On Access Point Association in Wireless Mesh Networks

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***Abstract*—End users getting connectivity from wireless access networks want to choose the "best" access opportunity, that is, the best base station in cellular systems, and the best access point in WLANs. The metrics used to drive the association procedures are usually based on "local" parameters like the received signal strength, and the base station/access point's load. In case connectivity is provided through a Wireless Mesh Network the quality perceived by the user upon association depends also on "global" network-wide parameters.**

This paper studies the dynamics of network association in Wireless Mesh Networks by resorting to game theoretic tools. We show how the association problem can be formalized as a non-cooperative game in which end users selfishly play to minimize a perceived association cost which accounts for characteristics of the entire path to reach the WMN gateway. The quality of the Nash Equilibria for the proposed game are then quantitatively analyzed, and preliminary numerical results on the perceived association cost are derived for sample network topologies.

***Keywords*-Wireless Mesh Networks, Association, Competition**

I. Introduction

The rapid diffusion of wireless technologies is nowadays prompting the end users with multiple and heterogeneous connectivity opportunities. Wireless connectivity is largely available in urban and metropolitan areas which actually feature private, public, and commercial wireless point of access. On the network's side, the most common wireless access paradigm is still the one based on hot-spots (e.g., WiFi-based) operating as bridges between the wireless realm (connection to the users), and the wired one (connection to the Internet). However, such access paradigm may have both economical and technical shortcomings under some network scenarios; as an example, the capillary coverage of large metropolitan areas may require high capital investments for cabling up all the required wireless access points, or cabling itself may simply be impossible or externally constrained (historical buildings, etc.).

To overcome the aforementioned limitations, the paradigm of Wireless Mesh Networking has been widely recognized as a cost effective solution for providing wireless connectivity/access to mobile users [1], [2]. Such success is mainly due to the high flexibility of the mesh networking paradigm which has many advantages in terms of self-configuration capabilities and reduced installation costs. Several WMNs deployments and initiatives have flourished worldwide with different goals and application targets [3][4].

Wireless Mesh Networks (WMNs) are composed of a mix of fixed and mobile nodes interconnected through multi-hop wireless links. Different from flat Mobile Ad hoc Networks (MANETs), the WMNS often feature a hierarchical architecture. At the top of the hierarchy, Mesh Gateways (MGs) are equipped with wireless/wired connectivity cards and act as gateways toward the wired backbone. The Mesh Routers (MRs) have twofold functionalities: they act as classical access points towards the end users (access segment), whereas they have the capability to set up a wireless backbone by connecting to other mesh routers through point to point wireless links to transport the access traffic to/from the MGs. The users, or user STAtions (STAs), can consequently get access to the network services through multi-hop paths towards one or more MGs.

Regardless the specific wireless access network (cellular systems, WLANs, WMNs), the STA always has to make decisions on network association. Namely, network association refers to the dynamic and automatic choice of the best "connectivity opportunity", that is, the cellular base station in classical cellular systems, the access point in WiFi WLANs, and the Mesh Router (MR) in WMNs. In classical hot-spot-like access networks (e.g., WLAN), the access decision is (almost) completely driven by the quality of the "last-mile" link, and the STAs decide to associate with the WLAN hot-spot providing the "best" wireless link accounting for the Signal to Interference and Noise Ratio - SINR, the average load, the nominal data rate, etc. Differently, in case the access network is a WMN, the user-perceived quality depends on the overall quality of the entire path towards the specific entry/exit MG(s); thus, the association to the specific MR in a WMNs should account for "global" quality parameters, other than only local ones.

The association process is intrinsically competitive in that each STA is willing to act to maximize her own perceived quality. Moreover, each single association choice by one STA impacts the perceived quality of other STAs. Roughly speaking, if a STA occupies a wireless resource (access point, wireless link, frequency band, etc.), it produces interference to all the other STAs on the same resource. To this extent, it becomes natural to study such competitive dynam-

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ics resorting to non-cooperative game theoretical tools [5].

In this work, we model the problem of association in wireless mesh networks as a special case of *congestion game* [6] where each STA act selfishly to maximize her perceived quality of service. To capture the end-to-end quality perceived by each STA, we introduce a simplified but consistent metric based on the average contention perceived by the user's flow along a given path of the WMN backbone (from the access MR to the MG). After formalizing the game, we show how to derive the associated Nash Equilibria, further characterizing their quality in terms of *Price of Anarchy* and *Price of Stability*. Finally, we play the association game in realistic sample network scenarios deriving numerical results on the related equilibria. To summarize, the main contributions of the present work can be listed as follows:

(i) we formalize the problem of association to Wireless Mesh Networks by defining a non-cooperative game where the STAs selfishly select the least congested path;
(ii) we characterize the equilibria of the association game resorting to Integer Linear Programming;
(iii) we derive numerical results on sample network scenarios.

The paper is organized as follows: Section II overviews the related work in the field and comments further on the novel contributions of the present work. In Section III, we formalize the association game for WMNs and comment on some game's properties. A mathematical programming formulation to derive the Nash Equilibria of the association game is proposed in Section IV. In Section V, numerical results are presented on the quality of the equilibria under realistic network scenarios. Section VI concludes the paper, commenting on future/ongoing research directions.

II. Related Work

Most of the currently deployed WLANs operate according to the IEEE 802.11 standard [7], which defines access point association procedures based on the Received Signal Strength Indicator (RSSI), only. Without going into the details of the association protocols, the STAs associate to the access point with the highest RSSI. It is commonly known that RSSI is not the proper metric to be used in the association phase [8]. Indeed, the relation between RSSI and actual throughout perceived by the STA is not often easily predictable, and high RSSI values do not necessary mean high access throughput. The main shortcoming of RSSI-based association comes form the fact that RSSI does not directly account for the contention/congestion at the specific access point, which can often lead to poor resource utilization. To this extent, much work have been carried out to improve the metrics used in the association phase in WLANs [9] by leveraging measures/estimates on access interference [10], on the actual access point bandwidth [11], [12], on user fairness, and network-wide load balancing [13], [14].

All the aforementioned references focus on the case of hot-spot-like access patterns, and consequently the metrics for association capture the "local" quality of the wireless access segment. On the other hand, the issue of designing effective association schemes in WMNs is fundamentally different, since the metric driving the association must account also for "global" quality parameters of the overall network. Within this field, the most common approach in designing association algorithms/protocols leverages the network *airtime* metric to assess the quality of multi-hop paths [15]. The airtime of the wireless link (i, j) in the wireless backbone is given by:

$$C_{ij} = (O_{ca} + O_p + \frac{B_t}{r})\frac{1}{1 - e_{pt}}, \tag{1}$$

being r the nominal data rate of link (i, j), e_{pt} the frame error rate, B_t the reference frame size, O_{ca} and O_p the overhead related to the channel access and the protocol, respectively.

Athanasiou *et al.* propose in [16] and later in [8] an association scheme which couples the quality and the current load of the access links with a modified version of the airtime metric accounting for both the uplink and downlink segments. The authors further propose a practical cross-layer protocol to implement the association procedures. Along the same lines, Wang *et al.* propose in [17] a dynamic association protocol which couples the plain airtime metric for the backbone links in Eq. (1) with an estimate of the access airtime at the mesh access points. On the other hand, the work in [18] focuses on the definition of metric to assess the quality of the access segment. Namely, two metrics are proposed accounting respectively for the expected transmission time and the average load of the mesh access points. A modified version of the airtime is considered also in [19], whereas Ashraf *et al.* propose an association metric which includes also the average load (queue length) of the gateways [20].

All the aforementioned approaches for WMNs share the common goal to design practical association protocols. Differently, in this work we are interested in studying the dynamics and equilibria of the association process in wireless mesh networks by leveraging tools and concepts of game theory.

Game theory is widely used to investigate the competition, cooperation, and interaction of multiple agents. Related to the current work, non-cooperative games have been previously used to study network selection dynamics in [21][22], [23]. In previous work [24], we model network selection through a non-cooperative congestion game where the metric driving the access is the load of the WLAN access point. The notable work in [25] also resorts to congestion games to analyze the association process in WLAN, but the used metric is the access airtime define in Eq. (1). The main novel contribution of the current work is in the fact that we also account for network-wide metrics in the game definition. To our best knowledge, this is one of the first attempts to formalize the problem of association in wireless mesh networks through a game.

III. Reference Scenario and Problem Formulation

We consider a generic wireless mesh network composed of $\mathscr{N}$ network devices, including mesh access points, mesh routers and gateways. Unless differently specified, in the following, we will use access points, routers and gateways to refer to mesh access points, mesh routers and mesh gateways, respectively. In particular, $\mathscr{A}$ is the set of the access points and $\mathscr{G}$ is the set of gateways. The network provides multi-hop access to a set of STAs $\mathscr{U}$. All the traffic is assumed to flow to/from the gateway, whereas cross-traffic among STAs is neglected at this stage[1]. To ease up presentation, we consider hereafter the case where the WMN uses a single radio resource (e.g., frequency channel)[2]. Each access point is connected through multi-hop paths to at least one gateway. The set $\mathscr{P}$ includes all the available routing paths in the network. The STAs can be potentially "covered" by multiple access points, and can consequently "decide" to get connectivity to/from one specific access point, which, in turn, will reach the gateway through a specific multi-hop path. Upon association to a specific access point, the quality perceived by the STA depends on the quality of the multi-hop path to/from the gateway. The set $\mathscr{P}_i \subseteq \mathscr{P}$ denotes all the routing path available for STA i.

The quality of wireless multi-hop path is a long-debated issue and depends on multiple parameters affecting/involving different layers of the communication protocols: the wireless propagation conditions, the specific wireless technologies, the path-wise interference of concurrent/contending flows. We are not interested in defining here a complete and refined end-to-end metric, but rather we are focusing on the study of the dynamics of association in WMNs. To this extent, we leverage a simplified but consistent cost function c_{ij} for the STA i over the routing path j, defined as:

$$c_{ij} = L_j + I_j^i, \tag{2}$$

being L_j the *path length* and I_j^i the *path contention cost*, that is, the contention experienced by the flow generated by STA i along path j.

Path length is simply the number of hops in the path, whereas, to define the *path contention cost*, we leverage the concept of *interfering set*. For every network device in $\mathscr{N}$, the *interfering set* includes all the other devices which

[1]Nevertheless the proposed approach can be extended to the case of cross-traffic.

[2]The same approaches can be extended to the case of more complex WMN with multi-radio, multi-frequencies devices.

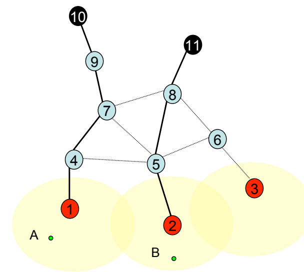

Figure 1. *Sample Topology.*

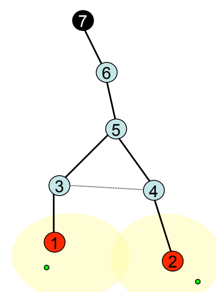

Figure 2. *The case of non disjoint paths.*

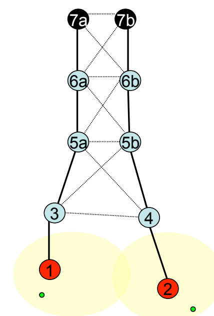

Figure 3. *Virtual Graph to calculate the path contention cost.*

interfere with the given one and are currently used to deliver STA's traffic. The *path contention cost* I_j^i can be calculated as the sum of the cardinalities of all the interference sets of all the nodes on path j. In Figure 1, dotted lines represent interference relations whereas bold lines represent traffic flows; STA A is associated to access point 1 and reaches gateway 10 through the path 1-4-7-9-10; STA B is associated to access point 2 and reaches gateway through path 2-5-8-11. Focusing on STA B, the interference set of device 5 is composed of nodes 4 and 7, whereas the interference set of node 8 is composed of node 7, only. The overall interference cost for path 2-5-8-11 caused by traffic of STA A over path 1-4-7-9-10 will then be equal to 3.

The same concept of *interference set* can be applied also to those cases where paths are not disjoint by properly defining *a virtual interference graph* to be used for calculating the interference cost. Figures 2 reports the case of two flows (to/from two STAs A and B) partially sharing the same path to the gateway, whereas Figure 3 reports the virtual graph used to calculate the interference cost of the two flows. In the **Wireless Mesh Network Association Problem** the STAs need to make wise decisions on which access point to connect to (and consequently on which path to use), by minimizing the perceived overall association cost. The decision process is intrinsically distributed (no coordination is allowed in the association phase), and competitive, in that each STA selfishly minimizes its association cost. Therefore, we model the Wireless Mesh Association Association Problem as a non-cooperative game in which STAs are rational players aiming at minimizing their costs, their strategy space is composed by all the available routing paths[3] and their pay-off is the association cost which accounts for the contention along the multi-hop paths to the gateway.

The contention-aware **Wireless Mesh Network Association Game (WMNAG)** can be formally defined as:

$$WMNAG = \langle \mathscr{U}, \{\mathscr{P}_i\}_{i\in\mathscr{U}}, \{c_{ij}\}_{i\in\mathscr{U}, j\in\mathscr{P}_i} \rangle.$$

Each STA maximizes her own pay-off, regardless of the status of the other STAs, i.e., each STA i selects the routing path $\overline{j} \in \mathscr{P}_i$ which minimizes the experienced cost c_{ij}:

$$\overline{j} = \underset{j\in\mathscr{P}_i}{\text{argmin}}\ c_{ij}.$$

Formally, the WMNAG is a multi-choice weighted congestion game with player-specific cost functions. Congestion games [6] are games in which the cost perceived by a player selecting a specific resource strictly depends on the number of other players doing the same choice. Our game is a congestion game in which the resources are the wireless links. Each STA, selecting a path, may interfere multiple wireless links (*multi-choice*), and the congestion of each STA to each link depends on the cardinality of the interference set (*weighted*). Furthermore, the cost function is player-specific because the cost of a STA depends only on a subset of the interfered links.

IV. Quality of Equilibria

The WMNAG presented in the previous section may admit in general multiple equilibria, and, as usual in non-cooperative games, these equilibria do not coincide with the optimal solution, i.e., the one that could be obtained using a centralized approach. One of the most common approach to analyze the difference between equilibria and the optimal solution is based on two indices, namely the Price of Stability (PoS) and the Price of Anarchy (PoA). They are, respectively, the ratio between the social cost of the best/worst equilibrium and the social cost of the optimal solution. The social cost can be defined as the sum of the costs of all the STAs.

To characterize the pure-strategy Nash equilibria of the game and to assess their quality we propose a mathematical programming formulation. In particular, we introduce a model that can be adopted to characterize the best and the worst equilibrium, as well as the global optimal solution of the game.

The parameters of the model are the following:

$$s_{lj} = \begin{cases} 1 & \text{if node } l \text{ belongs to path } j \\ 0 & \text{otherwise} \end{cases}$$

$$a_{lm} = \begin{cases} 1 & \text{if node } l \text{ and node } m \text{ interfere} \\ 0 & \text{otherwise} \end{cases}$$

$$d_{ij} = \begin{cases} 1 & \text{if STA } i \text{ can choose path } j \\ 0 & \text{otherwise} \end{cases}$$

We further introduce in our model the following variables, in order to associate each STA to a specific access point (and then to a specific routing path):

$$y_{ij} = \begin{cases} 1 & \text{if STA } i \text{ chooses path } j \\ 0 & \text{otherwise} \end{cases}$$

The constraints of the model are the following:

$$\sum_{j\in\mathscr{P}} y_{ij} = 1 \qquad \forall i \in \mathscr{U} \tag{3}$$

$$y_{ij} \leq d_{ij} \qquad \forall i \in \mathscr{U}, \forall j \in \mathscr{P} \tag{4}$$

Constraints (3) ensure that each STA selects only one path (i.e., access point) whereas constraints (4) force each STA to select a path only among the set of the available ones.

We define the optimal solution as the one that minimizes the sum of all the STAs' costs c_{ij}. To this extent, the following objective function is used:

$$\min \sum_{i\in\mathscr{U}} \sum_{j\in\mathscr{P}} c_{ij} y_{ij} \tag{5}$$

As defined before, the cost c_{ij} is composed by two terms:

$$c_{ij} = L_j + I_j^i \tag{6}$$

where

$$L_j = \sum_{l\in\mathscr{N}} s_{lj} - 1 \tag{7}$$

$$I_j^i = \sum_{\substack{r\in\mathscr{U} \\ r\neq i}} \sum_{u\in\mathscr{P}} \sum_{l\in(\mathscr{N}\setminus\mathscr{A})} \sum_{m\in(\mathscr{N}\setminus\mathscr{G})} s_{lj} s_{mu} a_{lm} y_{ru} \tag{8}$$

Constraints (8) refer to the case of uplink traffic, only. Indeed, it considers the set $\mathscr{N}\setminus\mathscr{A}$ (access points never suffer interference because they never receive) and the set $\mathscr{N}\setminus\mathscr{G}$ (gateways never cause interference to other nodes because they never transmit). A similar constraint can be written for the downlink traffic, as well as for mixed downlink/uplink traffic patterns.

The objective function in Eq. (5) is not linear, however it can be easily linearized as follows:

$$\min \sum_{i\in\mathscr{U}} \Big(\sum_{j\in\mathscr{P}} \sum_{l\in\mathscr{N}} s_{lj} y_{ij} - 1 + I_i \Big) \tag{9}$$

$$I_i \geq \sum_{\substack{r\in\mathscr{U} \\ r\neq i}} \sum_{u\in\mathscr{P}} \sum_{l\in(\mathscr{N}\setminus\mathscr{A})} \sum_{m\in(\mathscr{N}\setminus\mathscr{G})} s_{lj} s_{mu} a_{lm} y_{ru} + M(y_{ij} - 1) \qquad \forall i \in \mathscr{U}, \forall j \in \mathscr{P} \tag{10}$$

where M is a big number, so that when $y_{ij} = 0$, $l_i = 0$.

Note that I_i is the *path contention cost* of STA i for the path j he has actually chosen at the solution, i.e., when $y_{ij} = 1$.

The mixed integer/linear formulation with objective function (9) and constraints defined in (3), (4), and (10) can be used to characterized the global optimal solution. The very same formulation can be also used to derive the best Nash equilibria of the game, by adding the following constraints:

[3] As mentioned before, each STA actually choose one access point and not a path. However, we assume a one-to-one correspondence between access points and paths and here we consider paths since they are related to the cost function.

$$M(y_{ij}+d_{ih}-2)+\sum_{l\in\mathscr{N}} s_{lj}+ \\ +\sum_{\substack{r\in\mathscr{U}\\ r\neq i}}\sum_{u\in\mathscr{P}}\sum_{l\in(\mathscr{N}\setminus\mathscr{A})}\sum_{m\in(\mathscr{N}\setminus\mathscr{G})} s_{lj}s_{mu}a_{lm}y_{ru} \leq \\ \sum_{l\in\mathscr{N}} s_{lh}+\sum_{\substack{r\in\mathscr{U}\\ r\neq i}}\sum_{u\in\mathscr{P}}\sum_{l\in(\mathscr{N}\setminus\mathscr{A})}\sum_{m\in(\mathscr{N}\setminus\mathscr{G})} s_{lh}s_{mu}a_{lm}y_{ru} \\ \forall i\in\mathscr{U},\forall j,h\in\mathscr{P} \quad h\neq j \quad (11)$$

that enforce the definition of Nash Equilibrium. Indeed, constraints (11) requires each STA to select the path with the minimum association cost, having the other players already chosen their own paths.

Finally, to find the worst Nash Equilibrium, we replace the objective function (9) and constraints (10) with the following maximization of the social cost:

$$\max\sum_{i\in\mathscr{U}}\Big(\sum_{j\in\mathscr{P}}\sum_{l\in\mathscr{N}} s_{lj}y_{ij}-1+I_i\Big) \quad (12)$$

$$I_i \leq \sum_{\substack{r\in\mathscr{U}\\ r\neq i}}\sum_{u\in\mathscr{P}}\sum_{l\in(\mathscr{N}\setminus\mathscr{A})}\sum_{m\in(\mathscr{N}\setminus\mathscr{G})} s_{lj}s_{mu}a_{lm}y_{ru}+ \\ +M(1-y_{ij}) \quad \forall i\in\mathscr{U},\forall j\in\mathscr{P} \quad (13)$$

V. Numerical Results

In this section, we provide preliminary numerical results on the quality of the game's equilibria in realistic sample network topologies. Two types of performance evaluation are carried out: first, we characterize the association game by numerically deriving the PoS and PoA under different network topologies, then we compare the outcome of the association game under different association policies. The main findings out of this analysis are summarized hereafter:

(i) the equilibria of the association game are similar in quality. PoA and PoS are pretty close to 1 in all the tested scenarios;

(ii) association strategies accounting for end-to-end contention in the WMN backbone lead to lower interfered association paths compared with "interference-agnostic" strategies.

A. PoS and PoA of the WMN Association Game

To evaluate the association outcome, we have developed a network topology generator for WMN to deploy parametric topologies with different number of STAs N, number of access points, number of routers and number of gateways. The software randomly deploys all the network devices and STAs in a square area of side L and calculates the shortest paths between access points and gateways. Every device has a circular coverage region with radius r featuring the transmission/interference conditions. The tool also allows to pose additional requirements on the networks, including, as an example, the minimum number of access points covering a specific STA.

Table I

PoS and PoA for network topologies with 10 access points, 10 mesh routers and three gateways under different number of STAs.

	N=15	N=25	N=35	N=45	N=55	N=65
PoS	1,006	1,018	1,006	1,002	1,003	1,011
PoA	1,009	1,036	1,028	1,010	1,0144	1,016

Table II

PoS and PoA for network topologies with 4 access points, 9 mesh routers and 4 gateways under different number of association strategies per STA.

	2 Strategies		3 Strategies	
N	PoS	PoA	PoS	PoA
25	1,032	1,060	1,041	1,089
35	1,037	1,058	1,136	1,162

Table I refers to a small-size WMN deployment featuring 10 access points, 8 mesh routers, 3 gateways, $L = 1000$ meters, $r = 20$ meters and a variable number of STAs (N). STAs are randomly scattered throughout a square area with the constraint to be covered by at least two access points (and paths), and the end-to-end connectivity from each access point to at least one gateway is enforced by the tool. The numbers in the table represent the PoS and PoA averaged over 10 network deployments. The main result coming from the table is that the equilibria of the association game are almost of the same quality and very much close to the optimal association, i.e., PoS and PoA are similar and very close to 1. Said in other words, if the STAs play the association game selfishly according to the defined cost function, the "distributed" equilibrium is similar in quality to the "centralized" optimal solution. We note here that the network deployments of Table I may feature a low number of strategies for the end STAs, that is, the average number of access points covering each STA is around 2.5 for most of the cases. To this extent, it is worth studying whether similar results on the quality of nash Equilibria hold true for larger strategy spaces.

Table II reports the PoS and PoA for network topology constrained to having at least 2 and 3 association alternatives per STA. The quality of the equilibria is still close to the optimum, even if a slight increase in the PoS and PoA can be appreciated as the number of STAs and the number of strategies per STAs increase.

B. Evaluating Association Strategies

Table III compares the quality of the contention-aware association game against two other association policies, under the very same setting of Table I. $MinHopAssociation$ refers to the case where the access points closest to the gateway is chosen, whereas $ClosestAssociation$ policy favors the access point closest to the STA. The numerical values represent the increase (in percentage) of the association cost with respect to the global optimal association cost. Expectedly, the equilibria of the contention-aware association game provide association cost close to the optimum, whereas "interference agnostic" association strategies always lead to

Table III
ASSOCIATION COST INCREASE (WITH RESPECT TO THE OPTIMAL ASSOCIATION) UNDER DIFFERENT ASSOCIATION POLICIES. NETWORK TOPOLOGIES WITH 10 ACCESS POINTS, 10 MESH ROUTERS AND THREE GATEWAYS

	N=15	N=25	N=35	N=45	N=55	N=65
Best NE	0,006	0,018	0,006	0,002	0,003	0,011
Worst NE	0,009	0,036	0,028	0,010	0,014	0,016
Min Hop Association	0,0803	0,104	0,05	0,084	0,041	0,092
Closest Association	0,182	0,221	0,285	0,395	0,401	0,213

Table IV
ASSOCIATION COST INCREASE (WITH RESPECT TO THE OPTIMAL ASSOCIATION) FOR THE TFA NETWORK (17 ACCESS POINTS AND MESH ROUTERS, AND 4 GATEWAYS)

	N=50	N=75
Best NE	0.104	0
Worst NE	0.151	0.232
Min Hop Association	0.063	0.281
Closest Association	0.433	1.033

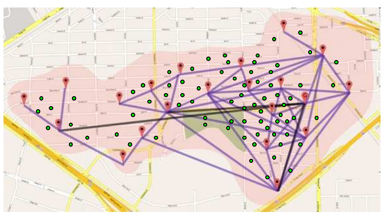

Figure 4. Reference TFA Network Scenario

higher association costs.

As a realistic test case, Table IV provides the numerical results obtained considering the network topology of the Technology For All (TFA)[3] initiative as a reference (see Figure 4). Such topology features 17 access points and mesh routers, and 4 gateways[4]. 50 and 75 STAs have been drawn randomly in the network area (circles in Fig. 4) and the presented results are averaged over 10 deployments. Each STA has, on average, 2.5 access point to associate to. The table confirms the existing gap in terms of association cost among the different association strategies. Expectedly, interference agnostic association strategies can lead to association cost increase up to 103% ($N = 75$ under *ClosestAssociation* policy).

VI. CONCLUDING REMARKS

The dynamics of network association in Wireless Mesh Networks have been analyzed in this work by resorting to game theoretic tools. Namely, we have formalized the association problem as a non-cooperative game in which STAs selfishly play to minimize a perceived association cost accounting for the path length and the path interference to reach the gateway. We have further proposed a quantitative framework to determine and characterize the Nash equilibria of the aforementioned game. The preliminary numerical results derived for small-size, sample network topologies suggest that the game features equilibria which are pretty close to the optimal (centralized) association pattern.

[4]The real TFA topology features 1 gateway directly connected through dedicated point-to-point links to three more "remote gateways". For the sake of the association dynamics, we have considered the additional "remote gateways" as gateways.

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REFERENCES

[1] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer Networks*, vol. 47, no. 4, pp. 445 – 487, 2005.

[2] R. Bruno, M. Conti, and E. Gregori, "Mesh networks: commodity multihop ad hoc networks," *IEEE Communications Magazine*, vol. 43, no. 3, pp. 123 – 131, March 2005.

[3] "Technology for all initiative." [Online]. Available: http://tfa.rice.edu/

[4] "Quail ridge wireless mesh network." [Online]. Available: http://spirit.cs.ucdavis.edu/quailridge/

[5] D. Fudenberg and J. Tirole, *Game Theory*. Cambridge, USA: The MIT Press, 1991.

[6] R. W. Rosenthal, "A class of games possessing pure-strategy Nash equilibria," *International Journal of Game Theory*, vol. 2, no. 1, pp. 65–67, 1973.

[7] IEEE, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, IEEE std. 802.11," 1999.

[8] G. Athanasiou, T. Korakis, O. Ercetin, and L. Tassiulas, "A cross-layer framework for association control in wireless mesh networks," *IEEE Transactions on Mobile Computing*, vol. 8, pp. 65–80, 2008.

[9] A. J. Nicholson, Y. Chawathe, M. Y. Chen, B. D. Noble, and D. Wetherall, "Improved access point selection," in *ACM MobiSys*, 2006, pp. 233–245.

[10] V. Mhatre and K. Papagiannaki, "Using smart triggers for improved user performance in 802.11 wireless networks," in *ACM MobiSys*, 2006, pp. 246–259.

[11] S. Vasudevan, K. Papagiannaki, C. Diot, J. Kurose, and D. Towsley, "Facilitating access point selection in IEEE 802.11 wireless networks," in *Proceedings of the 5th ACM SIGCOMM conference on Internet Measurement*, 2005, pp. 26–26.

[12] H. Lee, S. Kim, O. Lee, S. Choi, and S.-J. Lee, "Available bandwidth-based association in IEEE 802.11 Wireless LANs," in *ACM MSWiM*, 2008, pp. 132–139.

[13] Y. Bejerano, S.-J. Han, and L. Li, "Fairness and load balancing in wireless LANs using association control," *IEEE/ACM Transactions on Networking*, vol. 15, no. 3, pp. 560–573, 2007.

[14] B. Kauffmann, F. Baccelli, A. Chaintreau, V. Mhatre, K. Papagiannaki, and C. Diot, "Measurement-based self organization of interfering 802.11 wireless access networks," in *IEEE INFOCOM*, May 2007, pp. 1451 –1459.

[15] IEEE, "Draft amendment: ESS mesh networking, IEEE P802.11s draft 1.00," November 2006.

[16] G. Athanasiou, T. Korakis, O. Ercetin, and L. Tassiulas, "Dynamic cross-layer association in 802.11-based mesh networks," in *IEEE INFOCOM 2007*, May 2007, pp. 2090 –2098.

[17] H. Wang, W.-C. Wong, W.-S. Soh, and M. Motani, "Dynamic association in IEEE 802.11 based wireless mesh networks," in *ISWCS*, Sept. 2009, pp. 81 –85.

[18] L. Luo, D. Raychaudhuri, H. Liu, M. Wu, and D. Li, "Improving end-to-end performance of wireless mesh networks through smart association," in *IEEE WCNC*, April 2008, pp. 2087 –2092.

[19] S. Makhlouf, Y. Chen, S. Emeott, and M. Baker, "A network-assisted association scheme for 802.11-based mesh networks," in *IEEE WCNC*, April 2008, pp. 1339 –1343.

[20] U. Ashraf, S. Abdellatif, and G. Juanole, "Gateway selection in backbone wireless mesh networks," in *IEEE WCNC*, 2009, pp. 2548–2553.

[21] K. Mittal, E. M. Belding, and S. Suri, "A game-theoretic analysis of wireless access point selection by mobile users," *Computer Communications*, vol. 31, no. 10, pp. 2049–2062, 2008.

[22] J. Antoniou and A. Pitsillides, "4G converged environment: Modeling network selection as a game," in *16th IST Mobile and Wireless Communications Summit*, 2007, pp. 1–5.

[23] J. Antoniou, V. Papadopoulou, and A. Pitsillides, "A game theoretic approach for network selection," Tech. Rep., December 2008.

[24] M. Cesana, N. Gatti, and I. Malanchini, "Game theoretic analysis of wireless access network selection: models, inefficiency bounds, and algorithms," in *ValueTools*, 2008, pp. 1–10.

[25] K. Mittal, E. M. Belding, and S. Suri, "Association games in IEEE 802.11 wireless local area networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5136–5143, 2008.