Strategic Device-to-Device Communications in Backhaul-Constrained Wireless Small Cell Networks

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Abstract—Wireless small cell networks and device-to-device (D2D) communications are seen as two major features of next-generation wireless networks. In this paper, a novel approach for enabling D2D communication underlaid on a wireless small cell network is proposed. Unlike existing works which focus on network performance analysis given a chosen communication mode, in this paper, the strategic selection of a desired wireless communication mode between pairs of users is studied. On the one hand, communication using the small cells can provide reliable transmission but is limited by interference and backhaul constraints. On the other hand, D2D communication can provide high capacity due to devices’ proximity but is limited by increased interference. To capture these properties, the problem is modeled as a noncooperative game in which pairs of communicating users can strategically decide on whether to communicate with one another via the small cell infrastructure or via direct D2D communication. In this proposed game, each device selects its preferred communication mode while optimizing a utility function that captures the various involved tradeoffs between communication performance and associated costs. For solving this game, a distributed best response-based approach is proposed using which the users can reach a Nash equilibrium. Simulation results show that the resulting network at the equilibrium is composed of a mixture of D2D and small cell communication links. The results also show that the proposed approach yields a significant improvement in terms of the average utility per communicating pair when compared with the cases in which the users communicate via only the small cells or via only D2D.

I. INTRODUCTION

The proliferation of smartphones and bandwidth intensive wireless applications imposes stringent performance constraints on the next-generation of wireless cellular networks [1]. In this respect, wireless small cell networks and device-to-device (D2D) communications are seen as two promising approaches for boosting the capacity of wireless systems and meeting this surge in demand [2]. On the one hand, wireless small cell networks (SCNs) are based on the idea of deploying low-cost, low-power small cell base stations (SCBSs), overlaid on existing “macro-cellular” networks, and that can connect to existing backhauls such as DSL. SCBSs are an of different types such as user-deployed, indoor femtocells or operator-deployed outdoor picocells or microcells. The large-scale deployment of such SCBSs will reduce the distance between the users and their serving access points, thus yielding a significant increase in the wireless capacity [2]. On the other hand, the basic idea of D2D communication is to enable direct communication between mobile devices. Essentially, D2D communication allows devices to exchange data over the licensed band without going through the main cellular infrastructure. Using D2D is expected to reduce the load on the main cellular system and to enable novel applications such as proximity-based services and public safety [2], [3].

However, deploying SCNs and D2D communication requires overcoming various technical challenges such as network modeling, interference management, resource allocation, and backhaul management [2]. The work in [4] investigates the use of inter-cell coordination techniques to mitigate interference in outdoor deployments of picocells. Interference coordination in SCNs is further studied in [5] using belief propagation. In [6], a reinforcement learning technique is proposed to optimize, dynamically, the transmit powers of the small cells.

Further, as discussed in [2], unlike the high capacity backhaul of macro-cellular networks, the backhaul of SCNs can be of limited capacity, thus affecting the overall wireless performance. In this respect, the work in [7] studied the impact of a finite capacity backhaul on the outage probability when SCBSs are used as a relay for macrocell traffic. In addition, the authors in [8] derive metrics to quantify the overhead needed for coordination over a capacity-limited SCN backhaul.

From a D2D perspective, a large number of works have been done, mainly focusing on performance analysis and resource allocation [3], [9–11]. Optimal power control strategies for D2D communications are studied and analyzed in [3] for a cellular network with a single D2D link. In [9], the authors propose a novel approach for link discovery and interference management in a D2D system underlaid on a macro-cellular network. The authors in [10] propose the use of D2D underlaid on wireless SCNs for caching data at the mobile devices thus improving the performance of multimedia services and reducing the overall network load. Finally, in [11], the authors study the use of cooperative game theory for frequency selection and resource sharing in a single-cell D2D network. Additional related works are found in [12], [13].

Clearly, D2D and wireless small cell networks will constitute a major component in future wireless systems. However, beyond [10], most existing D2D work is tailored toward macro-cellular networks and do not capture small cell features such as backhaul limitations. Moreover, most of this existing literature is focused on resource allocation or performance analysis, under a given communication mode: either D2D-based or small cell-based. In practice, the wireless users might have an incentive to strategically decide on whether to communicate via D2D or via the main cellular infrastructure. In particular, this choice of a communication mode is strongly dependent on various network factors such as proximity of the devices,

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interference, or backhaul constraints. To our best knowledge, beyond performance analysis results in [3], [12], [13] and the single-cell communication mode selection study in [11], no work seems to have investigated how the wireless users can adaptively decide on their preferred communication mode (D2D or small cell), as proposed here. Indeed, compared to these existing works [3], [11] (and related works), we are interested in the overall dynamic network-wide operation, rather than on deriving fundamental performance analysis results.

The main contribution of this paper is to develop a novel approach for enabling strategic wireless transmission mode selection in a backhaul-constrained wireless small cell network with underlaid D2D communication. The problem is formulated as a noncooperative game in which pairs of communicating users can strategically decide on whether to communicate via the wireless small cell infrastructure or directly via D2D, depending on the potential performance benefits and associated costs. In this game, each pair of users chooses the preferred communication mode so as to optimize a utility function that captures key performance metrics such as interference (at small cell and D2D sides) and backhaul constraints (at the small cell side). For solving the game, we propose a distributed, best response-based algorithm using which the devices can reach a Nash equilibrium. Simulation results show that the resulting network encompasses a mixture of D2D and small cell-based communication. Moreover, the results also show that the proposed algorithm yields significant performance gain, in the average utility per communicating pair, when compared to a small cell-only and a D2D-only solution, respectively.

The rest of this paper is organized as follows: Section II presents the system model. In Section III, we present the proposed game-theoretic formulation and the associated algorithm. Simulation results are presented and analyzed in Section IV. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL AND GAME FORMULATION

Consider a small cell network consisting of $K$ SCBSs and let $\mathcal{K}$ denote the set of all such SCBSs. Note that this set can also encompass macro-cellular base stations, however, as the macro base stations and the SCBSs differ by only their capabilities, for ease of exposure, we will use the term SCBS to refer to any such base station. In this network, $N$ pairs of wireless users are deployed. Each pair $n \in \mathcal{N}$, $n = (i, j)$, consists of a transmitting user $i$ having data to send to a destination, receiving user $j$. Let $\mathcal{N}$ denote the set of all communicating pairs. The considered SCN operates using a frequency-division duplexing (FDD) mode such that the uplink and downlink transmissions occur at different carrier frequencies as is common in most practical models [2].

Consider the communication between the transmitting user $i$ and the receiving user $j$ of a given pair $n \in \mathcal{N}$. Here, each transmitting user can decide to transmit its data in one of two ways: a) Direct transmission to user $j$ via a D2D link or b) Transmission to user $j$ via an SCBS in $\mathcal{K}$ that will carry the data over the cellular infrastructure. Let $N_{D2D}^{SCB}$ and $N_{SCBS}^{SCB}$ denote, respectively, the set of all transmitting users that are communicating via D2D and the set of all transmitting users that are communicating via the SCN.

In the considered model, we assume that D2D communication occurs using a split spectrum model, such that the small cell and D2D transmissions use orthogonal resources and do not interfere with one another such as in [11]. Thus, when using D2D, the performance of the transmission between users $i$ and $j$ belonging to a pair $n = (i, j) \in \mathcal{N}$ can be captured via the achieved D2D rate, given by:

$$R_{i,j}^{D2D} = \log (1 + \frac{P_i h_{i,j}}{\sum_{m \neq i, m \in \mathcal{K}^{SCBS}} P_m h_{m,j} + \sigma^2}),$$  \hspace{1cm} (1)

where $P_i$ is the transmit power of user $i$, $h_{i,j}$ is the channel gain between users $i$ and $j$, and $\sigma^2$ is the variance of the Gaussian noise. Without loss of generality, hereinafter, we consider a path loss based, block fading channel, such that $h_{i,j} = \frac{1}{d_{i,j}^\alpha}$ with $\alpha$ being the path loss exponent, $\kappa$ being the path loss constant, and $d_{i,j}$ being the distance between users $i$ and $j$.

When a given pair of users $n = (i, j)$ is communicating over the small cell network, first, transmitting user $i$ will send its data in the uplink via its serving SCBS $k_i \in \mathcal{K}$. Subsequently, this data is forwarded by SCBS $k_i$ via the backhaul to the SCBS $k_j \in \mathcal{N}$ that is serving the receiving user $j$ of the pair $n$. Here, we assume that the small cell network’s backhaul is of finite capacity as is the case in practical deployments [2]. In turn, SCBS $k_j$ will complete the communication link of pair $n$ by transmitting the data in the downlink to the receiving user $j$. During this small cell-based transmission, the rate achieved by the uplink user $i$ is given by:

$$R_{i,k_i}^{n} = \log (1 + \frac{P_i h_{i,k_i}}{\sum_{m \neq i, m \in \mathcal{K}^{SCBS}} P_m h_{m,k_i} + \sigma^2}),$$  \hspace{1cm} (2)

where $h_{i,k_i}$ is the channel gain between user $i$ and its serving SCBS $k_i$. In the downlink, the rate achieved by the receiving user $j$ of communicating pair $n$ is given by:

$$R_{j,k_j}^{n} = \log (1 + \frac{P_j h_{j,k_j}}{\sum_{l \neq j, l \in \mathcal{K}^{SCBS}} P_l h_{l,j} + \sigma^2}),$$  \hspace{1cm} (3)

where $P_j$ is the downlink transmit power of SCBS $k_j$, $\mathcal{K}_{DL} \subseteq \mathcal{K}$ is the subset of SCBSs that are transmitting in the downlink, and $h_{j,l}$ is the channel gain between SCBS $l$ and the downlink receiving user $j$ of pair $n$.

Consequently, the overall performance of the communication link between user $i$ and user $j$ is a function of both the uplink and downlink transmission rates as well as the costs of backhaul data forwarding between the uplink SCBS and downlink SCBS. In this respect, given a communicating pair $n$ in which the transmitting user $i$ is served by an SCBS $k_i$ and the receiving user $j$ is served by an SCBS $k_j$, the end-to-end performance of pair $n$ over the small cell network can be given by the following metric:

$$v_{i,j}^{n} = \min (R_{i,k_i}^{n}, R_{j,k_j}^{n}) - C(k_i, k_j),$$ \hspace{1cm} (4)

where the first term represents the bottleneck transmission over the radio links (uplink/downlink) which represents the rate of the transmission direction which limits the overall end-to-end performance and the second term $C(k_i, k_j)$ represents the cost of transmission over the backhaul from SCBS $k_i$ to SCBS $k_j$. (4) represents the tradeoff between the benefits of
the transmissions over the radio environment and the backhaul constraints.

Modeling backhaul connectivity and performance in SCNs is currently a major research area with a diversity of challenges [2]. Essentially, most proposed backhaul solutions exhibit two key limitations: a) finite capacity and b) strong dependence of the performance on the route and distance. To this end, the cost function in (4) must be able to capture these two characteristics. In particular, the cost must be an increasing function of the load over each specific backhaul link as well as of distance traveled (which reflects the length of the route used by the packets). Consequently, to capture the costs of backhaul processing between two SCBSs $k$ and $l$, we propose the following function which satisfies the aforementioned requirements:

$$C(k, l) = -\alpha_{k,l} \cdot \log \left(1 - \frac{L_{k,l}}{\lambda_{k,l}}\right) + \beta_{k,l}d_{k,l},$$  

(5)

where $\alpha_{k,l}$ is a pricing parameter that reflects the cost pertaining to adding one more connection over the backhaul between SCBS $k$ and $l$, $L_{k,l}$ is the number of communicating pairs utilizing the backhaul link between SCBSs $k$ and $l$, $\lambda_{k,l}$ is the maximum capacity of the backhaul link between $k$ and $l$, $\beta_{k,l}$ is the cost per unit distance, and $d_{k,l}$ is the distance between SCBS $k$ and SCBS $l$.

Thus, the first term in (5) is a penalty function (similar to the barrier function in optimization [14]) that reflects the finite capacity of the link. As the number of pairs $L_{k,l}$ utilizing the backhaul between SCBSs $k$ and $l$ increases, the first term in (5) starts increasing slowly and then follows a steeper increase slope as the link becomes close to its maximum capacity. The second term in (5) simply represents the cost for routing the packets over longer distances. Notice that if a communicating pair $n = (i,j)$ is utilizing a single SCBS for uplink and downlink, i.e., $i$ and $j$ are connected to the same SCBS, then the second term in (5) is set to 0, as no distance costs are incurred. In such a case, only a cost for synchronizing the number of connections is maintained and captured via the first term in (5). Also, we note that the approach proposed in this paper can also be applied to any other cost function.

By clearly inspecting (1) and (4), we can see that the choice of a communication mode: small cells or D2D, yield different performance metrics. On the one hand, by utilizing the D2D connection, the users can avoid the backhaul costs, however, as the number of users over the D2D link increases, this can yield a significant increase in the overall interference, thus reducing the rate in (1). On the other hand, by communicating via the small cell network’s infrastructure, the pairs of communicating users can improve their radio access rate, as they can often a better channel at their serving SCBSs than between one another. However, the performance over the cellular network is limited not only by interference but also by backhaul constraints. Therefore, it is of interest to develop dynamic approaches that allow the users in a small cell network to strategically decide on whether to communicate via the small cells or via D2D, depending on the network parameters. An illustration of the proposed system model is shown in Fig. 1 for a network having a mixture of D2D-based and SCBS-based communication, with $N = 5$ communicating pairs and $K = 4$ SCBSs. Next, we propose a game-theoretic approach suitable to forming and characterizing networks with mixed D2D and small cell communications as illustrated in Fig. 1.

### III. PROPOSED GAME-THEORETIC APPROACH

In this section, we formulate the communication mode selection problem as a noncooperative game and, then, we develop an algorithm for characterizing the solution of the proposed game.

#### A. Game Formulation

In order to improve their overall network performance, the wireless devices can decide on whether to operate in a D2D mode or via the small cell network. In order to formally study the interactions between the different communicating pairs in $\mathcal{N}$, we adopt a noncooperative game theoretic approach [15].

Noncooperative game theory is the major branch of game theory that deals with the decision making processes of a set of independent decision makers or players that are looking to optimize a certain individual objective given a coupling between their strategies or actions [15]. In the studied model, the decisions of the different users are highly interdependent due to: a) interference on both the D2D and small cell sides and b) the backhaul constraints which depend on the number of users utilizing the different small cell base stations. Hereinafter, for ease of analysis, we assume that, for each pair $n = (i,j) \in \mathcal{N}$ of communicating users, the transmitting user $i$ makes the decision on which communication mode to use, on behalf of the pair $n$. As a result, if using a small cell mode, we consider that the receiving user $j$ will be by default connected to the closest SCBS while the transmitting user strategically optimizes the transmission mode.

Consequently, for the proposed system, we formulate a static noncooperative game in strategic form, $\mathcal{G} = (\mathcal{N}_{T}, \{A_{i}\}_{i \in \mathcal{N}_{T}}, \{U^{n}_{i}\}_{n \in \mathcal{N}_{T}})$, which is defined by its three main components: (i) the players which are the transmitting users whose set will be denoted by $\mathcal{N}_{T}$, (ii) the strategy $\alpha_{i}$ of each player $i \in \mathcal{N}_{T}$ which corresponds to the choice of either

![Fig. 1. Illustrative example of the proposed model for a system with $N = 5$ communicating pairs and $K = 4$ SCBSs. Here, 3 pairs are communicating via the small cell network while the 2 other pairs are using direct D2D transmission.](image)
an SCBS in $\mathcal{K}$ or the D2D mode, thus, we let $\mathcal{A}_i := \mathcal{K} \cup \{0\}$ denote the set of all strategies of user $i$, with the index 0 denoting the D2D mode, and (iii) the utility function $U^n_i$ of any player $i \in \mathcal{N}_T$ belonging to a pair $n \in \mathcal{N}$ which captures the benefits and costs from a given choice. In particular, the utility function achieved by player $i \in \mathcal{N}_T$ belonging to a pair $n \in \mathcal{N}$ that chooses action $a_i \in \mathcal{A}_i$ so as to communicate with receiving user $j$ is given by:

$$U^n_i(a_i, a_{-i}) = \begin{cases} R^{\text{D2D}}_{ij}(a_i, a_{-i}) & \text{if } a_i = 0, \\ v^n_{ij}(a_i, a_{-i}) & \text{otherwise.} \end{cases} \quad (6)$$

Here, $R^{\text{D2D}}_{ij}$ is given by (1), $v^n_{ij}$ is given by (4), and $a_{-i}$ is the vector of strategy choices of all players other than $i$. Note that, here, both $R^{\text{D2D}}_{ij}$ and $v^n_{ij}$ depend on $a_{-i}$, through the interference terms (for small cells and D2D) and the backhaul cost (for small cells).

In the proposed game, each communicating pair aims to maximize its utility function by choosing an optimal transmission mode $a_i \in \mathcal{A}_i$. One popular solution concept to solve strategic games such as the proposed game $\Xi$ is that of a Nash equilibrium [15]. Essentially, a Nash equilibrium represents a network state in which no player can further improve its individual utility by unilaterally deviating from its equilibrium strategy. The Nash equilibrium is formally defined as follows [15]:

**Definition 1:** Consider the proposed strategic noncooperative game for transmission mode selection $\Xi = (\mathcal{N}_T, \mathcal{A}_i \in \mathcal{N}_T, \{U^n_i\}_{i \in \mathcal{N}_T})$, with $U^n_i$ given by (6). A vector of strategies $a^*$ constitutes a Nash equilibrium (NE) of this game, if and only if, it satisfies the following set of inequalities:

$$U^n_i(a^*_i, a^*_{-i}) \geq U^n_i(a_i, a^*_{-i}), \quad \forall a_i \in \mathcal{A}_i, i \in \mathcal{N}_T. \quad (7)$$

The NE of the proposed game defines a network configuration, as in Fig. 1, in which no communicating pair can improve its overall performance by unilaterally changing its transmission mode from D2D to small cells or vice versa.

**B. Proposed Algorithm**

Having formulated a noncooperative game and identified its solution, the next step is to develop an algorithm that can model the interactions between the wireless communicating pairs seeking to choose their preferred communication mode. In the proposed game, each strategy choice $a_i$ by a transmitting user $i$ leads to a new network structure and operation model. To find a desired strategy, each device aims to maximize its utility, given any observation it has on the current network state. In this respect, to develop an algorithm for finding a solution of the game, it will prove useful to define the concept of a best response, as follows:

**Definition 2:** Given any user $i \in \mathcal{N}_T$ belonging to a communicating pair $n \in \mathcal{N}$, the best response $r(a_{-i})$ of this user to the profile of strategies $a_{-i}$ chosen by the other transmitting users is a set of strategies for $i$ such that

$$r(a_{-i}) = \{a_i \in \mathcal{A}_i | U^n_i(a_i, a_{-i}) \geq U^n_i(a'_i, a_{-i}), \forall a'_i \in \mathcal{A}_i\}. \quad (8)$$

Therefore, for any transmitting user $i \in \mathcal{N}$, when the strategies of the other players are determined as per $a_{-i}$ (i.e., for a given network configuration), any best response strategy (mode choice) in $r(a_{-i})$ is at least as good as every other available strategy in $\mathcal{A}_i$. Subsequently, the wireless users in the proposed noncooperative game can interact using a proposed algorithm consisting of three phases: network discovery, adaptive mode selection via best response, and wireless transmission. Initially, we assume that all transmitting users are connected to the nearest neighbor. This could be a direct D2D transmission to the receiving user or the closest serving SCBS.

In the first phase of the proposed algorithm, the wireless devices must discover neighboring SCBSs and estimate some of the required parameters such as interference, distance to destination (i.e., distance between pairs), and current load on the SCBSs backhaul. In a practical wireless network, interference can be relatively easily measured at the receiver, and, subsequently estimated [2], [16]. For estimating distances, the users can utilize classical signal processing techniques, as is extensively done in wireless cellular systems [16]. Moreover, to estimate the current backhaul load, two approaches can be followed. First, the SCBSs can broadcast over a control channel a basic estimate of their current load which can be projected by the users to estimate the backhaul cost in (5). Alternatively, the users can send a “Hello” packet over the cellular infrastructure and then measure the overall experienced delay. While the details of this estimation and discovery phase are very interesting, they fall out of the scope of this paper and will be studied in future work.

Following network discovery, the users engage in the second phase of the algorithm in which the adaptive mode selection occurs. First, having discovered the network, each transmitting user chooses its best response based on an estimated utility generated out of the device’s current knowledge about the estimated network parameters. Essentially, the best response of a transmitting user $i$ is chosen in response to the currently perceived vector of strategies $a_{-i}$, chosen by the other users. Here, we consider that the wireless users make their best response decisions, sequentially, in an arbitrary order. This order is generally determined by the practical operation of the network and is often dependent on factors such as application usage, device type, or others. This distributed and iterative process continues until convergence to an equilibrium. In general, when a best response algorithm converges, it is guaranteed to reach an equilibrium [15]. In this respect, best response dynamics-based algorithms have been proven to converge to such an NE for many classes of games and many advanced modifications have also been proposed to guarantee convergence [15].

Once the Nash equilibrium of the network is reached, the last phase of the proposed algorithm is the actual transmission phase during which all the communicating pairs in $\mathcal{N}$ would transmit their data using the equilibrium communication mode choices. During this third phase, whenever a communicating pair observes any change in the network parameters (e.g., entry of new users), it can re-engage in Phase 2 of the proposed algorithm so as to update the network state to a new equilibrium point. The proposed algorithm is summarized in Table I.
TABLE I
PROPOSED NONCOOPERATIVE GAME APPROACH FOR ADAPTIVE COMMUNICATION MODE SELECTION

<table>
<thead>
<tr>
<th>Initial Network:</th>
<th>Each transmitting user ( i ) of a communicating pair ( n \in N ) connects to its nearest neighbor. The nearest neighbor could be either the closest SCBS or the direct D2D link.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 - Network Discovery:</td>
<td>Each communicating pair discovers neighboring SCBSs. Each communicating pair estimates required network parameters via well known techniques [16].</td>
</tr>
</tbody>
</table>
| Phase 2 - Adaptive Mode Selection via Best Response: | **repeat, sequentially, in an arbitrary order**
- a) Each transmitting \( i \in N \) observes current strategy vector \( \alpha_{-i} \) of opponents. This is done, for example, by measuring current interference levels in either modes of transmission.
- b) Each transmitting \( i \in N \) selects its best response \( r_i(\alpha_{-i}) \).
- c) This best response selection can be seen as a temporary switch in communication mode for user \( i \).
- until convergence to a Nash equilibrium strategy vector \( \alpha^* \). |
| Phase 3 - End-to-End Wireless Transmission: | a) The communicating pairs transmit their data given the network formed using the NE strategies in \( \alpha^* \).
- b) If a change in network parameters is observed the users can re-engage in Phase 2 of the algorithm. |

Individually, decide on which communication mode to choose, at each iteration of the best response phase, until convergence to an equilibrium choice. This update of the best response can be done in a reasonably distributed fashion as the users are able to individually estimate the parameters required to estimate their utility, as previously discussed.

Finally, we note that, given that the proposed game \( \Xi \) involves discrete strategy sets and utilities that depend on the identity of the players (and not just on the base station load as in traditional congestion games [15]), it becomes difficult to ascertain, analytically, the existence of the NE [15]. Nevertheless, as shown in Section IV, numerical and empirical results suggest that the proposed game admits an NE as no cases of non-existence were faced in our extensive simulations. Nonetheless, in cases of non-existence, after observing a cycling trend of strategies during best response iterations, the devices can simply revert to communicating via their nearest neighbor (either D2D or closest SCBS). Also, in general, the NE solution may be non-unique; however, for this paper’s scope, we mainly focus on the NE that results from a practical pre-determined initial network state. The analysis for other NE points is analogous and is omitted due to space limitations.

IV. SIMULATION RESULTS AND ANALYSIS

For simulations, we consider a square area of \( 2 \times 2 \) km in which we randomly deploy the communicating pairs and the SCBSs. The transmit power of the wireless users is set to \( P_i = 10 \) mW, \( \forall i \in N \), the downlink transmit power of the SCBSs is set to \( P_k = 1 \) W, \( \forall k \in K \), the noise level is \(-90\) dBm, and, unless stated otherwise, the cost parameters are set to \( \alpha_k = 0.1 \) and \( \beta_k = 0.1 \) for all pairs of SCBSs \( k \) and \( l \) (other values can also be used without loss of generality). For path loss, we set the propagation loss to \( \mu = 3 \) and the path loss constant to \( \kappa = 1 \). The maximum capacity of the backhaul between any two SCBSs \( k \) and \( l \) is set to \( \lambda_{k,l} = 5 \) connections, which is a typical load value for small cells [2].

Fig. 2 shows, for a network \( K = 4 \) SCBSs, the average achieved utility per communicating pair resulting from the proposed game as the number of pairs \( N \) varies. The performance is compared with two baseline cases: a) the case in which all pairs communicate via D2D and b) the case in which all pairs communicate via the small cell network’s infrastructure. Fig. 2 shows that, for all three approaches the average utility per pair decreases as the number of pairs \( N \) increases. For the all D2D case, this decrease is due to the increasing interference. For the proposed approach and the all SCBS cases, the decrease is due to both the increased interference and backhaul load. However, in Fig. 2, we can clearly see that the proposed approach outperforms the all D2D and all SCBS schemes, at all network sizes. Fig. 2 clearly demonstrates that, at all \( N \), the proposed noncooperative game approach yields a significant performance improvement, in terms of the average utility achieved per pair, of at least 79% (at \( N = 15 \) pairs) and 189% (at \( N = 2 \) pairs), relative to the all SCBSs and all D2D cases, respectively. The results seen in Fig. 2 also imply that, at the equilibrium, the network will be composed of a mixture of communicating modes.

Fig. 3 shows the impact of the backhaul cost on the communication mode via the variation of the average utility per pair of communicating users as the pricing parameters \( \alpha_k,l = \beta_k,l = \epsilon \) (for all pairs of SCBSs \( k \) and \( l \)) increase, for a network with \( K = 4 \) SCBSs and \( N = 6 \) pairs. This figure also shows the results for the case in which all users are connected via D2D. In Fig. 3, we can clearly see that, as the cost for backhaul usage increases, the average utility resulting from the proposed noncooperative game decreases. This is mainly due to the increase in the cost for utilizing the small cell network’s infrastructure. Indeed, as the pricing parameters increase, Fig. 3 clearly shows that more users will switch toward the all D2D case. We note that, the average utility resulting from the all D2D scheme remains constant for all the pricing parameters as this scheme does not utilize the backhaul. Nonetheless, Fig. 3 also shows that, even for reasonably high backhaul costs, i.e.,
The proposed noncooperative game still maintains a significant performance advantage over the D2D case of at least 25%, relative to the all D2D case.

The convergence of the proposed best response algorithm is assessed in Fig. 4 which shows the average number of iterations required until convergence to a Nash equilibrium of the game for a network with \( K = 4 \) SCBSs, as the number of pairs, \( N \), varies. Each iteration consists of a sequence of best response choices made by the users, depending on their observed network state. Fig. 4 shows that as the network size \( N \) increases, a larger number of iterations is needed to reach the equilibrium of the game. The average number of iterations ranges from around 4 at \( N = 2 \) pairs to around 5.3 at \( N = 15 \) pairs. The results in Fig. 4 clearly demonstrate that the proposed algorithm presents a low complexity as it allows the wireless devices to interact, in a distributed manner, while requiring a very reasonable average number of iterations before converging, even for medium-sized networks.

V. CONCLUSIONS

In this paper, we have proposed a novel game-theoretic approach for adaptive mode selection in wireless small cell networks with underlaid device-to-device communications. We have modeled the problem as noncooperative game in which pairs of communicating users interact so as to strategically decide on whether to communicate via the small cell network’s infrastructure or via direct device-to-device communications. In the proposed game, each transmitting user chooses its preferred communication mode while optimizing a utility that captures key metrics such as interference and backhaul constraints at the small cell network’s side. To solve this game, we have proposed a distributed best response-based algorithm using which the wireless devices can reach a Nash equilibrium of the game. Simulation results have shown that, in a practical small cell network, the equilibrium solution consists of a mixture of small cell-based links as well as device-to-device links. The results also show that the proposed game-theoretic scheme yields significant performance gains, in terms of the average utility per communicating users pair, when compared to traditional networks in which the users communicate only via the small cell network or only via device-to-device communication links.

REFERENCES