

Cooperative Games Among Densely Deployed WLAN Access Points

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Abstract The high popularity of Wi-Fi technology for wireless access has led to a common problem of densely deployed access points (APs) in residential or commercial buildings, competing to use the same or overlapping frequency channels and causing degradation to the user experience due to excessive interference. This degradation is partly caused by the restriction where each client device is allowed to be served only by one of a very limited set of APs (e.g., belonging to the same residential unit), even if it is within the range of (or even has a better signal quality to) many other APs. The current chapter proposes a cooperative strategy to mitigate the interference and enhance the quality of service in dense wireless deployments by having neighboring APs agree to take turns (e.g., in round-robin fashion) to serve each other's clients. We present and analyze a cooperative game-theoretic model of the incentives involved in such cooperation and identify the conditions under which cooperation would be beneficial for the participating APs.

Keywords Dense Wi-Fi access points · Unmanaged wireless deployment · Graph theory · Game theory · Graphical game · Cooperation

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1 Introduction

1.1 *Need for Cooperation in Unmanaged Wireless Environments*

The low cost and easy deployment of wireless technologies, often results in the increase in the density of wireless networks in urban residential areas and consequently, unmanaged deployments of IEEE 802.11 (Wi-Fi) home networks that cause degraded experience for the home users. Very frequently in such deployments, an Access Point (AP) can be located within the range of dozens of other APs, competing for the limited number of channels offered by the IEEE 802.11 standard [1]. This is because such wireless networks are formed with no planning or central authority being present.

Wireless APs that operate in the same geographical region without any coordination typically cause degradation to their users' experience because, in the current standards, at any given time every terminal must be rigidly associated with one particular AP. This leads to a competition between collocated APs for the same communication resource (radio channel) and a reduced user quality of experience due to the resulting interference.

To mitigate the problem, it would be beneficial for individual APs that are in physical proximity to each other to form *cooperative groups*, where one member of the group would serve the terminals of all group members in addition to its own terminals, provided that the signal strength of the AP is sufficient to support the user activity. The rest of the APs in the group can be silent or even turned off, thereby reducing interference. The group members can take turns at regular intervals to serve all the terminals, as long as the coverage of the group does not change.

1.2 *Cooperation and Improved User Experience*

Clearly, it is important that such groups include only members whose signal strength and/or available bandwidth are sufficient to serve all group members without loss of user quality of experience. To maintain an incentive to cooperate, the group must be formed, so that the quality of experience for any individual terminal is not reduced; any reduction of signal quality at the physical layer (e.g., due to being served by an AP that is more distant than the 'native' one) should be compensated by the benefits from lesser interference at the MAC layer.

Since there is no centralized entity that can control the APs and force them to form cooperative groups, the creation of such groups must arise from a distributed process where each AP makes its own decisions independently and rationally for the benefit of itself and its terminals. We use game theory in order to model and investigate the feasibility of this cooperative operation among APs that selfishly maximize their own individual benefits under no central authority. More specifically,

two nearby APs that decide to cooperate may enter into a *bilateral agreement*, so that they (i) transmit in nonoverlapping time slots and (ii) whenever one of the APs is transmitting, it serves the clients of the other AP as well as its own.

1.3 Cooperative Approach

The chapter considers and expands on earlier works where a game-theoretic approach toward reducing interference in dense wireless deployments was presented [3, 4, 13]. Specifically, in [4], a graphical strategic game model was presented and the basic case of two interacting APs was studied, showing sufficient conditions for Nash equilibria to result in cooperation.

The benefit from cooperation between two players (APs) is determined by the weight of an edge connecting them in an underlying graph (which is in turn derived from the signal quality of the communication links, which is dependent on the wireless network deployment, among other factors). In particular, we consider the case where the APs are located very densely. This is a very common case in buildings where many APs may be active at the same time.

In such dense placement of APs, interference appears between almost any pair of APs, which in turn degrades the signal quality of the communication link. Thus, the assumption of a desire for an agreement between two cooperative APs of mutual service of all their clients is realistic since dense placements of APs are already a reality, especially in big cities, with high population density and high density areas, as for example a shopping mall. So, the number of nearby APs (with high potential interference) is limited to a relative small number (the APs inside that center). Moreover, the high density of the placement of the APs implies that each AP is assigned a relatively small number of clients. Thus, it is very probable that APs can serve, during their ON transmission mode, not only their clients but also the clients of their neighbors that are in cooperation agreement with them. Finally, the presented case study assumes for its modeling that guarantees for the nonlocal clients exist, such that even though they agree to be served by one AP, they will never get *higher priority* than the particular AP's own clients; this can be achieved through suitable values of the *weights* on the corresponding edges of a related graph obtained according to the modeling assumed. The next subsection discusses further the graph representation.

The implementation of the game in practice will require some sort of an interaction (via a specially designed communication protocol) between the APs, but this only needs to be done once in a while (in the order of minutes) so the overhead involved is insignificant in the long run. The same can be said about any loss of throughput due to the reassociation overhead for clients to the new AP, it is not significant since it is incurred only infrequently.

1.4 Clique Graph Representation

The chapter presents a particular case study that models these placements through a corresponding directed, weighted *clique* graph; i.e., for every pair of nodes of the graph, there exists a bidirectional edge connecting them [7]. Note that no edge between two nodes implies a weight of zero (0). Using this modeling, the chapter investigates under which conditions *cooperation* between APs is forced. Cooperation between two nearby APs concerns a bidirectional agreement on their *ON-OFF* transmission modes as well as the service they provide: they (i) transmit in nonoverlapping time slots and (ii) when each one of the two APs is transmitting, it serves *besides* its clients, *the clients of the other AP*.

Investigation of the placements of the APs forming a clique graph is motivated by the fact that in a very dense placement of APs, interference appears between almost any pair of two APs. Investigating when cooperation is enabled between dense APs forming other graph topologies constitutes a future work.

1.4.1 Edge Weights of the Clique Graph

The weight of a (directed) edge connecting an AP to its neighbor represents the measurement of the signal power received by the neighbor when the AP is *ON*. SNR is a measure that compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power and anything above 40 dB in wireless LANs is considered excellent, whereas anything above 25 dB is considered a very good signal. Anything within the signal range 15–25 dB is a low signal but can still be associated and is usually fast, however, lower than 10–15 dB is not desired. This signal is treated as interference when both the AP and its neighbor transmit at the same time over the same channel, but at the same time it indicates the strength of the (useful) signal that can be used to serve the neighbor's clients when the two APs are in a cooperation agreement.

While this chapter assumes that the weights in the graph correspond to the signal power, the weight can be any metric that represents the experienced quality of the user during cooperation. The model considered in this chapter focuses mainly on the quality of experience for the downlink traffic, which is typically the bulk of the communication in most applications, and ignores the uplink traffic which is usually minimal compared to the downlink.

Since SNR measures the success of transmitting packets, it is also a strong indication of the experienced quality of the user: high SNR results to minimal packet loss. Thus, high quality of service (directly related to the measure of quality of experience) is enabled as it concerns this parameter (success in transmitting packets). Furthermore, the SNR is measured on the downlink traffic, which is typically the bulk of the communication in most applications, and ignores the uplink traffic which is usually minimal compared to the downlink.

1.5 Security and Communication Concerns

The dense placements of APs are usually of relatively small size, compared to the number of clients in the area. Thus, it is reasonable to assume that APs can serve, during their ON transmission mode, not only their clients but also the clients of their neighbors that are in cooperation agreement with them.

It must be emphasized that cooperation between APs belonging to different service sets is not impossible even if they are required to use secure encryption/authentication (such as WPA in the 802.11 standard). At first sight, it may seem that such cooperation would require the APs to share their secret passwords, which is of course undesirable in an uncoordinated deployment. However, there are known techniques that allow a group of cooperating APs to establish a common “trust group,” and share a secret key and/or authenticate their clients without a need to expose their passwords, as well as reduce the authentication delay when a client is handed off between neighboring APs [10].

Therefore, cooperation is still feasible even in the presence of encryption and authentication; i.e., when the traffic between each AP and its clients is encrypted and requires authentication with a secret password that precludes an AP from sharing others’ clients. In other words, if AP1 and AP2 wish to cooperate, we need a mechanism that allows a client of AP1 to “prove” to AP2 that it knows the password for AP1, without actually disclosing the password. This is a relatively easy and long solved cryptographic problem; for example, in [10] a trust group or cloud is presented, establishing security key sharing for authentication of the members in the group, aiming to achieve a fast authentication in a 802.11 network.

Nevertheless, security restrictions and software/hardware incompatibilities may exist in such cooperative scenarios. Such issues do not pose a restriction to the modeling considered in this chapter, since they may be abstracted as non-cooperative APs that cause a constant additional interference that the cooperating APs (and hence the cooperating users) cannot avoid; (either through cooperations or not). In other words, these *non-cooperative* APs, result in a constant decrease of the quality of experience the AP can provide which is irrelevant to the cooperation agreements of the AP. So the modeling itself may ignore such issues.

Also, note that this modeling does not consider the uplink traffic sent *from* the clients of a given AP *to* the AP; the chapter investigates and tries to minimize interference only for communication *from* the AP to its clients. Although, this traffic is minimal, it is not zero. However, this chapter concentrates on the *most* of the communication between clients and AP, which is the one from the AP to the client. Incorporating the uplink communication too in a game-theoretic modeling consist a future work.

1.6 Chapter Contribution

The contribution in this chapter focuses on proving the necessary and sufficient conditions in order for all APs of the (clique) graph to join a cooperation group, where all APs maximize their users' quality of service. The main result proved in the chapter is that, if for *each* AP in the network, the signal strength received from any other AP (as represented by the weight of the respective graph edge) surpasses a certain threshold, then joining a cooperation group with all other APs is a best-response strategy (therefore leading to Nash equilibrium), which enables the given AP to provide a better quality of experience to its clients. More specifically, the agreement obtained in clique graphs consists of a (not necessarily equal) split of the total time period into nonoverlapping, nonzero time slots $T_1, T_2, \dots, T_n$, such that during time slot T_i only the AP i is transmitting, serving all the clients in the clique.

Moreover, since the number of APs forming the clique is limited, it is necessary that these APs can satisfy the increased service demands obtained from the cooperation. It is shown that this translates to a constraint on the weights of the edges which becomes a necessary condition for a global agreement setting to be Nash equilibrium. Thus, we obtain a characterization of the necessary and sufficient conditions for agreement settings between the APs to be sustained in Nash equilibria.

2 Related Work

Game Theory has been extensively used in networking research as a theoretical decision-making framework, e.g., for mechanisms and schemes used for purposes of routing [25], congestion control [16], and resource sharing [20]. Coalitional game theory (or cooperative games) investigate the formation of cooperative groups, (coalitions) that allow the involving players to increase their gain by joining a coalition and receive (individually or by sharing between players of a common coalition) the benefits resulted by the cooperation. Coalitional Game Theory [19] has been successively utilized for enabling efficient communication of wireless networks in a number of works; for interference networks [14, 15], spectrum sensing [24], and other networking issues [19]. For a comprehensive work on coalitional games and their potential applications in communication networks see [21, 22].

Cooperative communication strategies, studied in [11], particularly focusing on multiple access networks using a coalitional game approach. The authors of [11] considered two different modes of operation showing an advantage of a dynamic setting compared to a static one. In the dynamic setting, users alternate at random between two modes of operation: an active state and a dormant state. Users within the same coalition share knowledge of their active states and a scheduler assigns the right to transmit within a coalition. Collisions occur when users belonging to

different coalitions transmit simultaneously. In this setup, the *grand coalition* formed by all users is sum rate optimal and is also stable in the sense that no user has incentive to leave the coalition. The second mode of operation is the static setting. Here, users are scheduled for transmission in a static round-robin fashion. However, members of the same coalition can share their right to transmit in a given time slot. In this case, the grand coalition although optimal can be unstable.

The benefits of cooperation between providers offering wireless access service to their respective subscribed customers through potentially multi-hop routers have been further investigated in [23]. In particular, the authors using coalitional game theory investigated the benefits of the providers when cooperating, i.e., pool their resources, such as spectrum and base stations and agree to serve each other's customers. They first considered the case where the providers share their aggregate revenues and modeled such cooperation using transferable payoff coalitional game theory [19]. Then, they considered the scenario that locations of the base stations and the channels that each provider can use have already been decided a priori and showed that the grand coalition is stable in this case, i.e., if all providers cooperate, there is always an operating point that maximizes the providers' aggregate payoff, while offering each such a share that removes any incentive to split from the coalition. They also examined cooperation when providers do not share their payoffs, but still share their resources, so as to enhance individual payoffs and showed that the grand coalition continues to be stable.

Ways of reducing interference in densely deployed wireless networks through cooperation were considered in [3] by making use of the *Prisoner's Dilemma/Iterated Prisoner's Dilemma* game model and proposing a group strategy to motivate adjacent neighbors into cooperation. The Prisoner's Dilemma and Iterated Prisoner's Dilemma [12] has been widely used in research as models for motivating cooperation [2]. In particular, the publication of Axelrod's book in 1984 [6] was the main driver that boosted the concept of cooperation of entities with seemingly conflicting interests outside of game theory. The empirical results of the Iterated Prisoner's Dilemma (IPD) tournaments showed that group strategies performed extremely well and defeated well-known strategies in round-robin competitions in the 2004 and 2005 IPD tournaments [9].

3 A Graph-Theoretic, Cooperative Game

Here, we introduce the theoretical background used in [5] to develop their theoretical framework also described here next.

3.1 Background

3.1.1 Graph Theory

A weighted *digraph* $G(V, \vec{E}, \vec{W})$ consists of three types of elements, namely *nodes* constituting the set V , *edges* constituting the set $\vec{E}$, and finally the *weights* of the edges constituting the set $\vec{W}$. An edge e is specified by the *ordered* pair $e = (u, v) \in E$ iff there exists a (directional) connection (or link) *from* node u *to* node v , where $u, v \in V$ with positive weight $w(u, v) > 0$ in the graph G . $w(u, v)$ is positive if and only if $(u, v) \in \vec{E}$.

For any node v , the set $Neigh_G$ denotes the set of (other) nodes of the graph connected to that node via a communication link, i.e., $Neigh_G = \{u \in V \mid (u, v) \in \vec{E}, (v, u) \in \vec{E}\}$. When clear from the context, we omit the graph subscript. A weighted digraph $G(V, \vec{E}, \vec{W})$ is a *clique* iff for every pair $u, v \in V$, there exists a pair $(u, v) \in \vec{E}, (v, u) \in \vec{E}$ and $w(v, u) > 0$.

A graph G is said to be of size k if $|V| = k$. Throughout the chapter, for an integer $n \geq 1$, denote $[n] = \{1, \dots, n\}$. This chapter is concentrated on weighted, directed clique graphs. In the following, when we refer to a clique graph, we imply a weighted, directed clique graph.

3.1.2 Game Theory

A simple (one-shot) *strategic game* Γ is defined by a set of players N and a set of available strategies (behaviors) for each player $i \in N$, denoted as S_i . A (pure) profile σ of the game Γ specifies a particular strategy σ_i , one for each player $i \in N$. For a profile σ , each player i has an *utility* that depends on the specific player's current strategy as well as the other players' current strategies, and is denoted as $U_\sigma(i)$.

A profile σ of the game is said to be Nash equilibrium [17, 18] if, for every player, the utility in that profile is not smaller than the utility gained if that player unilaterally changes its strategy to any other $x_i \neq \sigma_i, x_i \in S_i$. Denote as σ^{x_i} the new profile obtained. Then, if σ is Nash equilibrium, it must be that $U_\sigma(i) \geq U_{\sigma^{x_i}}(i)$, for every $i \in N$.

Graphical Games are games in which the player strategies (and, consequently, their utilities) are related to, and defined in terms of, a graph G . The components of the graph (i.e., its nodes and edges) are said to capture the *locality* properties among the players, or, in other words, how the game is affected by the player's positioning [5] considers a graphical game.

3.2 The Mathematical Framework

Next, we present the mathematical framework and the corresponding graphical, cooperative game obtained as defined in [5].

3.2.1 The Graph

Consider a set of nodes $V = \{v_1, v_2, v_3, \dots, v_n\}$ corresponding to the set of APs located in a geographical area. Each node in fact represents an entity comprising of one server (the AP) and a number of its clients (mobile stations). In an arbitrary case, we may assume that this number is approximately the same for all APs, so we may assume that each server serves one client. At a time t , say that server node v (an AP) is active or *ON*, if it is transmitting (to its own client). Otherwise, say that the node is inactive or *OFF*. We are concerned primarily with the decisions made by the server nodes (the APs); therefore, when we refer to a node, henceforth we refer to an AP.

Consider two nodes, u, v which are within range of each other's signals. In particular, node v (and its clients) may receive information from node u when it is *OFF*, while node u is *ON*, i.e., when node u broadcasts. If the quality of the signal received by node v (and its clients) from node u is above some lower bound value assumed by the node v , it is assumed that there exists a *directed edge* from node u to node v , denoted as (u, v) . Moreover, the quality of the received signal is quantified by a weight $w(u, v)$ associated with the directed edge (u, v) . For purposes of normalization, the function $w(u, v) \in [0, 1]$ is defined. The weight value is analogous to the quality of the received signal, i.e., good quality reception corresponds to a value of $w(u, v)$ close to 1. In [5] these values are assumed to be known; if necessary, they can be discovered through a distributed process initiated and executed locally at any AP.

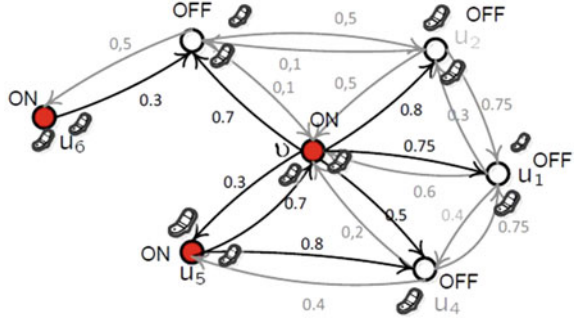
Summing up, from this setting of APs and the communication of their clients, the following weighted graph, defined initially in [4], is derived:

Definition 1 (*The Weighted Digraph*) Consider a set of nodes (APs) $V = \{v_1, \dots, v_n\}$ located in a geographical area. Consider two nodes u and v , such that (the clients of) node v can receive transmissions from node u when (the server of) v is *OFF*, while node u is *ON*, with a quality above some lower bound value. Then, define a directed edge to exist from node u to node v , denoted as (u, v) , of a positive weight $w(u, v) \in (0, 1)$ representing the quality of the received signal at node v .

Further assume that if $w(u, v) > 0$, then $w(v, u) > 0$ for all nodes $v, u \in V$.

An example weighted graph is illustrated in Fig. 1.

Fig. 1 An example weighted graph in operation at some given time t . The *ON* nodes and their outgoing edges are highlighted



3.2.2 Time

As in [4], a basic unit of time period T is considered, e.g., 1 h, and we split the time period T into x smaller time slots $T_1, T_2, \dots, T_x$, such that for each $T_k \in T$ there exists at least one node that in a group of nodes that may alternate between the *ON* and *OFF* node and remains *ON/OFF* for the whole time slot T_k . So, $\bigcup T_k = T$ and $T_k \cap T_l = \emptyset$, $k \neq l$, i.e., the sum of the time slots is the time period T and no two time slots overlap. By $|T_k|$, we denote the time elapsed from the beginning of time slot T_k until the end of the time slot T_k .

Fix a time slot T_k . Then, denote:

$$ON(T_k) = \{v \in V \mid \text{node } v \text{ is } ON \text{ in time slot } T_k\} \text{ and}$$

$$OFF(T_k) = \{v \in V \mid \text{node } v \text{ is } OFF \text{ in time slot } T_k\}$$

So, for node v , the time period T can be partitioned into two sets $ON_Time_T(v) = \{T_k \in T \mid v \in ON(T_k)\}$ and $OFF_Time_T(v) = \{T_k \in T \mid v \in OFF(T_k)\}$. Denote $Mode_T(v) = \{ON_T(v), OFF_T(v)\}$.

For the example graph of Fig. 1, $ON(t) = \{v, u_5, u_6\}$. For a sample time split of nodes v, u_1 , see Fig. 2.

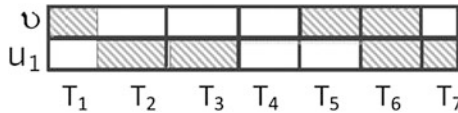


Fig. 2 An example of a time split for nodes v, u_1 . In the shaded areas, the corresponding APs are *ON*

3.2.3 (Non-)Cooperative Neighbors

Given a weighted digraph G , for any node $v \in V$, $Neigh(v)$ denotes the set of neighbors of node v in G , i.e., $Neigh(v) = \{u \in V \mid (u, v) \text{ and } (v, u) \in \vec{E}\}$. For the example graph of Fig. 1, $Neigh(v) = \{u_1, u_2, u_3, u_4, u_5\}$. Within a given time slot T , node v may be in *agreement* or in *cooperation* with some of its neighboring nodes. For any node v , being in agreement with node u , $u \neq v$ means that: (i) node v (or u) transmits *only* when u (respectively, v) does not transmit; and (ii) node v (u) serves the client(s) of the other node, in addition to its own client(s), during the time that it (v or u , respectively) is *ON*. The set of the neighbors of node v that are in agreement during time T , is denoted by $Coop_T(v) \subseteq Neigh(v)$. Thus, $ON_Time_T(v) \cap ON_Time_T(u) = \emptyset$. On the other hand, the set of neighbors with which v is not in agreement with is denoted as $NCoop_T(v)$, where $NCoop_T(v) \subseteq Neigh(v)$ and it may be that $OFF_Time_T(v) \cap OFF_Time_T(u) \neq \emptyset$.

3.2.4 Experienced Quality

As in [4], for any node $v \in V$, the quality experienced by a node's clients can be quantified through measurements of the signal strength received at the clients of node v , at any time slot T_k during the time period T and it is denoted as $QoE_{T_k}(v)$. There are two cases: when the node is *ON* and when it is *OFF*.

- *ON Operation.* During any time slot T_k , if a node is *ON*, there are two possibilities: (i) none of its neighbors transmit at that time slot or (ii) some of them do. In the first case, the clients of the node experience the best quality (no interference), so we set the quality measure to be equal to a unity in this case, i.e.,

$$QoE_{T_k}(v) = 1. \quad (1)$$

In the second case, if the node is *ON*, some of its neighbors are *ON* during the time slot T_k . In this case, due to interference, the signal received is poorer and the experienced quality is degraded. This degradation is cumulative, i.e., increases with the total active time and signal strength of the competing nodes, captured by the weight $w(u, v)$. Thus, in this case of the *ON* operation of node v the quality of its clients is denoted as:

$$QoE_{T_k}(v) = \max\{0, 1 - \sum_{\substack{u \in Neigh_T(v) \\ u \in ON(T_k)}} w(u, v)\} \quad (2)$$

- *OFF Operation.* When node v is *OFF*, the quality of the signal received at node v 's clients, and hence the quality experienced, depends on the number of neighbors in cooperation with node v (i.e., in the set $Coop_{T_k}(v)$) that are *ON* at time T_k , and are serving the clients of node v as well as their own clients. If there exists only one such neighboring node u , the quality of the signal received at

node v is captured by the weight $w(u, v)$ of edge (u, v) . However, if there exist more than one neighboring nodes not in cooperation with node v that are *ON* at the same time, this results in interference received at node v , degrading the experienced quality at the node's clients.

As in [4], we assume that the service of v 's clients is dominated by the *strongest* signal of its neighbors in the set $Coop_T(v_i)$, which is then degraded by the sum of the received signals from all the other neighbors that are *ON* at that same time (including other cooperating as well as the noncooperating neighbors). Thus, for the case of the *OFF* operation of node v , its experienced quality can be denoted as:

$$QoE_{T_k}(v) = \max\{0, (w(m, v) - \sum_{\substack{u \in Neigh_T(v), u \neq m \\ u \in ON(T_k)}} w(u, v))\}, \quad (3)$$

where $m = \arg \max_{\substack{u \in Coop_T(v) \\ u \in ON(T_k)}} \{w(u, v)\}$.

3.3 The Graphical Game

Using the above mathematical framework, we can now introduce resulting strategic game of [4]. This is a one-shot strategic game where the players are the nodes (APs). In any profile, given the decisions of the players (namely, whether to operate in *ON* or *OFF* mode) during each time slot $T_k \in T$, the utility of player $v \in V$ is equal to the quality of experience of its clients, i.e., $QoE_{T_k}(v)$. A formal definition of the game, defined initially in [4], follows:

Definition 2 Consider an one-shot strategic game Γ played on a weighted digraph $G(V, \vec{E}, \vec{W})$. The set of players of the game is V . A profile σ of the game is associated with the basic time period T of the scenario described. T is split into time slots $T_1, T_2, \dots, T_x$, such that $\bigcup_{T_k} = T$ and $T_k \cap T_l = \emptyset, k \neq l$, T_k corresponding to the time slot allowing alterations between *ON* and *OFF* operations of the nodes.

The strategy of any player (node) $v \in V$ in a profile σ is defined as follows:

$$\sigma_v = (ON_Time_\sigma(v), OFF_Time_\sigma(v), Coop_\sigma(v)),$$

$$where \quad ON_Time_\sigma(v) = \{T_k \in T \mid v \in ON_\sigma(T_k)\}$$

$$OFF_Time_\sigma(v) = \{T_k \in T \mid v \in OFF_\sigma(T_k)\},$$

and $ON_\sigma(T_k)$ ($OFF_\sigma(T_k)$) denotes the set of nodes in V that are in *ON* (*OFF*) operation during T_k according to σ . $Coop_\sigma(v) \subseteq Neigh(v)$ is the set of neighboring nodes of node v , with which node v has decided to cooperate with in σ . Cooperation

means that for each such cooperative neighbor u of node v , (i) $ON_Time_{\sigma}(v) \cap ON_Time_{\sigma}(u) = \emptyset$ and (ii) the two nodes are in agreement to serve each other's clients.

For player (node) v denote,

$$MaxCoop_{\sigma}(T_k, v) = \{m \in Neigh(v) | w(m, v) = \max_{\substack{u \in Coop_{\sigma}(v) \\ u \in ON_{\sigma}(T_k)}} w(u, v)\}$$

Then, the utility of player (node) v corresponding to the QoE for the ON/OFF operations of Eqs. (1)–(3), is given by:

$$U_{\sigma}(v) = \sum_{T_k \in ON_Time_{\sigma}(v)} ONU_{\sigma}(v, T_k) \cdot |T_k| + \sum_{T_k \in OFF_Time_{\sigma}(v)} OFFU_{\sigma}(v, T_k) \cdot |T_k| \quad (4)$$

where the quality experienced for the ON operation of the node is determined by Eqs. (1) and (2):

$$ONU_{\sigma}(v, T_k) = \max \left\{ 0, 1 - \sum_{\substack{u \in Neigh(v) \\ u \in ON_{\sigma}(T_k)}} w(u, v) \right\} \quad (5)$$

and similarly

$$OFFU_{\sigma}(v, T_k) = \max \{ 0, (w(MaxCoop_{\sigma}(T_k, v), v) - \sum_{\substack{u \in Neigh(v) \\ u \in ON_{\sigma}(T_k) \\ u \neq MaxCoop_{\sigma}(T_k, v)}} w(h, i)) \} \quad (6)$$

The linear model, which appears to simplify the relationship between interference and experienced quality provides, nevertheless, insight that allows for the problem at hand to be more generically understood, i.e., the fact that APs need to have strong links to each other in order to sustain cooperation. Future work will consider a more exact mathematical modeling of the relationship between interference and experienced quality.

Note that the time structure of the model is only a (theoretical) split (separation) of a continuum time period into a number of discrete time units. I.e., the model separates the whole time period into smaller continuous time units for purposes of ease of analysis, while overall the whole continuous time period is considered. Furthermore, while mixed strategies could be considered that would result in expected payoffs rather than deterministic payoffs, which are preferable for the specific case study.

4 Agreement Nash Equilibria for Clique Networks

Instances of the game Γ where the graph G is a clique of size q are mainly investigated in [5]. For simplicity, in this section, any time we refer to a graph we imply a clique graph. The work exploits the graph theoretical properties of clique topology in order to show when cooperation is feasible between the APs when they are placed close to each other.

4.1 Agreement Profiles

Next, a formal profile of cooperation between the players of the game, is defined. Then, for an arbitrary agreement profile, a corresponding simplified agreement profile (called *ordered agreement* profile) is considered, and equivalence regarding the utilities of the two players is shown (Sect. 4.2). Then, the corresponding simplified agreement profile is used to show stability (i.e., it is Nash equilibrium) of the original profile (Sects. 4.3 and 4.4). Specifically, they first define agreement profiles:

Definition 3 A profile σ is called **agreement** if all nodes of the graph G have agreed to cooperate with each other in σ .

They further define a subclass version of agreement profiles in which any AP has a single, continuing *ON* time slot. The profile is applicable for an arbitrary graph. The formal definition follows:

Definition 4 A profile σ is called **ordered agreement** if:

- it is an agreement profile; and
- assuming the time T is split into n time slots $T_1, \dots, T_n$, where $n = |V|$, such that $T_i \cap T_j = \emptyset \forall i, j \in V$, any player $i \in V$ is *ON* at time slot T_i only and is *OFF* in all the remaining time slots $T_j, j \neq i$.

Applying ordered agreement profiles on clique graphs, observe:

Observation 1 Agreement profiles on Clique graphs Consider an agreement profile σ in the game Γ , over a clique graph G of size q . Then, consider any time slot $T_k \in ON_\sigma(T)$ and the corresponding (single) node k which is *ON* during T_k . Thus, by Eq. (5), $ONU_\sigma(k, T_k) = 1$. Also, the node k serves all other nodes of the clique during the time T_k . Thus, for any player $j \neq k$ (who is therefore *OFF* during time slot T_k), $OFFU_\sigma(j, T_k) = w(k, j)$.

4.2 Analysis of Agreement Profiles

Agreement profiles are equivalent to ordered agreement profiles as shown next. The equivalence relation is first defined:

Definition 5 A profile σ is said to be **equivalent** to another profile σ' if each player $i \in [q]$ has $U_\sigma(i) = U_{\sigma'}(i)$.

Equivalence between agreement and corresponding ordered agreement profiles is next shown, as presented in [5]:

Claim 1 Consider any agreement profile σ of a game Γ over a clique graph G of size q . Then, there exists an ordered agreement profile σ' , such that σ and σ' are equivalent.

Proof Consider any player i in the profile σ . Note that the time slots in which the player is *ON* may not be continuous. Let $T_{i_1} \cdots T_{i_x}$ be the time slots where the player i is *ON* in σ . $\square$

Note that, since σ is an agreement profile,

$$ONU_\sigma(i, ON_Time_\sigma(i)) = 1$$

and that for each $t_k \in ON_Time_\sigma(k)$, $k \neq i$,

$$OFFU_\sigma(i, t_k) = w(k, i).$$

Thus, summing up, from Eq. (4) and Observation 1, we get:

$$\begin{aligned} U_\sigma(i) &= ONU_\sigma(i, ON_Time_\sigma(i)) \cdot |ON_Time_\sigma(i)| + \sum_{\substack{t_k \in ON_Time_\sigma(k) \\ k \in [q] \setminus i}} OFFU_\sigma(i, t_k) \cdot |t_k| \\ &= 1 \cdot |ON_Time_\sigma(i)| + \sum_{\substack{t_k \in ON_Time_\sigma(k) \\ k \in [q] \setminus i}} w(k, i) \cdot |t_k| \\ &= 1 \cdot |ON_Time_\sigma(i)| + \sum_{k \in [q] \setminus i} w(k, i) \cdot |ON_Time_\sigma(k)| \end{aligned} \quad (7)$$

Now, construct a modified profile σ' , such that for each player $i \in [q]$, we set its *ON* mode to a *single* time slot T_i , which is equal to the total duration of its *ON* time slots in σ ; i.e., $|T_i| = |T_{i_1}| + |T_{i_2}| + \cdots + |T_{i_x}|$. Moreover, we start the *ON* time slot of the first player at time 0 and continue until time $|T_1|$, for the second player we start its (single) time slot at time $|T_1| + 1$ and continue until time $|T_1| + |T_2|$, and so on, so that player k is *ON* only during the time slot T_k and $|T_k| = |T_{k_1}| + |T_{k_2}| + \cdots + |T_{k_x}|$.

Note that, by construction, σ' is ordered, and it is an agreement profile (since the time slots allocated to different players are nonoverlapping). Moreover,

$ON_Time_{\sigma'}(i) = ON_Time_{\sigma}(i)$ for each $i \in [q]$. It follows that for any player $i \in [q]$, $ONU_{\sigma'}(i, T_i) = 1$.

Also, note that for each one of the time slots $T_k \in T \setminus T_i$, only player k , which is ON and serves all other players. Thus, during the time slot T_k , the player i (which is in OFF mode) is served by the player k . So, $OFFU_{\sigma}(i, T_k) = w(k, i)$. It follows that,

$$\begin{aligned} U_{\sigma'}(i) &= ONU_{\sigma'}(i, ON_Time_{\sigma'}(i)) \cdot |ON_Time_{\sigma'}(i)| + \sum_{\substack{T_k \in ON_Time_{\sigma'}(k) \\ k \in [q] \setminus i}} OFFU_{\sigma'}(i, T_k) \cdot |T_k| \\ &= 1 \cdot |ON_Time_{\sigma'}(i)| + \sum_{\substack{T_k \in ON_Time_{\sigma'}(k) \\ k \in [q] \setminus i}} w(k, i) \cdot |T_k| \\ &= 1 \cdot |ON_Time_{\sigma'}(i)| + \sum_{k \in [q] \setminus i} w(k, i) \cdot |ON_Time_{\sigma'}(k)|. \end{aligned}$$

Since $|ON_Time_{\sigma'}(i)| = |ON_Time_{\sigma}(i)|$ and for each player $k \in [q] \setminus i$, $|ON_Time_{\sigma'}(k)| = |ON_Time_{\sigma}(k)|$, the above equation becomes,

$$U_{\sigma'}(i) = 1 \cdot |ON_Time_{\sigma}(i)| + \sum_{k \in [q] \setminus i} w(k, i) \cdot |ON_Time_{\sigma}(k)| \quad (8)$$

By Eqs. (7) and (8), it follows that for $U_{\sigma'}(i) = U_{\sigma}(i)$, as claimed.

The following useful information is proved for agreement profiles [5]:

Claim 2 Assume an agreement profile σ for the game Γ over a clique graph G of size q . Then, for any player $i \in [q]$,

$$U_{\sigma}(i) = |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k|.$$

Proof By Claim 1, assume without loss of generality that σ is an ordered agreement profile (equivalently, if σ' is the equivalent ordered agreement profile, then set $\sigma = \sigma'$ without changing the utility values). Consequently, node i is the only node in ON operation during time slot T_i . Thus, by Eq. (5), $ONU_{\sigma}(i, T_i) = 1$. Also, the node is OFF for the rest of the time and during any other time slot $T_k \in T \setminus T_i$ it is served by node k which is the only one node on ON operation during time slot T_k , for each $T_k \in T \setminus T_i$. Thus, by Eq. (6), $ONU_{\sigma}(i, T_k) = w(k, i)$ for each $T_k \in T \setminus T_i$. We therefore obtain, by Eq. (4),

$$\begin{aligned}
U_{\sigma}(i) &= \sum_{T_k \in ON_Time_{\sigma}(i)} ONU_{\sigma}(i, T_k) \cdot |T_k| + \sum_{T_k \in OFF_Time_{\sigma}(i)} OFFU_{\sigma}(i, T_k) \cdot |T_k| \\
&= ONU_{\sigma}(i, T_i) \cdot |T_i| + \sum_{T_k \in T \setminus T_i} OFFU_{\sigma}(i, T_k) \cdot |T_k|, \\
&= 1 \cdot |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k|,
\end{aligned}$$

as claimed. $\square$

On the other hand, it is proved in [5]:

Claim 3 Assume an agreement profile σ of a game Γ over a clique graph G of size q . Then, no player can increase its utility by unilaterally decreasing its *ON* time and increasing its *OFF* time.

Proof By Claim 1, assume without loss of generality that σ is an ordered agreement profile. Consider any player $i \in [q]$. Then, by Claim 2, the node gets a utility of

$$U_{\sigma}(i) = |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k|. \quad (9)$$

$\square$

If the player i increases its *OFF* period by some $|t| > 0$, it follows that its new *ON* time slot will be $|T'_i| = |T_i| - |t|$, thus $t \leq |T_i|$. Let σ' be the resulting profile. Since σ is an agreement profile, there is no other player that is *ON* during time period t . So, its $OFFU_{\sigma'}(i)$ remains the same as in σ . Moreover, its $ONU_{\sigma'}(i)$ must be decreased by t . Summing up, in the resulting profile its new utility becomes:

$$\begin{aligned}
U_{\sigma'}(i) &= ONU_{\sigma'}(i, T'_i) \cdot |T'_i| + \sum_{T_k \in T \setminus T'_i} OFFU_{\sigma'}(i, T_k) \cdot |T_k| \\
&= 1 \cdot (|T_i| - |t|) + \sum_{T_k \in T \setminus T'_i} w(k, i) \cdot |T_k| \\
&= |T_i| - |t| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k| + 0 \cdot |t| \\
&= -|t| + \left(|T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k| \right) \\
&= -|t| + U_{\sigma}(i).
\end{aligned}$$

Since $t > 0$, it follows that $U_{\sigma'}(i) > U_{\sigma}(i)$, so that the player does not increase its utility by unilaterally increasing its *OFF* mode operation.

4.3 Necessary Conditions for Nash Equilibria

Using previous analysis on agreement profiles on clique graphs, the authors of [5] proceed to prove when such profiles are stable for the game, i.e., that when such profiles are Nash equilibria for the game. In particular, it is shown in this section that there exists a necessary condition for an agreement profile to be Nash equilibrium of the game. In the following sections, they provide sufficient conditions for stability of agreement profiles [5].

Proposition 1 *Consider an agreement profile σ for a game Γ over a clique graph G of size q . Then, if σ is Nash equilibrium, then for any of the players $i, j \in [q]$, it holds that $w(i, j) \geq \frac{1}{2}$.*

Proof Recall that by Claim 1, we may assume that σ is an agreement, continuous *ON/OFF* time slots profile. Also, by Claim 2, the utility of player i is:

$$U_{\sigma}(i) = |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k|. \quad (10)$$

□

Since σ is Nash equilibrium, no player that can increase its utility by unilaterally increase its *ON* time period. Assume now, by way of contradiction that there exists a player $i \in [q]$, such that $w(j, i) < \frac{1}{2}$ for some player $j \in [q]$. Assume now that the player i increases its *ON* time period to:

$$|ON_Time_{\sigma'}(i)| = |T'_i| = |T_i| + |t_j|,$$

where $t_j \in T_j$. Denote the resulting profile by σ' . Recall that node j was the only node in *ON* mode at the time slot T_j . Thus, during time t_j where the node i switches to be *ON*, the utility of node i is decreased due to the interference caused by node j . In particular, by Eq. (5), $ONU_{\sigma'}(i, T_i) = 1$ while $ONU_{\sigma'}(i, t_j) = (1 - w(j, i))$.

Moreover, observe that in σ' the player is *OFF* during time equal to:

$$OFF_Time_{\sigma'}(i) = T \setminus \{T_i \cup t_j\}$$

or

$$|OFF_Time_{\sigma'}(i)| = \sum_{T_k \in T \setminus T_i} |T_k| - |t_j|$$

For each $T_k \in T \setminus \{T_i \cup T_j\}$ where the node i is *OFF* and served by node k , by Eq. (6), its utility is $OFFU_{\sigma'}(i, T_k) = w(k, i)$. During the decreased time period $T_j \setminus t_j$, it also gets $OFFU_{\sigma'}(i, T_j \setminus t_j) = w(k, i)$.

In summary,

$$\begin{aligned}
U_{\sigma'}(i) &= ONU_{\sigma'}(i, T_i') \cdot |T_i'| + \sum_{T_k \in T_i'} OFFU_{\sigma'}(i, T_k) \cdot |T_k| \\
&= ONU_{\sigma'}(i, T_i) \cdot |T_i| + ONU_{\sigma'}(i, t_j) \cdot |t_j| + \sum_{T_k \in T \setminus \{T_i \cup T_j\}} OFFU(i, T_k) \cdot |T_k| \\
&\quad + OFFU(i, T_j \setminus t_j) \cdot (|T_j| - |t_j|) \\
&= 1 \cdot |T_i| + (1 - w(j, i)) \cdot |t_j| + \sum_{T_k \in T \setminus T_i \cup T_j} w(k, i) \cdot |T_k| + w(j, i) \cdot (|T_j| - |t_j|) \\
&= |t_j| + U_{\sigma}(i) - 2w(j, i) \cdot |t_j|,
\end{aligned} \tag{11}$$

by Eq. (10).

Since σ is Nash equilibrium, it must be that

$$\begin{aligned}
U_{\sigma}(i) &\geq U_{\sigma'}(i) \\
&= U_{\sigma}(i) - 2w(j, i) \cdot |t_j| + |t_j|,
\end{aligned}$$

by Eq. (11). Thus, it must be that

$$2w(j, i) \cdot |t_j| \geq |t_j|.$$

Thus, it must be that $w(j, i) \geq \frac{1}{2}$, which is a contradiction since $w(j, i) < \frac{1}{2}$ by assumption. The proposition is therefore proved.

4.4 Sufficient Conditions for Nash Equilibria

In this section, we present the sufficient condition for an agreement profile to be Nash equilibrium of the game [5].

Theorem 1 *Assume an agreement profile σ for the game Γ over a clique graph G of size q . If $w(i, j) \geq \frac{1}{2}$, for every pair $i, j \in [q]$, then σ is Nash equilibrium.*

Proof Again, by Claim 1, we may assume without loss of generality that σ is an ordered agreement profile. By Claim 2, the utility of player i is:

$$U_{\sigma}(i) = |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k|. \tag{12}$$

□

Assume now that in contrary σ is *not* Nash equilibrium. Then, for at least one player $i \in [q]$, there exists an alternation of its *ON/OFF* time slots, so that he gets more (that is his utility is increased compared to σ). Note first that by Claim 3, the

node can not gain more by increasing its *OFF* time period. Accordingly, assume that the player unilaterally increases its *ON* time period as follows: $T'_i = T_i \bigcup_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} t_k$, where $t_k \geq 0$ for all k , and $t_k > 0$ for at least one k . Thus,

$$|ON_Time_{\sigma'}(i)| = |T'_i| = |T_i| + \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} |t_k|.$$

Recall that in σ , each node $k \in [q]$, is the only node on *ON* mode at the time slot T_k . Thus, during time $t_k \in T_k$ where the node i switches to *ON* operation in σ' , the node gets decreased utility due to the interference received by node k . In particular, by Eq. (5), $ONU_{\sigma'}(i, t_k) = 1 - w(k, i)$ for each such $t_k \in T_k$, while $ONU_{\sigma'}(i, T_i) = 1$.

Moreover, observe that in σ' , the player is *OFF* during time equal to:

$$OFF_Time_{\sigma'}(i) = T \setminus \{T_i \bigcup_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} t_k\}$$

Thus,

$$|OFF_Time_{\sigma'}(i)| = \sum_{T_k \in T \setminus T_i} (|T_k| - |t_k|)$$

Thus, Eq. (4) becomes:

$$\begin{aligned} U_{\sigma'}(i) &= \sum_{T_k \in ON_Time_{\sigma'}(i)} ONU_{\sigma'}(i, T_k) \cdot |T_k| + \sum_{T_k \in OFF_Time_{\sigma'}(i)} OFFU_{\sigma'}(i, T_k) \cdot |T_k| \\ &= ONU_{\sigma'}(i, T'_i) \cdot |T'_i| + \sum_{T_k \in T \setminus T'_i} OFFU_{\sigma'}(i, T_k) \cdot |T_k| \\ &= ONU_{\sigma'}(i, T_i) \cdot |T_i| + \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} ONU_{\sigma'}(i, t_k) \cdot |t_k| + \sum_{T_k \in T \setminus T_i} OFFU_{\sigma'}(i, T_k \setminus t_k) \cdot (|T_k| - |t_k|) \\ &= 1 \cdot |T_i| + \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} (1 - w(k, i)) \cdot |t_k| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot (|T_k| - |t_k|) \\ &= |T_i| + \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} |t_k| - 2 \cdot \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} w(k, i) \cdot |t_k| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k| \end{aligned} \quad (13)$$

Since, by assumption, σ is not Nash equilibrium, it must be that $U_{\sigma'}(i) > U_{\sigma}(i)$. Thus, by Eqs. (12) and (13), combined with $U_{\sigma}(i) < U_{\sigma'}(i)$, it must be that

$$\begin{aligned} |T_i| + \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k| &< |T_i| + \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} |t_k| - 2 \cdot \sum_{\substack{t_k \in T_k, \\ T_k \in T \setminus T_i}} w(k, i) \cdot |t_k| \\ &+ \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |T_k| \end{aligned}$$

It follows that it must be that,

$$2 \cdot \sum_{\substack{t_k \in T_k \\ T_k \in T \setminus T_i}} w(k, i) \cdot |t_k| < \sum_{\substack{t_k \in T_k \\ T_k \in T \setminus T_i}} |t_k| \quad (14)$$

Since for all $i, j \in [q]$, $w(j, i) \geq \frac{1}{2}$,

$$2 \cdot \sum_{T_k \in T \setminus T_i} w(k, i) \cdot |t_k| \geq \sum_{T_k \in T \setminus T_i} |t_k|,$$

a contradiction to Eq. (14). It follows that σ is indeed Nash equilibrium.

4.5 A Characterization for Nash Equilibria

Proposition 1 implies that the condition $w(i, j) \geq \frac{1}{2}$, for any pair $i, j \in [q]$ is a necessary condition in order an agreement profile to be Nash equilibrium. Moreover, Theorem 1 implies that the condition is also a sufficient condition in order to have Nash equilibrium. Thus, based on [5],

Corollary 1 *An agreement profile of the game Γ over a clique graph G of size q is Nash equilibrium if and only if $w(i, j) \geq \frac{1}{2}$ for all pairs $i, j \in [q]$.*

5 Simulation Evaluation

The theoretical evaluation of the proposed model resulted in identifying necessary and sufficient conditions for cooperation to be possible. In this section, we demonstrate the potential benefits of cooperation by simulation. Specifically, we implement the scenario of densely deployed APs in a widely used network simulator (OPNET) and compare the performance, in terms of signal-to-noise ratio (SNR), between the default (noncooperative) case where all APs serve their own clients independently at the same time, and the cooperative case where all clients are served by one AP at a time.

The following scenarios are statically configured, i.e., the configuration of nodes does not change throughout the simulation (Fig. 3). A single content generating server in the background is assumed to be connected via a fast wired backhaul router to all the APs. Each scenario has an initial setup time, recorded in the results, which can be seen an oscillating initial behavior of the collected statistics. The authors do not consider this phase as part of the discussion of the collected results,

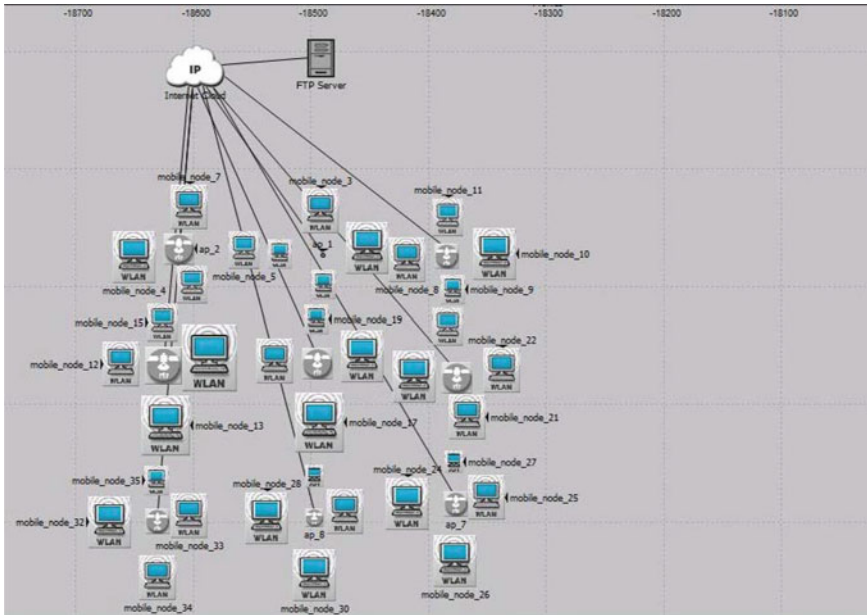


Fig. 3 The 9-AP configuration used by the simulation scenarios

as this is a simulator-generated behavior that is irrelevant to the effect of our model on the simulated behavior. At a time of 100 s after the start of the simulation, all the nodes start retrieving content from the server via FTP. All the wireless connections between the APs and the clients use standard Wi-Fi at a maximum 802.11 g rate (54 Mbps). All the active APs are configured to use the same resource (Channel 1), in order to study the interference resulting from simultaneous broadcasting of nearby APs due to lack of coordination.

Using this configuration, we study two separate scenarios:

1. the wireless clients are served by their own APs (default);
2. the wireless clients are served by the central AP (cooperative).

Furthermore, the simulations consider that there is no wireless noise, so a transmitted packet is always received perfectly by anyone in the range, unless a collision occurs.

We first show the results for the first (default) scenario. Figure 4 presents the SNR values recording in this case for each of the 9 players. Figure 5 presents the SNR of the second (cooperative) scenario. We observe that the SNR shows a sizeable increase (more for some users than others), clearly indicating the reduced interference in the environment, since the signal of the serving AP was not modified in any way.

To show that this has a positive effect on the user experience, we present in Figs. 6 and 7 the actual throughput results for the users in both scenarios. These figures

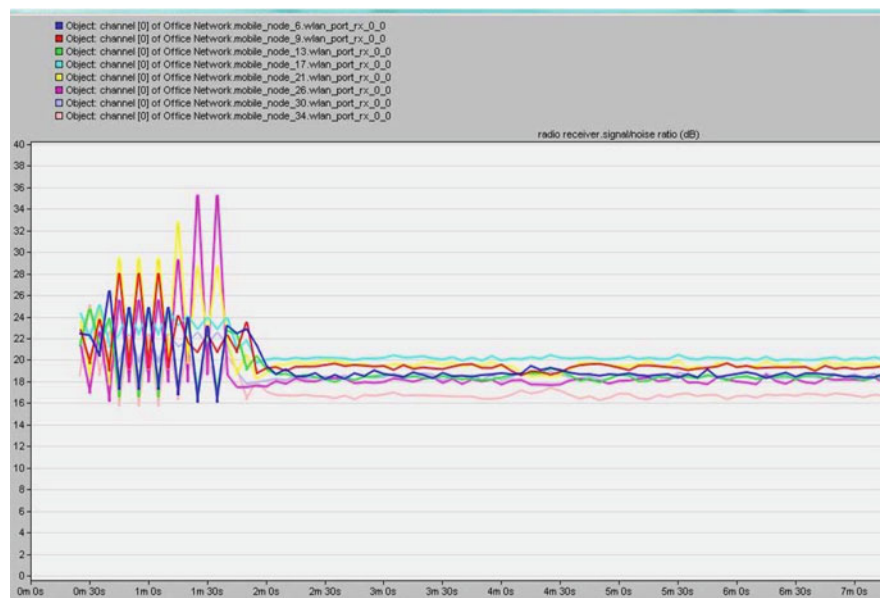


Fig. 4 The SNR values of the 9 users in a noncooperative scenario

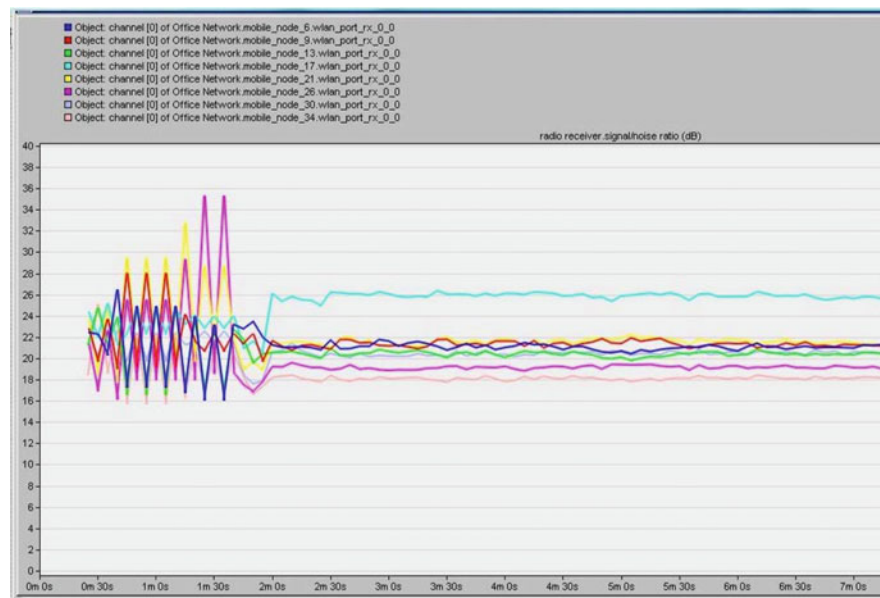


Fig. 5 The SNR values of the 9 users in a cooperative scenario

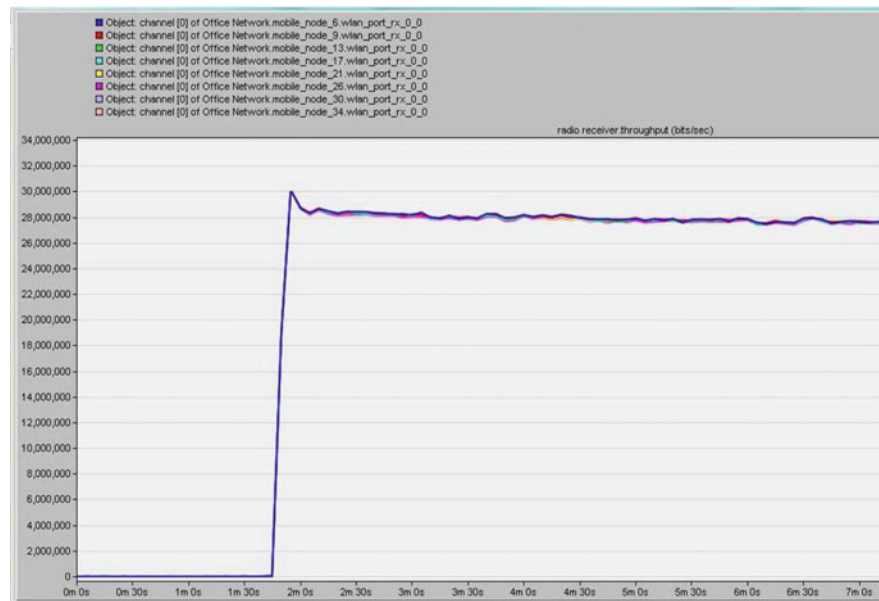


Fig. 6 The throughput of the 9 users in a noncooperative scenario

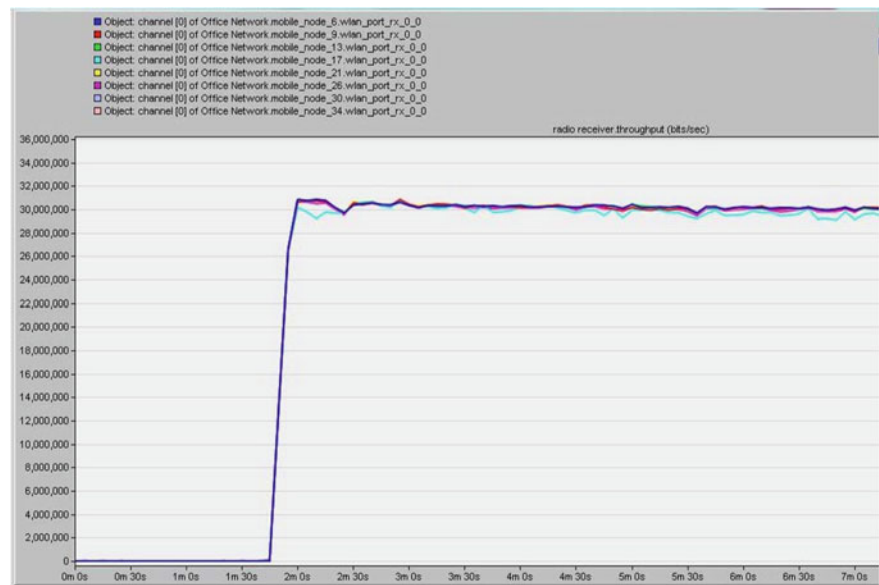


Fig. 7 The throughput of the 9 users in a cooperative scenario

show that the increased SNR translates into a better throughput as well. Recall that the oscillating startup behavior is due to the simulation scenario setup phase, so the measurement of throughput is recorded after approximately 100 s when the application of FTP application is activated in the users.

6 Conclusions and Future Work

In this chapter, we considered a method to mitigate the interference caused by many individual wireless Access Points (AP) located in a dense area and transmitting using the same or overlapping channel via cooperation among the APs, such that they serve each other's clients at different times. We modeled the situation using a graphical game, particularly focusing on the case where the underlying graph is a clique with heterogeneous edge weights. We characterized the conditions under which agreements between all APs to jointly serve each other's clients are possible and achieve the maximum benefit for their clients.

Due to practical constraints, our results apply mainly in clique networks of small size. This is because Observation 1 relies on the assumption that in any time slot where an AP is *ON*, it can serve all the clients of other APs, which may be unrealistic for large cliques due to bandwidth limitations. While dense deployments resulting in large clique networks, where a client can be served by a large number of alternative APs with good signal strength, are arguably uncommon, an extension of our model to consider bandwidth-constrained equilibria that may arise in this case, as well as other more general graph topologies that fall short of a full clique, is left as a subject for future work.

The work presented in this chapter revealed that agreement behaviors of APs under some conditions are preferable for the APs. However, how such agreement behaviors are initiated and applied in practice, especially in a distributed manner, under no central authority, consists a next major step of our work, also considering security issues. Furthermore, investigating agreement profiles for deployments of APs that form other dense graph topologies are subject of future work. As a future work, one can target more complex simulation scenarios in terms of topologies and mix of applications as well as positioning of the users, and can experiment with a rotational scheme for serving users by the different APs in the neighborhood. This work is expected to lead to the design of a protocol leading to cooperation among neighboring APs.

Finally, let it be noted that various alternative physical layer technologies have been proposed in the recent literature to reduce interference between nearby APs, such as directional antennas and cooperative MIMO [8]. An extended model that would allow these ideas on cooperation among APs to be applied in combination with such technologies remains a topic for future work.

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