition, an analytical expression with respect to the individual access probability is also derived. Performance evaluation using simulation results shows that throughput under the refined policy is larger than under the probabilistic policy for a fixed common access probability and improves further when the individual access probability is considered, thus, confirming the analytical findings. Furthermore, it is shown that the total number of transmissions is reduced, thus conserving energy from potentially corrupted transmissions due to collisions.

In Section 2, relevant past related work is presented. In Section 3, the deterministic and probabilistic policies are described, followed by the presentation of the proposed refined policy in Section 4. In Section 5 an analytical expression regarding throughput is derived as well as for the individual access probability. The performance evaluation of the proposed policy is presented in Section 6, and finally, the conclusions are drawn in Section 7.

2. PAST RELATED WORK

While the main focus of most probabilistic-based work in the literature is on higher layers [20], the implementation of probabilistic approaches in MAC policies and transmission schemes has been investigated over the years. Regarding broadcast and flooding schemes for ad hoc networks, several schemes have been proposed [21]. It has been seen that the probabilistic broadcast ones are more suitable, 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 [22], that bases packet broadcasting on a probability, has been the case for much of the work in the literature. For example, in [23] 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 [24] 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 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 [25], 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 [26]. 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 [27] 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 [28]. 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 [29], Liu et al. proposed a protocol for packet transmissions in Internet of Things (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 rebroadcast to other nodes or not.

Chen et al. in [30] 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 accesing 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 [31] presented a probabilistic alternative of Distributed Color System (DCS), earlier shown by Waldrop et al. in [32]. 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 [33] have implemented 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 [34] 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.

Recently, Hu et al. in their work in [35] 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).

Regarding TDMA policies immune to the underlying topology, most work is based on the earlier mentioned Chlamtac and Faragó's original work [17] which is presented in detail in the next section. In [36], Ju and Li propose an enhancement of the algorithm proposed in [17] which increases minimum guaranteed throughput with the trade-off of a larger frame length.

Another independent approach for creating topology-immune scheduling is Ju and Li's work in [37] where an algorithm based on latin squares is proposed. Their solution is suitable for multichannel systems.

In [38] Colbourn et al. formulate the problem of the creation of topology-independent 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 [39] Xu et al. propose a scheduling algorithm based on balanced incomplete block design. They conclude that their algorithm is superior to [17] and [36] in terms of guaranteed throughput, minimum and maximum delay.

In Su and Yi-Sheng's work in [40] 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 [41] Qiao et al. extend [17] by employing learning-based approaches. The authors make use of artificial intelligence techniques for allocating slots to the nodes and utilizing unused slots, thus improving throughput.

In [42] Xiao et al. propose a topology-independent scheduling scheme which uses polynomial rings. The proposed scheme improves on the theoretical bounds of the 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 work includes [43] where Dash et al. propose a topology-independent scheduling protocol for multi-hop wireless networks with MIMO-enabled transceivers and [44] 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 [45] Kar et al. present a survey of topology-independent schemes. The authors analyze and discuss the various proposed schemes and a comparison is made between them with respect to various evaluation metrics. Additionally, direction for possible future work is 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.

3. ON TOPOLOGY-INDEPENDENT MAC POLICIES

As already mentioned, the proposed policy is based on the deterministic and the probabilistic policies. The key elements of these policies that are also part of the refined policy are presented next. It should be noted that the focus here is on the MAC operation thus, the underlying physical medium is considered as ideal and transmissions fail only due to collisions.

Under the deterministic policy [17], each node u is assigned a unique random polynomial $f_u(x) = \sum_{i=0}^{k} a_i x^i$ where $a_i \in \{0, 1, 2, \ldots, q-1\}$. 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 slot $i \in \Omega_u$, always assuming a *heavy traffic load* in the sense that there is data available for transmission. Apparently, it is not allowed to transmit during the *non-assigned* ones $i \notin \Omega_u$. The assigned polynomial (actually, its coefficients) 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 slot from each subframe s. The slot's position within each subframe s is given by $f_u(s) \mod q$, where $s = 0, 1, \ldots, q-1$. Consequently, $|\Omega_u| = q$. The k and q parameters are derived from the network size (total number of nodes) N and the maximum node degree (number of neighbor nodes) D [17]. Eventually, $q \geq kD + 1$ is satisfied and it is ensured that at least one transmission will be collision-free per frame for all nodes, even under heavy traffic conditions. Note that as *neighbor nodes* of a certain node are the ones one hop away or *1-hop neighbors*. The *2-hop neighbors* correspond to these nodes two hops away from a certain node.

Under the probabilistic policy [19], nodes are allowed to transmit during non-assigned time slots, according to a fixed *access probability* p common for all nodes. Nodes transmit during assigned time slots as under the deterministic policy. This utilizes additional time slots and a range of values for p allows for throughput increment compared against the deterministic policy.

However, allowing to transmit during non-assigned time slots increases energy consumption. Although these additional transmissions eventually contribute to the throughput gain, some are bound to become corrupted due to collisions. If these transmissions (that would eventually become corrupted) could be deterred, this will result in energy savings while throughput will remain increased.

4. THE PROPOSED 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 $u \to v$, 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 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 $u \to v$ may take place according to the access probability p. Thus,

The Refined Policy: Provided there is data available for transmission at slot i, then for transmission $u \to v$:

- *If slot $i \in \Omega_u$, then transmission $u \to v$ always takes place;*
- *If slot $i \in F_u$, then transmission $u \to v$ 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 slot allocations of every neighboring node. The initial value for F_u is all unassigned time slots and it constantly adapts as successful transmissions are received. This adaptation helps in the case of dynamic topology changes since node u always adapts the free slots set F_u.

4.1 A frame example

The frame corresponding to a simple line network of three nodes (a, b and c) is depicted in Fig. 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 slot may be assigned to more than one node (e.g., slots 0 and 7). Consequently, when node a or node c transmits during slot 0 towards node b, a collision will occur (since all nodes operate under heavy traffic conditions). Still, it is guaranteed that there will be at least one successful transmission for each node (e.g., time slots $4, 5, 8$).

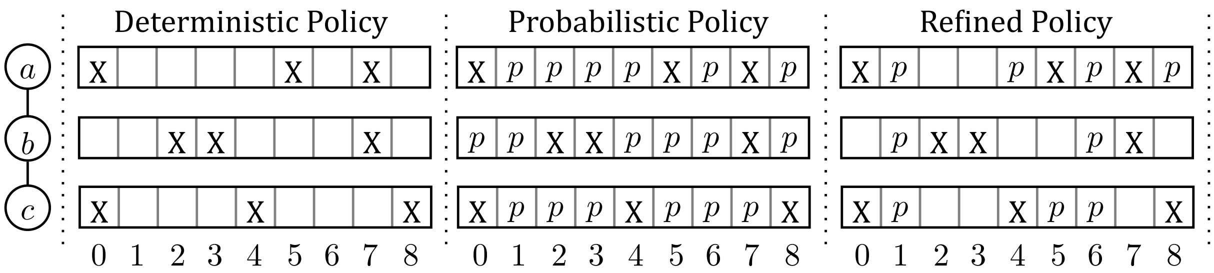

Fig. 1 – The frame for an example line network of three nodes (a, b and c) as appears under the deterministic, probabilistic and refined policies. It consists of three subframes and there are three time slots for each one (0-1-2 , 3-4-5 , 6-7-8, respectively). Time slots marked (i) with X correspond to assigned slots; (ii) with p correspond to those non-assigned 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.

For the frame under the probabilistic policy, nodes are allowed to transmit during non-assigned slots, which are marked with p. Probabilistic transmissions introduce collisions among neighbors for time slots that transmissions would have been successful under the deterministic pol- icy (e.g., a, b and c during slot 2) . However, as shown in [19], 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.1 corresponds to the proposed refined policy. Every node is aware of its neighbors' assigned 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 shown later, the refined policy increases system throughput even compared to the probabilistic policy and at the same time reduces the overall number of trans- missions.

4.2 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 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 a 2-hop neighbor might perceive these 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 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 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 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 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.
- $S^{2hop}_{u\rightarrow v}$: 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 $S^{2hop}_{u\rightarrow v}$.
  - $|S^{AF_{u\rightarrow v}}|$: 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 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 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:

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

4.3 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. 3. It is a ring topology where each node is neighbor to the two nearest left-side nodes and the two nearest right-side nodes.

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

Based on Fig. 2 and Table. 1, the following observations can be made:

- The value of $|AA_{u \to v}|$ depends on the receiver node, i.e., node v. For example, when transmission $a \to b$ takes place, $|AA_{a \to b}| = 2$, but when the transmission $a \to g$ takes place, $|AA_{a \to g}| = 3$.
- The same applies to $|FF_{u \to v}|$. For example when transmission $a \to c$ takes place, $|FF_{a \to c}| = 4$, while for the transmission $a \to h$ takes place, $|FF_{a \to h}| = 6$.
- $S_i^{AF_{u \to v}}$ is different for every time slot. For example, when transmission $a \to c$ takes place during time slot 5, $|S_{05}^{AF_{a \to c}}| = 2$, while for the same transmission during time slot 20, $|S_{20}^{AF_{a \to c}}| = 1$. It is also observed that $|S_i^{AF_{u \to v}}|$ changes for different transmissions taking place at the same time slot.
- The same applies to the $S_i^{FF_{u \to v}}$ set. For example, when transmission $a \to h$ takes place at time slot 17, $|S_{17}^{FF_{a \to h}}| = 2$, but when the same transmission takes place at time slot 24, $|S_{24}^{FF_{a \to h}}| = 4$. As before, $|S_i^{FF_{u \to v}}|$ changes for different transmissions taking place during the same time slot.
- $S_{u \to v}^{2hop}$ depends on the relative position of nodes u and v in the network. For example, when transmission $a \to b$ takes place, $S_{a \to b}^{2hop} = \{d\}$ but when $a \to c$ takes place, $S_{a \to c}^{2hop} = \{d, e\}$. It can also be observed that $|S_{u \to v}^{2hop}|$ 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 $|S_{u \to v}^{2hop}|$ is an integer value between 1 and $\frac{K}{2}$.

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

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

5. 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.

5.1 Throughput

The first step is to calculate throughput for a particular slot i and a particular transmission $u \to v$. This corresponds to the probability of transmission $u \to v$ being successful and is denoted as $P_{R,i,u \to v}$. 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 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 $u \to v$ during slot i, thus,

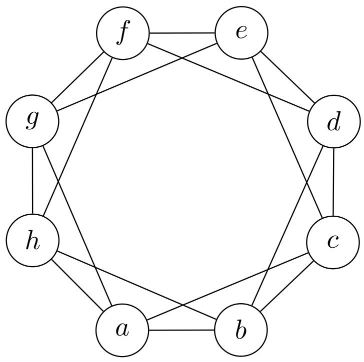

Fig. 3 – Regular graph example with eight nodes and four neighbors.

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

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

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

As $S_i^{AF_{u\to v}}$ and $S_i^{FF_{u\to v}}$ 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 $|S_i^{AF_{u\to v}}| = |S^{AF_{u\to v}}|$ and $|S_i^{FF_{u\to v}}| = |S^{FF_{u\to v}}|$.

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

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

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., $P_{R,u\to v}$) over the total number of nodes (assuming that each node always transmits to the same neighbor node). Thus,

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

However, as already mentioned, sets $AF_{u\to v}, S^{AF_{u\to v}}, FF_{u\to v}$ and $S^{FF_{u\to v}}$ 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 $|AF_{u\to v}| = |AF|$, $|S^{AF_{u\to v}}| = |S^{AF}|$, $|FF_{u\to v}| = |FF|$ and $|S^{FF_{u\to v}}| = |S^{FF}|$. Eventually, P_R, is given by,

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

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

Position 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
Position 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
a	$0x+0$	X	p		p		X					X		p			X	p	p		p	X			p	p
b	$1x+2$			X	p					X			p			X	X	p	p		p		X			p
c	$2x+4$				p	X		X	p				p		X		X	p		p	p			X		p
d	$3x+1$		X				p		p		X		p	X			X			p	p	p			X	p
e	$4x+0$	X					p		p	p	X				X	p			X		p		X			p
f	$1x+3$				X		p	p		p	X	X				p		X			p			X		p
g	$2x+2$		p	X				p		p	X		X	p		p				X	p	X			p	p
h	$3x+4$		p			X		p	X			X		p	p				p	X	p		X		p	p

Fig. 2 – The frame corresponding to the network of Fig. 3. 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.

5.2 The individual access probability

So far, the analysis assumed a fixed access probability p, common for all network nodes. The next step is to allow each node to calculate its *individual access probability*. Two cases will be considered. The first, motivated by an analysis on complete graph topology, is based on the 1-hop neighbor nodes, thus will be denoted as $\hat{p}_1(u)$ for each node u. The second will consider 2-hop neighbors and, thus, will be denoted as $\hat{p}_2(u)$ for each node u.

Assuming the complete graph network example depicted in Fig. 4, then under the refined policy, every node is aware of the time slot assignments of any other node in the network. Time slots perceived as free will be common among all nodes since there are no 2-hop neighbors to provide any additional information.

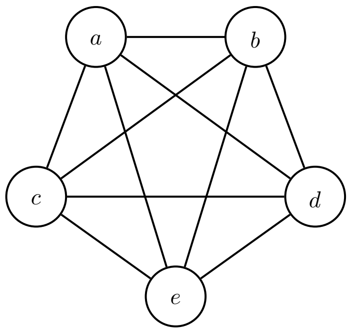

Fig. 4 – Five nodes in a complete graph topology.

Throughput during a (perceived as free) slot i for a particular transmission $u \to v$ is given by,

$$P^F_{R,i,u\to v} = \hat{p}_1(u)(1-\hat{p}_1(u))^{|S_i^{FF_{u\to v}}|}. \qquad (7)$$

Studying the roots of the first derivative of this expression with respect to $\hat{p}_1(u)$, throughput is maximized at $\hat{p}_1(u) = \frac{1}{|S_i^{FF_{u\to v}}|+1}$. Note that for a complete graph network topology, $|S_i^{FF_{u\to v}}| = D$.

Going to the general case, i.e., topologies that both 1-hop and 2-hop neighbors exist, a formula for $\hat{p}_2(u)$ will be derived next. Throughput for transmission $u \to v$ during a time slot perceived as free by node u depends on whether or not this time slot has been assigned to its 2-hop neighbors. On a regular graph topology as the one in Fig. 3, node u will be aware of its D 1-hop neighbors. Furthermore, D nodes can corrupt transmission $u \to v$, but these nodes will come from a different set: the 1-hop neighbors of node v, including node v and excluding node u. Those nodes may either be 1-hop neighbors or 2-hop neighbors to node u (thus the latter will belong to the $S^{2hop}_{u\to v}$ set). This means that node u might perceive time slot i as free, but this time slot may not be free because it has been assigned to a 2-hop neighbor and node u is unaware of this. In this case, it would be best if $u \to v$ would not take place at all, thus during this slot it should be $\hat{p}_2(u) = 0$.

It is also possible that time slot i may indeed be free. In this case, the transmission will succeed if no other of the previously mentioned D nodes transmits (probabilistically) at the same time slot. Let D_u and D_v denote the number of neighbor nodes of node u and v respectively. Note that $D_u = D_v = D$ for the regular graph network considered here. If each one of the D_v nodes (excluding u and including v) perceives time slot i also as free, the particular value of $\hat{p}_2(u)$ that maximizes throughput is equal to $\frac{1}{D_u+1}$ (as given by the first derivative of Equation *(7)*). However, it is possible that some nodes, due to their own locally obtained information, will not perceive slot i as free and never transmit there. In this case, the probability for the transmission $u \to v$ should be larger than $\frac{1}{D_u+1}$. Still, this information is not available to node u. Consequently, node u will assume that every node able to corrupt $u \to v$ transmission perceives time slot i as free as well, so for this case, the value $\frac{1}{D_u+1}$ is a good choice regarding the access probability for time slot i. This will be demonstrated later using simulation results.

Based on these observations, let the access probability of node u for a particular slot i that is based on 2-hop information $\hat{p}_2(i,u)$ be given by,

$$\hat{p}_2(i,u) = \begin{cases} 0, & i \in FA_{u\to v}; \\ \frac{1}{D_u+1}, & i \in FF_{u\to v}. \end{cases} \qquad (8)$$

Since there is no single value to satisfy every slot perceived as free, thus an average value will be considered next. In particular, node u perceives as free $|F_u| = |FA_{u\to v}| + |FF_{u\to v}|$ time slots and will probabilistically transmit during them. Furthermore, every node has been assigned q slots from a total of q^2 and this means that the probability of time slot i not having been assigned to a single node is $\frac{q^2-q}{q^2}$ or $\frac{q-1}{q}$. Consequently, the probability of time slot i not having been assigned to at least one of the nodes able to corrupt the transmission is $(\frac{q-1}{q})^{|S^{2hop}_{u\to v}|}$.

As before, an average value regarding $|S^{2hop}_{u\to v}|$ will be calculated, as it depends on transmission $u \to v$. As shown in Table 1, for the particular type of K-regular graph topology, depending on the transmitter and the receiver nodes' positions within the topology, $|S^{2hop}_{u\to v}|$ can be an integer value taking values from 1 to $\frac{K}{2}$. Since the target node is randomly selected, all values within the interval, as mentioned earlier, have an equal probability of appearing. Consequently, the average number of nodes able to corrupt a (probabilistic) transmission is given by $|S^{2hop}| = \frac{1+\frac{K}{2}}{2}$.

Let the average access probability $\hat{p}_2(u)$ when 2-hop information is acquired be given by,

$$\hat{p}_2(u) = \frac{1}{|F_u|} \sum_{\forall i \in F_u} \hat{p}_2(i,u), \qquad (9)$$

for each time slot i given by Equation *(8)*.

For the $|F_u|(\frac{q-1}{q})^{|S^{2hop}|}$ time slots (where $\widehat{p}_2(i,u) = \frac{1}{D_u+1}$) and $|F_u|(1 - (\frac{q-1}{q})^{|S^{2hop}|})$ time slots (where $\widehat{p}_2(i,u) = 0$ since the transmission will always be corrupted), the previous expression can be written as, $\widehat{p}_2(u) = \frac{\frac{1}{D_u+1}|F_u|(\frac{q-1}{q})^{|S^{2hop}|}}{|F_u|}$, thus,

$$\widehat{p}_2(u) = \frac{1}{D_u+1}(\frac{q-1}{q})^{|S^{2hop}|}. \qquad (10)$$

Later in the performance evaluation section, both $\widehat{p}_1(u)$ and $\widehat{p}_2(u)$ will be considered and evaluated against the obtained simulation results. Both equations will be applied to random geometric graphs and regular graph networks. Although their derivation was based on different types of networks (e.g., a complete graph for $\widehat{p}_1(u) = \frac{1}{D_u+1}$) and under certain assumptions, it is interesting to observe how they perform in a wide range of topologies.

6. 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 slots separately. Additionally, the individual access probability calculation is evaluated, compared to a range of 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 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 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 slots and how this decrement will affect the overall performance.

Finally, $\widehat{p}_1(u)$ and $\widehat{p}_2(u)$ 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.

6.1 Experimental setup

A simulation program was developed using the OMNET++ platform [46] and simulations are conducted to evaluate the proposed refined policy compared to both the Probabilistic and the deterministic policy. Ten different networks are created, each one of $N = 1000$ nodes, positioned according to a Random Geometric Graph (RGG) topology model [47]. After the initial setup, the topology remains unchanged for the duration of each experiment. 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 $q = 37$. Note that the derived value of q is the lowest prime number satisfying the requirements described in Section 3. 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 slots. The simulation duration is 20 frames or 27380 time slots.

Additionally, K-regular graph topologies of $N = 1000$ nodes are considered with $K = 18$. Again, ten different networks are created. The same parameters $k = 1$ and $q = 37$ are also used, leading to the same frame length and number of assigned slots per node. 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 *(6)*. Node clocks are considered fully synchronized and each node operates under a heavy traffic load, meaning that there is always data available for transmission whenever a node is allowed to transmit. For the RGG 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 it's 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 slot and upon successful message transmission, thus notifying the source node for the successful reception.

6.2 Simulation results for RGG topologies

Fig. 5 depicts throughput simulation results for the random geometric graphs, as a function of the access proba-

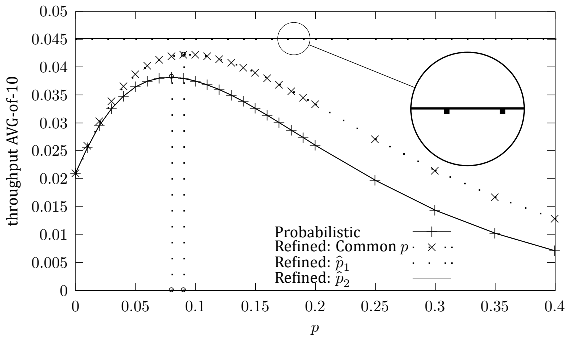

Fig. 5 – Throughput as a function of the access probability p. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the probabilistic policy and the refined policy assume the maximum throughput under common p, respectively. Confidence intervals are no greater than 2.5%.

bility 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 (0.042) is about 10% higher than under the probabilistic policy (0.038). 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 $\hat{p}_1$.

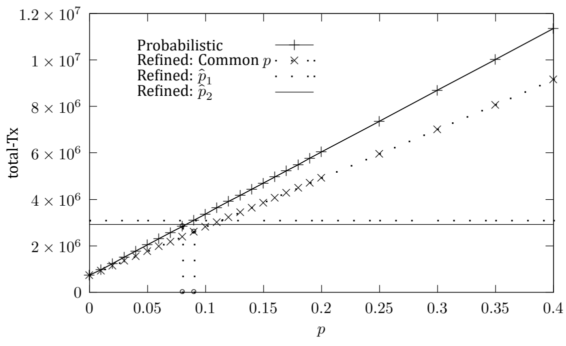

Fig. 6 – The total number of transmissions as a function of the access probability p. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the probabilistic policy and the refined policy assume the maximum throughput, respectively. Confidence intervals are no greater than 0.13%.

Fig. 6 depicts the number of total transmissions 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 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 $\hat{p}_1$.

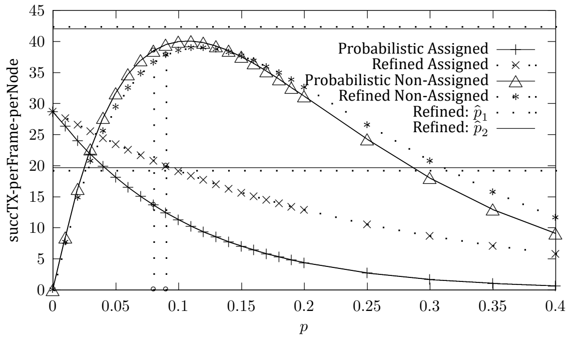

Fig. 7 – Average number of successful transmissions for assigned and non-assigned slots per node per frame as a function of the access probability p. The vertical lines correspond to $p = 0.8$ and $p = 0.9$ where the probabilistic policy and the refined policy assume the maximum throughput, respectively. Confidence intervals are no greater than 3.5%.

Fig. 7 depicts the average number of successful transmissions per node per frame during assigned or non-assigned slots separately. For the assigned 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 slots, nodes under the refined policy succeed on 37.8 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 slots outweighs the decrease of successes during the non-assigned slots. Regarding the individual access probability cases, it is observed that the successes during assigned 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 slots are increased.

6.3 Simulation results for regular topologies

Fig. 8 depicts throughput under the probabilistic and the refined policies for an 18-regular graph topology. Similar to the RGG topology case, 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

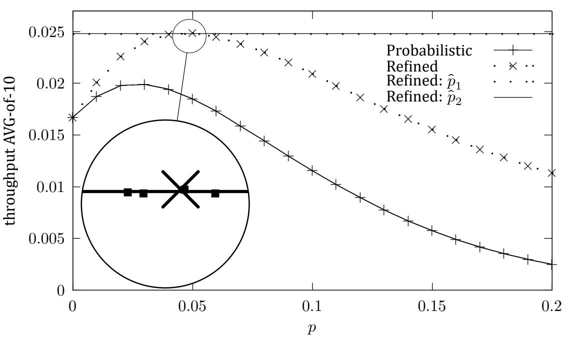

Fig. 8 – Average throughput of ten networks for an 18-regular graph topology. The magnifying glass depicts the largest throughput value under common access probability, compared to both individual access probability values.

cases match the throughput of two of the common access probability scenarios, which is to be expected since it is a regular graph 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 5.2, can be attributed to the fact that some nodes that were expected to transmit probabilistically during some slots, do not transmit at all because, based on their own local information, they do not perceive those slots as free.

6.4 Simulation results for various RGG topologies

Figures 9, 10, 11 and 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 *(6)*. Results from these simulations are used as input for Equation *(6)*.

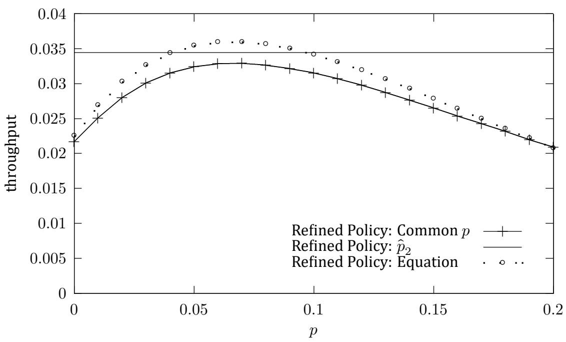

Fig. 9 – Throughput evaluation for an RGG network topology with the following parameters: $N = 961$, $D = 25$, $k = 1$, $q = 31$.

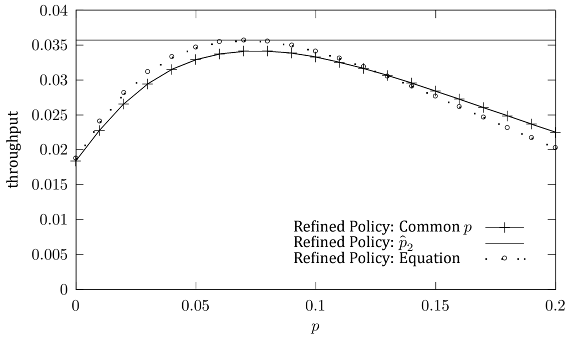

Fig. 10 – Throughput evaluation for an RGG network topology with the following parameters: $N = 1681$, $D = 23$, $k = 1$, $q = 41$.

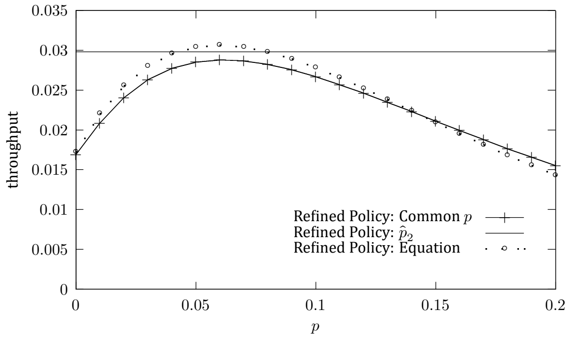

Fig. 11 – Throughput evaluation a RGG network topology with the following parameters: $N = 1849$, $D = 25$, $k = 1$, $q = 43$.

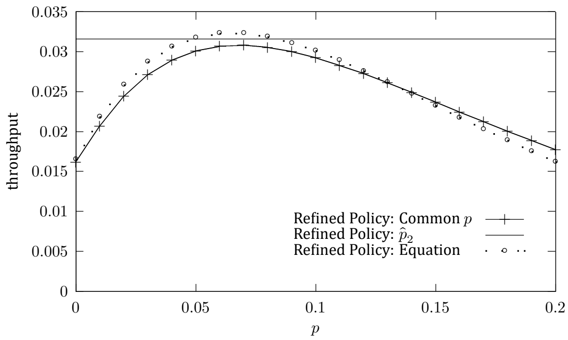

Fig. 12 – Throughput evaluation for a network topology with the following parameters: $N = 2209$, $D = 24$, $k = 1$, $q = 47$.

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 *(6)* introduce a deviation to the calculated values that eventually affect the overall performance.

Finally, two tables 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 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.

Table 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
$\|S^{AF_{a\to b}}\|$	4,06	4,76	4,4	0,10
$\|S^{FF_{a\to b}}\|$	16,43	16,54	16,49	0,02
$\|AF_{a\to b}\|$	19	29	22,89	1,41
$\|F_a\|$	799	820	809,8	3,25
$\|FF_{a\to b}\|$	696	715	705,46	3,05

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

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

7. CONCLUSIONS

In this work, a TDMA-based MAC policy independent of the underlying topology has been proposed, which attempts to increase throughput by utilizing non-assigned slots while at the same time conserving energy by avoiding transmissions that have a high probability of collision. Each node can derive its neighbors' slot allocations and identify time slots that may transmit with an individual access probability. The discovery of the neighbors' slot allocations and the calculation of the individual access probability occur without integrating additional information within the transmitted messages. Simulation experiments were used to evaluate the proposed refined policy against the other two policies in the literature. More specifically, the results demonstrate that the proposed policy, compared to its predecessors, achieves better throughput and, at the same time, reduces the total number of transmissions.

Future work may include a more precise calculation of the individual access probability's value which will be closer or equal to the best possible one with respect to the maximum achievable throughput. A comparison of the proposed policy with other existing topology-independent policies would be interesting and will also be included in future work. Besides with average throughput and energy consumption, additional evaluation metrics may also be considered, e.g minimum guaranteed throughput, frame length, transmission delays and network size scalability being some of them. Finally, new probabilistic schemes similar to the refined policy may be considered and implemented as extensions to other topology immune schemes which, as presented in the past related work section, are based on approaches independent of the Galois field approach used in this work.

ACKNOWLEDGEMENT

This work was supported in part by project "Corfu Virtual Exhibition Site for Tourism-Culture-Environment (v-Corfu)," (MIS 5031252), which is partially funded by the European and National Greek Funds (ESPA) under the Regional Operational Programme "Ionian Islands 2014-2020."

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