Game Theoretic D2D Content Dissemination in 4G Cellular Networks

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Abstract

The widespread proliferation of mobile devices has motivated Device-to-Device (D2D) communications as a means of cell offloading towards better Quality of Service (QoS) and higher energy efficiency. Although Wi-Fi networks have the lion's share regarding the D2D communications in the unlicensed spectrum, it is uncertain whether they constitute the best option as technology evolves. In particular, the increasing transmission data rates, the novel interference cancelation techniques, as well as the potential of centralized network support, stress the need for new Medium Access Control (MAC) protocols, especially in content dissemination scenarios, where all nodes share the same goal. In this article, we study the suitability of Wi-Fi technology in content dissemination scenarios with multiple available source nodes, and we propose two energy-aware game theoretic MAC strategies (a distributed and a network-assisted) as possible alternatives. Our simulation results show the effectiveness and the flexibility of our proposed solutions, highlighting the necessity for new MAC designs.

Index Terms

D2D Communications, Game Theory, MAC Protocols, Data Dissemination, Energy Efficiency

I. Introduction

According to Cisco, by the end of 2013, the number of mobile-connected devices will exceed the number of people on earth, while by 2017 there will be nearly 1.4 mobile devices per capita [1]. Nowadays, users crave an “any-time-any-place” connectivity, using cutting edge devices, such as smartphones, tablets, e-book readers and netbooks, among others. These high-end devices have bridged the gap between performance and hand-held size mobility, enabling the “on-the-move” use of bandwidth-hungry applications.

The vast proliferation of mobile devices, which is mainly attributed to the wide usage of social networks and multimedia sharing websites, has led to the introduction of 4G communications technologies, such as the Long Term Evolution Advanced (LTE-A), designed to provide higher data rates and increased network capacity. However, although the content popularity (video, music and gaming) is one of the main reasons for this tremendous growth, it raises important issues for the operators in terms of cell overloading, resource management and offered Quality of Service (QoS), thus revealing the need for effective traffic offloading.

A key advantage to address all these issues is the interest of specific (usually collocated) user groups in the same digital content. For instance, let us consider social events, such as music concerts or football games, where the organizers establish multimedia servers whose content (music video clips, former matches, commercials, etc.) can be accessed by the attendees. Another example, stemming from the everyday life, is related to the workplace, where the colleagues in a company/university could be potentially interested in downloading the same information, either educational or recreational.

Apparently, the aforementioned examples highlight the potential of avoiding the direct links by exploiting users’ proximity. In addition, the raising importance of energy efficiency in wireless communications is another crucial factor that stimulates the cell offloading and the reduction of the high-power direct LTE-A links. Hence, the battery constraints of the mobile devices along with the energy efficiency requirements set by the information and communication technology industry have motivated the development of Device-to-Device (D2D) communications which enable the direct, low-power communication between devices in the same area.

The concept of D2D communications as an underlay to LTE-A networks has been recently introduced [2], causing an intense debate on whether the communication should take place in the licensed or the unlicensed spectrum. In particular, communicating in the licensed frequency band offers important advantages to the operators, since they can control the interference, while maintaining full monitoring of the network. In addition, they are able to provide enhanced QoS for both the cellular and the D2D connections through efficient scheduling and radio resource management. Due to these reasons, D2D communications in the licensed spectrum have attracted a lot of attention and several research studies have focused on the coexistence issues of cellular and direct connections [3], [4].

Nevertheless, despite their inherent benefits, D2D licensed communications are still not the first choice for traffic offloading in cellular networks, since one third of total mobile traffic was offloaded to the fixed network through Wi-Fi connections in 2012 [1]. In addition, according to [5], the projected savings in network cost in 2016 are estimated up to 200 billion euros for the European Union. The most important advantages of exchanging data in the unlicensed spectrum are: i) the negligible interference to the cellular connections, and ii) the non-consumption of the cellular radio resources by the direct connections. These traits, along with the popularity of IEEE 802.11 Standard, have motivated the development of Wi-Fi Direct that enables devices to communicate at typical Wi-Fi speeds without requiring a wireless access point for their connection. However, the volatile topology of current networks stresses the need for new protocols that allow the efficient and equitable use of the system bandwidth at the Medium Access Control (MAC) layer.

In this article, we investigate MAC issues in wireless D2D content dissemination scenarios, where a set of nodes (hereafter denoted as *sources*) have already received the data information via direct LTE-A connections and they are responsible for further distributing the content to the remaining interested users (hereafter denoted as *sinks* or *destinations*) through D2D connections. In such scenarios, the existence of multiple source nodes generates conflicting situations, taking into account the selfish behavior of the wireless devices that want to save energy and maximize their battery lifetime. Bearing in mind the energy efficiency importance, we propose two game theoretic medium access strategies, based on energy-aware utility functions: i) a distributed approach for D2D communications where the nodes act individually, and ii) a coordinated approach, where the base station or evolved NodeB (eNB) occasionally intervenes to facilitate the dissemination procedure.

The rest of the article is organized as follows. First, we present some potential scenarios for wireless D2D content dissemination in cellular networks, along with related concepts such as the peer discovery and the network assistance. Next, we focus on MAC issues in content dissemination scenarios, reviewing the widely used Distributed Coordination Function (DCF) of IEEE 802.11 Standard and introducing our energy aware game theoretic strategies. Subsequently, we evaluate the performance of our proposals to justify their effectiveness and, finally, we summarize the main conclusions of our work.

II. D2D Content Dissemination: Scenarios and Challenges

The wireless content delivery [6] becomes more and more popular with the increasing penetration of portable devices. This constitutes the main motivation for the deployment of Content Delivery Networks (CDNs), which use multiple servers in several geographic locations to improve the delivery of static and streaming content. Hence, the wireless users can accelerate their access to the particular content with lower packet loss. Apart from the CDNs, the content dissemination can be further improved by exploiting the proximity between the users, especially in dense areas such as workplaces or big social events.

Figure 1 depicts a realistic setup for content dissemination in cellular networks assisted by D2D communications between adjacent users. In this particular scenario, there is a group of users interested in downloading the same content (e.g., music or video files) either from the central eNB or from distributed CDNs. The data dissemination takes place in two stages: During the first stage, there are n users (sources of the dissemination) that download the content using direct LTE links to the eNB or the closest CDN, while, in the second stage, these users disseminate the information to the remaining l users (sinks of the dissemination) in the network, using D2D connections.

Despite the obvious advantages of lower energy consumption for the terminals and cell offloading, several issues arise in the second phase of the dissemination due to the D2D operation of multiple transmitters in the unlicensed spectrum. Specifically, the mutual interference between the transmitting radio signals allows for only one transmission in every time slot, thus hindering the realization of multiple parallel transmissions. To that end, the implementation of a MAC mechanism is essential to coordinate the transmissions by many source nodes in the network.

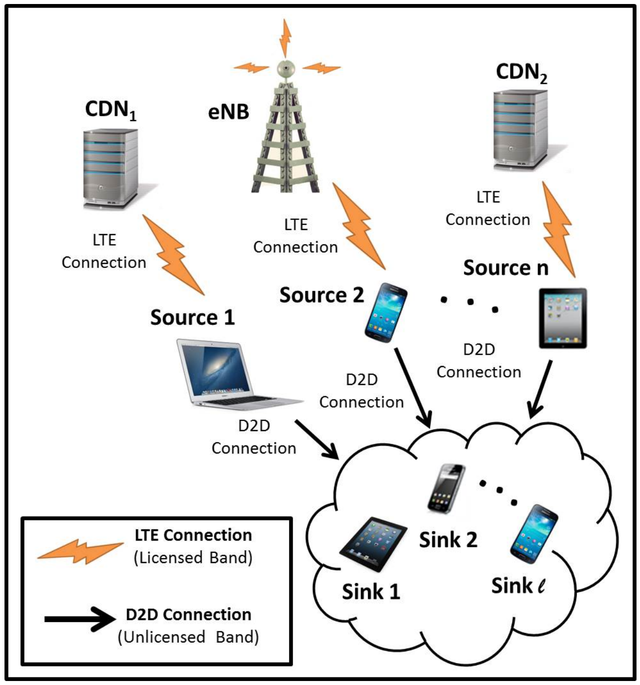

Fig. 1. D2D assisted content dissemination scenario

However, prior to the coordination problem, there are fundamental aspects that need to be addressed towards an efficient content dissemination. Peer and service discovery have been identified as key functions in D2D communications by recent studies [7]. This context information is even more important in dissemination scenarios, where the wireless devices should be aware of other devices in their proximity that either distribute or request the same content.

The aforementioned key functions are a major issue in distributed networks, taking into account the complicated communication process among the peer devices. In particular, peer discovery without central support is generally a very cumbersome and energy consuming procedure that may involve interaction with the end user. On the other hand, the existence of a central entity, such as the eNB in LTE technology, can significantly facilitate the peer discovery, exploiting the network context information [8]. Therefore, the same process assisted by the network can be more energy efficient and user friendly, while the intervention of a central controller could be also beneficial in the MAC layer of the D2D communication.

III. MAC Strategies for D2D Content Dissemination

Let us recall that the prevalence of IEEE 802.11 Standard has made Wi-Fi networks the first choice for traffic offloading in cellular networks. Operating in the unlicensed band has also important collateral advantages, since the D2D connections neither bind the system resources nor interfere with the LTE transmissions. Nonetheless, the coexistence of multiple source nodes in content dissemination scenarios may cause network congestion that needs to be resolved through appropriate and efficient MAC mechanisms. In the following sections, we briefly review the recently introduced Wi-Fi Direct along with the well known DCF of IEEE 802.11 and we propose two game theoretic MAC strategies for fast and energy efficient content dissemination applicable in distributed and centralized networks, respectively.

A. Wi-Fi Evolution

The Wi-Fi certification, issued by the Wi-Fi Alliance, guarantees backwards compatibility and interoperability between hardware devices that use the IEEE 802.11 Standard [9]. The DCF is the fundamental MAC technique of IEEE 802.11, based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method.

According to DCF, a station is required to sense the channel idle for a DIFS (DCF Inter Frame Space) interval before initiating a data transmission. If the channel is sensed busy during this interval, the transmission is postponed until the medium is sensed free. In addition, when the DIFS elapses, the station defers its transmission for an additional random backoff time, selected from a predefined Contention Window (CW), in order to minimize the probability of collision. With regard to the control packets, the transmission takes place after the stations have sensed the channel idle for a SIFS (Short Inter Frame Space) period of time, in order to distinguish the priorities between data and control plane. Last but not least, it is worth noting that the control packets are usually transmitted at a lower bit rate compared to data packets, to decrease the loss probability in the wireless medium.

The recently released Wi-Fi Direct enables the direct connection between Wi-Fi devices and facilitates the content transfer or sharing at typical Wi-Fi speeds [10]. In fact, only one of the devices needs to support Wi-Fi Direct in order to take the role of an access point and transmit data either to another device or to a whole group of devices (multicast mode). In this way, the communication maintains all the advantages of Wi-Fi (data rate, range, etc.) and becomes more flexible, bypassing the barriers of central operation.

However, it is still questionable whether Wi-Fi Direct is suitable for wireless D2D content dissemination of multiple sources, mainly because of the possible scenarios. In particular, there are two contingencies: i) only one of the source nodes becomes access point and undertakes the responsibility of broadcasting the information to the remaining interested users, and ii) all source nodes participate in the content dissemination, following the DCF rules. Regarding the former case, fairness issues arise, since the sender's role implies energy wasting and, therefore, it would be unjust having one node transmitting the total information. On the other hand, the participation of all sources in the dissemination carries all the disadvantages of the DCF, such as the idle slots due to the backoff counters in the network. In addition, the collision avoidance, which is the great advantage of DCF, tends to be eliminated as technology progresses (e.g., support of increased data rates, introduction of interference cancelation techniques), making the impact of collisions negligible for the network performance.

B. Game Theoretic D2D Content Dissemination

Game theory has come into play to study mathematical models of conflict and cooperation between intelligent rational decision-makers. In particular, during the last decade, game theoretic frameworks have been broadly proposed to investigate and model the medium access contention problem in wireless networks. The vast majority of these works focus on estimating the Nash Equilibrium (*NE*) point of a given game [11], which can be defined as a steady-state condition that corresponds to the mutual best response of all players. Hence, a strategy combination achieves the *NE* if no player can improve their utility by unilaterally deviating from her own strategy.

In our scenario, the global goal of all nodes is the successful and timely content dissemination. However, as we have already mentioned, the sender's role entails extra energy consumption, hence particular incentives should be provided to a particular user in order to take up this role. On the contrary, if no one transmits, the nodes will waste all their energy in idle state, thus hindering the data dissemination. To analyze this conflicting situation exploiting the context information, we model the access scenario as a *static non-cooperative* *game with complete information*, where each user selects the strategy that maximizes their own utility.

In game theory, a game Γ is represented by a tuple $\Gamma = (\mathcal{N}, (\mathcal{A}_i)_{i\in\mathcal{N}}, (U_i)_{i\in\mathcal{N}})$, where $\mathcal{N} = \{1, ..., n\}$ is the set of players. For each player $i \in \mathcal{N}$, $\mathcal{A}_i$ is a finite set of actions, while U_i is a *utility* (or *payoff*) function, given a set of actions. Our game consists of n players (*source* nodes) who decide if they transmit or not in each slot. Therefore, we use the following notations to be compatible with the game theory rules: $\mathcal{N} = \{1, ..., n\}$ and $\mathcal{A}_i = \{Transmit(T), Wait(W)\}$. Furthermore, in order to focus on the energy aspect of the problem, the utility function has been chosen such that to quantify the lifetime of the nodes. Defining $\mathcal{E}_{TOTAL}$ as the total energy amount available to each node and $\mathbf{E}[\mathcal{E}_i]$ as the average amount of energy consumed by the node's i wireless interface in each slot, the utility function of player i is given by $U_i = \frac{\mathcal{E}_{TOTAL}}{\mathbf{E}[\mathcal{E}_i]}$.

The strategic form of the proposed game is presented in Table I. The peer-to-peer nature and the symmetry of the problem have allowed us to formulate it as an n-player game, considering 2 macro-players: Player 1 represents node i, while Player 2 includes the rest $n-1$ nodes except for node i. The table's contents correspond to the Player's 1 energy costs with regard to the different contingencies in Player's 2 set. In particular, the values $\mathcal{E}_T$ and $\mathcal{E}_W$ represent the energy amounts spent during transmission and idle mode, respectively, while $\mathcal{E}_C$ corresponds to the cost in case that the dissemination does not proceed either due to collisions or idle slots. Although $\mathcal{E}_C$ does not denote actual energy consumption, it is of fundamental importance in our game formulation, since it indicates a long-term cost for the nodes, in the case that the dissemination is not completed. In the following sections, we study the impact of this parameter on the outcome of the proposed game.

TABLE I

Game Formulation for the Energy Costs of Player 1

<table>
<tr><td></td><td colspan="4">Player 2 (all the other n-1 nodes)</td></tr>
<tr><td rowspan="4">Player 1 (node i)</td><td></td><td colspan="2">T</td><td>W</td></tr>
<tr><td>T</td><td colspan="2">$\mathcal{E}_T + \mathcal{E}_C$</td><td>$\mathcal{E}_T$</td></tr>
<tr><td rowspan="2">W</td><td>Successful Transmission</td><td>Failed Transmission</td><td rowspan="2">$\mathcal{E}_W + \mathcal{E}_C$</td></tr>
<tr><td>$\mathcal{E}_W$</td><td>$\mathcal{E}_W + \mathcal{E}_C$</td></tr>
</table>

Given the system model, five possible outcomes are derived by Table I for each slot. Two of them result in successful transmissions, while the rest three lead to unsuccessful/failed slots, either idle or collided. In particular:

$s1$) Player 1 transmits - All nodes in Player 2 wait$\Rightarrow$ Successful transmission.

$s2$) Player 1 waits - Exactly one node of Player 2 transmits$\Rightarrow$ Successful transmission.

$f1$) Player 1 transmits - At least one node of Player 2 transmits$\Rightarrow$ Collision.

$f2$) Player 1 waits - At least two nodes of Player 2 transmit$\Rightarrow$ Collision.

$f3$) Player 1 waits - All nodes in Player 2 wait$\Rightarrow$ Idle slot.

The formulation of our problem in a strategic form reveals n *NE* in pure strategies. These *NE*, which are usually common in medium access games, correspond to the successful transmissions in the system, i.e., the case of only one node transmitting. However, the unfairness of pure strategies *NE*, along with the requirement for central coordination to achieve a collision-free network have motivated us to study the problem in the mixed strategies domain, in order to provide feasible and applicable solutions for distributed systems. In the following sections we introduce two game theoretic medium access policies: i) a distributed approach where the wireless nodes individually estimate the *NE* channel access probabilities according to the adopted energy-based utility function, and ii) a coordinated approach for infrastructure networks, where the nodes act individually to achieve the *NE*, while a central controller is occasionally used to facilitate the dissemination procedure.

C. Distributed Access Strategy

In the distributed access strategy, the nodes estimate their transmission probabilities in a totally decentralized manner, by calculating the *NE* with regard to the global utility function. The lack of efficient equilibria in pure strategies enables each source node (Player 1) to select a transmission probability, s_i, independently of the other $n-1$ nodes, which transmit with a common probability s_j due to the symmetry of the game. Considering the energy costs in the strategic form of the proposed game (Table I), the expected energy consumption for node i, $\forall i \in \mathcal{N}$ is calculated according to the probability of each of the five aforementioned potential contingencies of each slot and the respective energy consumption, as defined in Table I[1].

Following this formulation, the number of source nodes (n) in the network is the only required information for the estimation of the best response strategy in a distributed manner. Although this information can be provided by the eNB to the nodes in LTE, the context-awareness is currently an active research topic [13] and it is expected that, during the next few years, such kind of information will be available to all nodes even in decentralized systems.

D. Coordinated Access Strategy

The application of the proposed distributed game theoretic channel access scheme to the system potentially causes unsuccessful or empty slots in the network due to either collisions or idle slots when the nodes mutually transmit or wait, respectively. Hence, in order to bound the time needed to complete the content dissemination, we exploit the existence of a central entity (eNB) in the network and we propose a variation of the distributed access strategy, so called game theoretic coordinated channel access strategy, applicable in infrastructure networks.

In particular, in the coordinated approach we adopt the use of a central controller that deterministically provides the source nodes with channel access in case of k_f consecutive unsuccessful slots. More specifically, the controller is able to distinguish between idle slots, successful transmissions and collisions by sensing the energy level in the channel [14] and, accordingly, to select the node to transmit in case of k_f successive failed slots in the network. It is worth noting that unlike pure centralized systems where the central controller schedules the total transmissions, in our proposed strategy the controller intervenes only occasionally by polling one station, hence reducing the control packet overhead and preserving valuable energy. Although out of the scope of our work, the optimal selection of k_f constitutes a challenging research problem and its study would reveal intriguing tradeoffs for different topologies and scenarios. For instance, small values of k_f would lead in frequent polling, while big values of k_f imply higher degree of decentralization.

[1]For further technical details, we refer the interested reader in [12].

In our work, we examine a particular case study of $k_f = 2$ in order to investigate the changes that the existence of a central controller can bring in the game formulation and, consequently, in the protocol design. Hence, considering $k_f = 2$ and given the operation of the game theoretic coordinated medium access strategy, there are three possible cases before the controller's intervention:

i) 1^{st} slot: either successful or unsuccessful transmission.
ii) 2^{nd} slot: unsuccessful transmission in the first slot followed by either successful or unsuccessful transmission.
iii) 3^{rd} slot: unsuccessful transmissions in the first two slots and the central controller defines which node is going to transmit.

Apparently, the differentiation in the access strategy directly reflects to the utility function. In this particular case, the expected energy can be estimated considering a horizon of three slots, as the possibilities for each slot are no longer independent.

E. NE numerical results

Independently of the adopted access strategy, the *NE* probabilities (s^*) are derived by maximizing the utility function of the nodes (i.e., setting $\frac{\partial U_i}{\partial s_i} = 0$ or, equivalently, $\frac{\partial (\mathbf{E}[\mathcal{E}_i])}{\partial s_i} = 0$). Without loss of generality, let $\mathcal{E}_W = a \cdot \mathcal{E}_T$ and $\mathcal{E}_C = b \cdot \mathcal{E}_T$. In addition, having as a benchmark the IEEE 802.11g Standard [9], where the power level of the reception (P_R) and idle state (P_I) is the 70% of the transmission power (P_T) [15], we set $a = 0.7$. Regarding b, which is the weight factor of the energy cost in case that the dissemination does not proceed, we assume three different values ($b = 0.8$, $b = 1.0$ and $b = 1.2$), with respect to the impact that the standstill of the dissemination causes on the network. To this end, the *NE* transmission probabilities for different number of source nodes in the network are presented in Table II, where we observe that the *NE* transmission probability increases with b, as the nodes adopt an "aggressive" attitude to complete the process. Conversely, for fixed values of b, the transmission probability decreases as the number of competing source nodes increases in the network.

Regarding the coordinated strategy, we can see that the estimated values of *NE* are higher compared to the *NE* probabilities in the distributed strategy, under the same conditions and variables. This trend can be rationally justified by the presence of the central controller that acts as a safeguard to guarantee correct transmission after consecutive unsuccessful slots. Hence, the nodes are enabled to estimate higher transmission probabilities without taking into account the threat of collisions.

TABLE II
NE TRANSMISSION PROBABILITIES

	Distributed			Coordinated		
n	$s^*(b = 0.8)$	$s^*(b = 1.0)$	$s^*(b = 1.2)$	$s^*(b = 0.8)$	$s^*(b = 1.0)$	$s^*(b = 1.2)$
2	0.312	0.350	0.375	0.423	0.432	0.439
3	0.180	0.207	0.225	0.259	0.268	0.275
4	0.127	0.147	0.161	0.185	0.193	0.199
5	0.097	0.113	0.125	0.144	0.150	0.156
6	0.080	0.092	0.102	0.117	0.123	0.128
7	0.067	0.078	0.086	0.099	0.104	0.108
15	0.030	0.035	0.038	0.044	0.046	0.048
17	0.026	0.030	0.034	0.039	0.041	0.043
19	0.023	0.027	0.030	0.034	0.036	0.038

IV. Performance Aspects

A. Simulation Scenario

We have carried out Monte Carlo simulations to evaluate the performance of the proposed strategies. For our experiments, we consider a network topology similar to that of Fig. 1 and we focus on the second stage of the content dissemination, where the proposed game theoretic medium access techniques are applied to resolve the conflicts among the source nodes. In addition, the nodes are capable of applying random linear network coding to the packets to be transmitted, before further forwarding them. The file to be exchanged among the nodes is an RGB image of dimensions 256×256 (translated as 256 packets of 256 pixels). The resolution of the image and, consequently, the color "depth" of the pixels determine the packet size. In particular, a 4-bit "depth" (16-colors) results in 128 bytes, while an RGBA image (32-bit "depth") results in 1024 bytes packet payload. In our simulations we consider packet lengths of $PHY + MAC + NC_H + Payload$ bytes, where PHY and MAC are the physical and the MAC headers, respectively, with $PHY = 192$ bits and $MAC = 224$ bits. NC_H is the network coding header, while $Payload$ is the packet payload which varies between 128 and 1024 bytes with regard to the image resolution.

The coding of the packets is performed over a finite Galois Field - GF(2^8), since it has been proven to be sufficient for linear independence among the packets [16]. The specific field implies that the number of the encoding packets reflects to the number of the bytes in the encoding vector. If we use one generation of 256 packets, the extra overhead in each packet will be 256 bytes, which is huge especially for small size payloads. Therefore, we have chosen to create 16 generations of 16 packets each, which results in NC_H of 17 bytes in total (16 bytes for the encoding vector, 4 bits for the generation size and 4 bits for the generation identifier).

The time slot in our system has been selected equal to 20 μsec according to the IEEE 802.11g physical layer [9], while the power level values have been chosen according to wireless interface power consumption measurements [15]: $P_T = 1900$ mW[2], $P_R = P_I = 1340$ mW.

In order to evaluate our game theoretic approaches, we compare the proposed policies with the DCF of the legacy IEEE 802.11g [9] where backoff windows are used to reduce the collisions among the source nodes. We consider the multicast operation of IEEE 802.11g, since there is no need for transmitting explicit ACK packets, while we adopt a minimum contention window (CW_{min}) equal to 32. The simulation parameters are summarized in Table III.

B. Simulation Results

Figure 2 illustrates the simulation results with regard to the dissemination completion time of our proposed game theoretic access schemes versus the legacy IEEE 802.11 DCF. In this particular experiment, the number of source nodes varies between 2 and 19, assuming $b = 0.8$ and $Payload = 1024$ bytes. It is also worth noting that the completion time is independent of the number of sink nodes, as all sink nodes are located in the transmission range of the same sources, thus having a one-hop communication. In Fig. 2, we observe the

[2]The value of P_T has been selected as an average value of transmission consumed power, since it varies according to the Radio Frequency (RF) power level.

TABLE III
SIMULATION PARAMETERS

Parameter	**Value**	**Parameter**	**Value**
Packet Payload	128-1024 bytes	σ	20 μs
MAC+PHY Header	52 bytes	*NC Header*	17 bytes
Data Tx.Rate	54 Mb/s	*Generation Size*	16
CW_{min}	32	*DIFS*	50 μs
P_T	1900 mW	P_I, P_R	1340 mW

great time enhancement that the game theoretic approaches offer compared to the IEEE 802.11 Standard. In particular, the distributed access strategy improves the completion time up to 80% ($n = 2$), while the improvement under the coordinated approach exceeds 100%. With respect to the lowest dissemination completion time for the DCF ($n = 7$), the distributed and the coordinated approach achieve gains of 32% and 65%, respectively. The second worthwhile observation concerns the dependence between the dissemination completion time and the number of source nodes in the network. More specifically, the flexibility of game theoretic access strategies allows for their smoothest adaption in networks with many sources. Therefore, the dissemination completion time in our proposed schemes is not significantly affected by the total number of source nodes. On the other hand, we can see that the CW dynamics in IEEE 802.11 are not able to bound the dissemination completion time, a fact that can be intuitively conceived by considering the backoff mechanism operation. More specifically, in case of few (e.g., $n = 2$) or many (e.g., $n = 19$) source nodes in the network, the completion time increases by either idle slots or collisions, respectively, generating a fluctuation of approximately 34%.

Figure 3 presents the energy efficiency performance of the proposed strategies, assuming $n = 3$ and $n = 19$ sources in the network in order to study the scalability of our policies. In this point, it should be clarified that the energy efficiency is calculated by the ratio of the number of useful bits (i.e., packet payloads) that have been disseminated in the network over the total energy consumption of the devices. With regard to the case where $n = 19$, we can see that the gain we achieve applying the distributed game theoretic access strategy

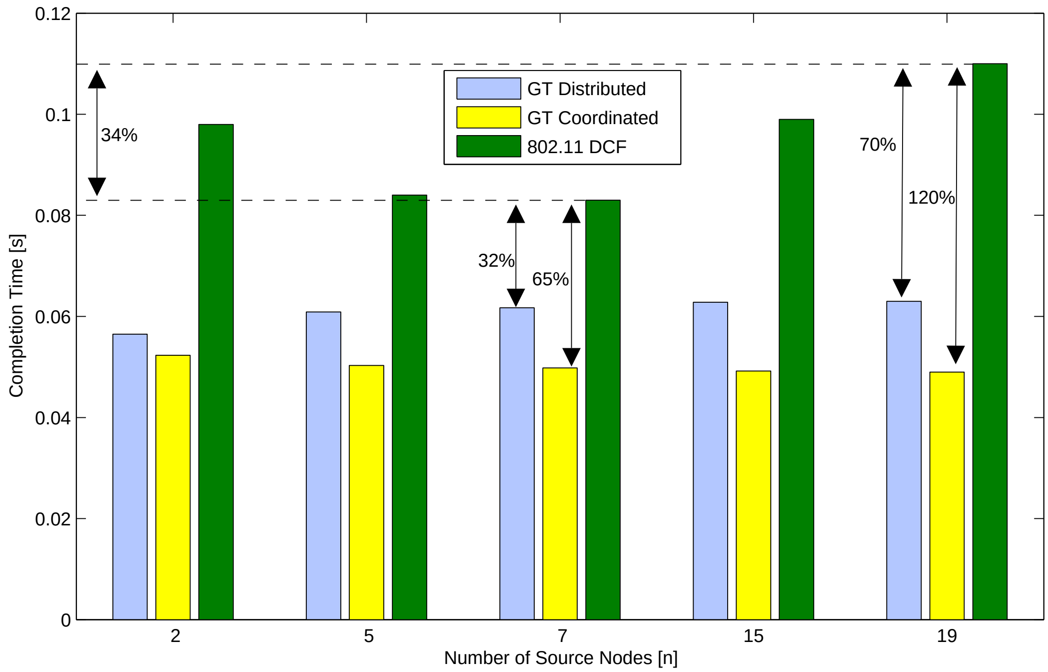

Fig. 2. Data dissemination completion time vs. Number of source nodes ($b = 0.8$, $Payload = 1024$ bytes)

remains steadily over 100% compared to the DCF, while in the coordinated policy the gain reaches up to 300%. On the other hand, we observe a slightly different trend in the case of few source nodes in the network ($n = 3$). In this case, the gain of the distributed access strategy over the IEEE 802.11 Standard decreases as the packet payload grows, even though the initial gain for payload of 128 bytes reaches 100%. This fact can be explained by considering again the DCF implementation, which is designed to avoid collisions. This design is beneficial for packets of high payload but, on the contrary, creates idle slots in the network, thus affecting the energy performance for small packet payloads. Our proposed adaptive game theoretic strategies handle these points efficiently, hence dealing effectively with energy efficiency issues.

V. Conclusion

In this article, we have focused on MAC issues in D2D communication scenarios for wireless content dissemination. We have introduced two game theoretic strategies (a distributed

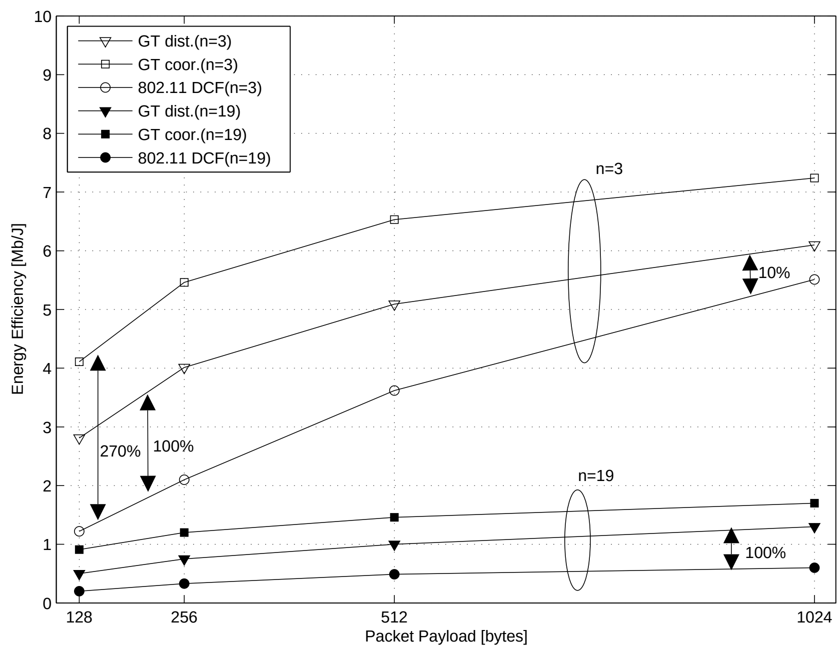

Fig. 3. Energy efficiency of game theoretic access strategies vs. IEEE 802.11 DCF ($b = 1.0$, $l = 1$)

and a coordinated one) that estimate the *NE* transmission probabilities in networks with multiple sources. Our simulation results have shown that our proposed MAC strategies significantly outperform the IEEE 802.11 DCF, reducing the content dissemination completion time, while at the same time they increase the energy efficiency in the network. These results can be used as guidelines for novel MAC protocol design, taking into account that traditional approaches - designed mainly for collision avoidance in wireless networks - tend to be obsolete as technology evolves.

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