Abstract—In this paper we propose a game theoretic medium access strategy for data dissemination in wireless networks. In data dissemination scenarios, where the global target is the spreading of a particular content in a network, the main goal of the wireless nodes is twofold: i) to guarantee a low completion time, and ii) to increase their battery lifetime. Hence, the existence of many active sources in the network implies conflicting situations, since the nodes have to balance a trade-off between proceeding the dissemination and saving energy. To model these conflicts, we introduce a $n$-player medium access game using energy-based utility functions. Both analytical and simulation results are provided to evaluate our proposed strategy.

Index Terms—Energy Efficiency; Nash Equilibrium; Data Dissemination; Network Coding.

I. INTRODUCTION

Recent studies have indicated the importance of non-voice traffic in wireless networks. In particular, data traffic, video and file sharing are increasingly dominating the mobile data traffic and they are expected to account for more than 95% of the total data traffic by 2015 [1]. Because of this trend, data dissemination has attracted great attention, especially in the context of wireless networks [2]-[6]. In such scenarios, the dissemination of a digital content constitutes the common goal of all nodes in the network.

The problem of data dissemination in ad-hoc networks is further complicated due to the instability of the wireless links, as well as the lack of any infrastructure. To combat these issues, network coding [7] has been recently introduced as an alternative routing mechanism in the network layer. Network coding has the potential of achieving the multicast capacity [8] by exploiting the broadcast nature of the wireless medium and facilitating the elimination of control mechanisms (i.e. acknowledgement packets) in the network.

The particular treats of network coding have enabled its application in several data dissemination studies [9]-[11]. In addition, Lucani et al. [11] recently demonstrated that the completion time of the dissemination is expedited by assigning higher transmission priority to the node with the greatest impact\(^1\) on the network. Motivated by these works and inspired by the recent developments in game theory [12], we proposed in [13] a game-theoretic Medium Access Control (MAC) scheme to resolve the conflicts between two source nodes in data dissemination scenarios. Game theory has been proven a reliable tool for the specific problem, considering the selfish nature of the nodes along with their conflicting interests, since all nodes have profit of the dissemination completion, but at the same time they aim at preserving their individual energy status. However, the consideration of two source nodes in [13] restricts the application of the scheme in realistic wireless networks, where the existence of multiple source nodes can not be neglected.

To overcome the above limitations, this paper introduces a general $n$-player game theoretic medium access strategy for data dissemination in wireless networks where many source nodes have conflicting interests. We propose a strategic game, where the goal of each player\(^2\) is to identify a steady state (Nash Equilibrium - NE [14]) in order to balance a trade-off between saving energy and proceeding the data dissemination. Our contribution is summarized in the following:

1) The proposed game formulation can be successfully applied to realistic networks where multiple sources compete for access to the wireless channel.

2) We present an analytical probabilistic model to evaluate the network performance under the NE, while we show that the proposed strategy is still more energy efficient than other, well-known, approaches.

The rest of this paper is organized as follows. Section II briefly reviews the State of the Art in game theoretic applications in wireless networks, especially in the MAC layer. In Section III we introduce the system model, the game formulation and the analytical model for the system performance. The validation of the model along with numerical results are provided in Section IV. Finally, Section V concludes the paper.

II. RELATED WORK

During the last decade, game theoretic frameworks have been widely used to investigate the medium access problem in wireless networks using contention-based access protocols. In their seminal work [15], MacKenzie and Wicker proposed a game theoretic layout to model the behavior of selfish nodes in slotted Aloha systems. The same authors extended their

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\(^1\)Impact is defined as the number of sink nodes that receive a new packet in one transmission.

\(^2\)Please note that the terms “player” and “node” are used interchangeably in this paper.
We focus our attention in the second phase of the dissemination, where we further assume that the transmission ranges of the source nodes are partially overlapped and each source node affects the same number of sink nodes, thus having equal and, at the same time, the greatest impact on the network. However, the mutual interference experienced among the source nodes prevents the parallel simultaneous transmissions in the network. Hence, one transmission is considered successful, if and only if exactly one node transmits in a specific slot. Apparently, MAC mechanisms have to be proposed in order to resolve the conflicting situations caused by the existence of many nodes with the greatest impact on the network.

Regarding the data transmissions, random linear network coding (RLNC) techniques [24] are adopted to facilitate the data dissemination. In particular, the nodes transmit linear combinations of the packets instead of just forwarding the information flows, thus eliminating the need of control packets (i.e. acknowledgements). However, an extra overhead is added to the packets, since the network coding header contains information necessary for the decoding process, such as the coding vector, the generation size and the generation identifier [25].

Figure 1. System Model

### III. Game Theoretic Medium Access Strategy: N-Player Version

In this section, we present the system model, our game formulation and the analytical model for the theoretical estimation of the dissemination completion time.

#### A. System Model

In our model, we adopt a slotted system, where the node with the greatest impact on the network gains the channel access to transmit in each slot. The considered network, depicted in Fig. 1, consists of: i) a Base Station (BS) that holds the digital content to be disseminated (for example video/image/audio files), ii) a set of \( n \) nodes inside the transmission range of the BS, and iii) a set of \( l \) nodes outside the BS’s coverage area. The data dissemination is conducted in two distinct phases: In the first phase, the BS broadcasts the digital content to the \( n \) nodes inside its coverage area, while in the second phase, the \( n \) nodes that have already received the information (so called source nodes) forward the data to the rest \( l \) interested nodes (so called sink nodes).

As a result, the data dissemination scenario can be modeled as a non-cooperative game where the nodes (both source and sink nodes) are players and the data transmission is the action at each slot. Each node aims at maximizing its perceived utility.

#### B. Game Formulation

In our scenario, the global goal of all nodes is the completion of the data dissemination. However, the transmitter’s role implies energy wasting, hence particular incentives should be provided to a particular player, in order to take up this role. On the other hand, if no one transmits, the nodes will waste all their energy in idle state, thus hindering the data dissemination. To analyze this conflicting situation, we model the access scenario as a static non-cooperative game with complete information [12], where each player selects the strategy that maximizes her own utility.

In game theory, a game \( \Gamma \) is represented by a tuple \( \Gamma = (N, A = (\alpha_i)_{i \in N}, (U_i)_{i \in N}) \), where \( N = \{1, \ldots, n\} \) is the set of players. For each player \( i \in N \), \( \alpha_i \) 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
Both players transmit:

The expected energy wasted for node $i$ is given by:

$$U_i = \frac{E_{TOTAL}}{E[E[i]]}.$$  

(1)

The strategic form of the proposed game is presented in Table I. We have formulated our problem as a game with 2 players, where player 1 represents node $i$, while player 2 includes the rest $n-1$ nodes except for node $i$. Regarding the table’s contents, the costs $E_T$ and $E_W$ correspond to the energy amounts spent during transmission and idle mode, respectively, while $E_C$ represents the cost in case that the dissemination does not proceed either due to collisions or idle slots.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>STRATEGIC FORM OF THE PROPOSED GAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Player 1 (node i)</td>
<td>Player 2 (all the other $n-1$ nodes)</td>
</tr>
<tr>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>W</td>
</tr>
<tr>
<td>W</td>
<td>T</td>
</tr>
<tr>
<td>W</td>
<td>W</td>
</tr>
</tbody>
</table>

Since, as we have already mentioned in the beginning of this subsection, there is no efficient symmetric equilibrium in pure strategies that the nodes could follow without the assistance of a central scheduler, each source node selects a transmit probability, $s_i$, independently of the others. Therefore, given the strategic form of the proposed game, the expected energy wasted for node $i$, $\forall i \in N$, is given by:

$$E[i] = p^a \cdot (E_T + E_C) + p^b \cdot E_T + p^c \cdot (E_W + E_T) + p^d \cdot (E_W + E_C) + p^d \cdot (E_W + E_C).$$

(2)

where $p^a$, $p^b$, $p^c$, and $p^d$ are used to denote the probabilities of having the following possibilities $a$, $b$, $c$, $1$, $c$, $2$, and $d$, respectively:

- **a. Both players transmit**: The nodes waste energy $E_T$ for the transmissions, while the collision of the packets adds an extra cost $E_C$, since the dissemination does not proceed.
- **b. Player 1 transmits - Player 2 waits**: The transmitting node wastes energy $E_T$ for the transmission, while the rest backoff nodes consume the minimum energy $E_W$, since they are in idle state.
- **c. Player 1 waits - Player 2 transmits**: Since player 2 includes a set of $n-1$ nodes, the following possibilities are derived:
  1. If the transmission is *successful*, i.e. exactly one out of the $n-1$ nodes transmits, player 1 wastes $E_W$ while player 2 consumes energy $E_T$ due to the successful transmission.
  2. If the transmission is *unsuccessful*, i.e. there is a collision among the $n-1$ nodes, both players are burdened with an extra cost $E_C$, since the dissemination does not proceed.
- **d. Both players wait**: The nodes waste the minimum amount of energy $E_W$ since they remain idle, but they also have an extra cost $E_C$, since the dissemination does not proceed.

The probabilities $p^a$, $p^b$, $p^c$, $p^d$ can be further analyzed and calculated as:

$$p^a = s_i \cdot (1 - s_j^{n-1}), \forall i, j \in N, n \in \mathbb{Z}, n \geq 2 \quad (3)$$

$$p^b = s_i \cdot s_j^{n-1}, \forall i, j \in N, n \in \mathbb{Z}, n \geq 2 \quad (4)$$

$$p^c = s_i \cdot (n-1) \cdot s_j^{n-2}, \forall i, j \in N, n \in \mathbb{Z}, n \geq 2 \quad (5)$$

$$p^d = s_i \cdot s_j^{n-1}, \forall i, j \in N, n \in \mathbb{Z}, n \geq 2 \quad (6)$$

For simplicity reasons and without loss of generality, let us assume that $E_W = a \cdot E_T$ and $E_C = b \cdot E_T$. The partial derivative of the utility function $U_i = \frac{E_{TOTAL}}{E[E[i]]}$, with respect to $s_i$, is equal to:

$$\frac{\partial U_i}{\partial s_i} = \frac{E_{TOTAL}}{(E[i])^2} \cdot \frac{\partial (E[E[i]])}{\partial s_i}$$

(8)

The best response of $s_i$ to the strategy $s_j$ - and consequently the NE $s^*$ - is given by setting $\frac{\partial U_i}{\partial s_i} = 0$ or, equivalently (from Eq. (8)), $\frac{\partial (E[E[i]])}{\partial s_i} = 0$. Therefore,

$$\alpha \cdot (s_j - 1) \cdot (s_j^{n-1} - s_j + 1) + b \cdot (n \cdot s_j + s_j - 2) \cdot s_j + (s_j - 1)^2 = 0 \quad (9)$$

**Theorem - NE Existence**: In our game theoretic medium access strategy there always exists a NE.

**Proof of Theorem**: Let $f(x) = \frac{\partial (E[E[i]])}{\partial s_i}$. The function $f(x)$ is defined and continuous on the interval (0, 1). Moreover,

$$f(0 + \varepsilon) < 0, \forall n \geq 2, \varepsilon > 0 \quad (10)$$

$$f(1 - \varepsilon) > 0, \forall n \geq 2, \varepsilon > 0 \quad (11)$$

Therefore, according to Bolzano’s Theorem, there exists at least one point $c \in (0, 1)$, such that $f(c) = 0$. ■

As a use case, we consider the IEEE 802.11g Standard [26], where the power level of the reception ($P_R$) and idle state ($P_I$) corresponds to the 70% of the transmission power ($P_T$) [27], and hence we set $a = 0.7$. Table II presents the transmission probabilities in the NE for different number of players (source nodes) in the network, assuming three different key values of $b$, which is the weight factor of the energy cost in case that the dissemination does not proceed. In particular, we assign to $b$ the values of 0.8, 1.0 and 1.2, which correspond to cost smaller, equal or higher of the transmission cost, respectively. In the table, we can see that the transmission probability in NE increases with $b$, since the nodes adopt an “aggressive” attitude to complete the process. On the contrary, the transmission probability decreases as the number of competing source nodes increases in the network.

We use the notation $\bar{s}_i$ to denote the complementary probability of $s_i$, i.e. $\bar{s}_i = 1 - s_i$.  

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3We use the notation $\bar{s}_i$ to denote the complementary probability of $s_i$, i.e. $\bar{s}_i = 1 - s_i$.  

---

---
TABLE II

<table>
<thead>
<tr>
<th>n</th>
<th>(s^*(b = 0.8))</th>
<th>(s^*(b = 1.0))</th>
<th>(s^*(b = 1.2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.180</td>
<td>0.207</td>
<td>0.225</td>
</tr>
<tr>
<td>4</td>
<td>0.127</td>
<td>0.147</td>
<td>0.161</td>
</tr>
<tr>
<td>5</td>
<td>0.097</td>
<td>0.113</td>
<td>0.125</td>
</tr>
<tr>
<td>6</td>
<td>0.080</td>
<td>0.092</td>
<td>0.102</td>
</tr>
<tr>
<td>7</td>
<td>0.067</td>
<td>0.078</td>
<td>0.086</td>
</tr>
</tbody>
</table>

C. Completion Time Analytical Model

The total completion time\(^4\) can be represented as:

\[
E[T_{total}] = E[R] \cdot (p_s \cdot T_{tr} + p_i \cdot \sigma + p_c \cdot T_c)
\]  

(12)

where \(E[R]\) is the average number of slots that are needed in order to accomplish the data dissemination. The probabilities of having a successful transmission, an idle slot or a collision are given by \(p_s, p_i\) and \(p_c\), respectively. Moreover, the terms \(T_{tr}\), \(\sigma\) and \(T_c\) represent the duration of a transmission, an empty slot and a collision, respectively. The slot time \(\sigma\) is a system parameter, while \(T_{tr}\) depends on the packet length and the transmission data rate. Furthermore, we consider that \(T_c = T_{tr}\), since the collisions are detected on the receiver’s terminal.

The term \(E[R]\) can be further analyzed as:

\[
E[R] = \frac{R_{ideal}}{p_s}.
\]  

(13)

where \(R_{ideal}\) is the minimum number of slots in case of ideal scheduling among the nodes, i.e. contention-free scheme. As it has been already demonstrated in [11], it can be written as:

\[
R_{ideal} = M \cdot \left\lfloor \frac{l}{J} \right\rfloor,
\]  

(14)

where \(M\) is the number of the information data packets, \(l\) is the number of the sink nodes, and \(J\) represents the impact of the source nodes on the network.

Given that the source nodes estimate a common transmission probability \(s^*\) according to the NE, we are able to derive closed-form formulas for the probabilities \(p_s, p_i\) and \(p_c\). The probability that at least one of the \(n\) sources attempts to transmit in a given slot can be expressed as:

\[
p_{tr} = 1 - (1 - s^*)^n,
\]  

(15)

while the probability of a successful transmission, i.e. one station transmits conditioned on the fact that at least one station transmits, is given by:

\[
p_{s|tr} = \frac{n \cdot s^* \cdot (1 - s^*)^{n-1}}{1 - (1 - s^*)^n}
\]  

(16)

Therefore, the probabilities of having a successful \(p_s\), collided \(p_c\) or idle \(p_i\) slot can be written as:

\[
p_s = p_{tr} \cdot p_{s|tr}
\]  

(17)

\[
p_c = p_{tr} \cdot (1 - p_{s|tr})
\]  

(18)

\[
p_i = 1 - p_{tr}
\]  

(19)

Accordingly, applying the formulas (12)-(19) in a particular network topology, we are able to theoretically estimate the expected time of disseminating a given number of information data packets.

IV. PERFORMANCE EVALUATION

We have implemented a custom-made, event-driven C++ simulator that executes the rules of the proposed strategy. Monte carlo simulations have been carried out to evaluate the performance of our policy and further validate the analytical results. In the following subsections we present the simulation scenario, along with the performance results.

A. Simulation Scenario

We consider three different scenarios (Fig. 2) with 3, 4 and 5 sources, respectively, where each source affects 2 sink nodes, thus having the same and, at the same time, the greatest impact on the network. In our experiments, the goal is the dissemination of a bunch of data packets that constitute 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 length. In particular, a 2-bit “depth” (grey-scale) results in 64 bytes, while an RGBA image (32-bit “depth”) results in 1024 bytes packet payload. In our simulations we consider packet lengths of \(PHY + MAC + NC_H\) + \(P\) 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 \(P\) is the packet payload which varies between 64 and 1024 bytes with regard to the image resolution.

Network coding techniques are used to eliminate the necessity of acknowledgements. In particular, we assume that the sink nodes need 256 linearly independent packet combinations in order to extract the total information. The coding of the packets is performed over a finite Galois Field - \(GF(2^8)\), while we have chosen to create 16 generations of 16 packets each, which results in network coding header \((NC_H)\) 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 duration has been selected equal to 20\(\mu\)s according to the IEEE 802.11g physical layer specifications [26], while we consider a medium transmission data rate of 24 Mb/s. Regarding the power consumed by the wireless interface, we have chosen the following values, based on the measurements conducted by Ebert et al. [27]: \(P_T = 1900mW\), \(P_R = P_I = 1340mW\). The simulation parameters are summarized in Table III.

B. Performance Results

Figure 3 presents the performance results (both analytical and numerical) with regard to the completion time of our proposed distributed game theoretic (GT) policy. First, we can see that the simulation results almost perfectly match
Fig. 2. Simulation Scenario with a) 3 source nodes b) 4 source nodes, and c) 5 source nodes

TABLE III
SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Payload</td>
<td>128-1024 bytes</td>
<td>$\sigma$</td>
<td>20 $\mu$s</td>
</tr>
<tr>
<td>MAC+PHY Header</td>
<td>52 bytes</td>
<td>NC Header</td>
<td>17 bytes</td>
</tr>
<tr>
<td>$Ts$Rate</td>
<td>24 Mb/s</td>
<td>Generation Size</td>
<td>16</td>
</tr>
<tr>
<td>$P_T$</td>
<td>1900 mW</td>
<td>$CW_{min}$</td>
<td>32</td>
</tr>
<tr>
<td>$P_R$</td>
<td>1340 mW</td>
<td>$P_I$</td>
<td>1340 mW</td>
</tr>
</tbody>
</table>

is huge, since the impact of collisions on the completion time is almost negligible. On the other hand, as the packet payload increases, the gain over the IEEE 802.11g decreases. This fact can be intuitively conceived, as the transmission of big data packets in relatively low data rates makes the collisions particularly harmful for the network performance. Therefore, these results might constitute a useful guide for the design and implementation of next-generation protocols, where the impact of collisions might be eliminated by transmitting with high data rates or applying advanced interference cancelation techniques, such as analog network coding [28].

V. CONCLUSION

In this paper we presented a network coding-aided $n$-player game theoretic medium access strategy for data dissemination in wireless networks. The proposed MAC policy efficiently resolves the potential conflicting situations caused by identical interests among wireless nodes in data dissemination.
scenarios. The common nature and the selfish behavior of the nodes inspired us to model the access problem as a non-cooperative game with complete information, where all nodes transmit according to a commonly estimated Nash Equilibrium (NE). In addition, the adopted energy-based utility function led to an energy efficient MAC policy, while we further demonstrated that the completion time for the dissemination does not strongly depend on the number of sources in the network. Our future work will focus on the application of various network coding schemes (physical, MIMO, etc.) in our scenarios.

ACKNOWLEDGMENTS

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