ANGEL: Analog Network-Coded Game Theoretic Energy Efficient Layout for Data Dissemination

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Abstract—In this paper we present an analog-network-coding-aided layout for data dissemination. We propose a game theoretic Medium Access Control (MAC) protocol that exploits the recent developments in network coding domain to enhance the system performance. In particular, random linear network coding is used to eliminate the need of exchanging control packets, while ZigZag decoding techniques are applied to resolve the data packet collisions. Our proposed protocol is proved to enhance both the provided Quality of Service and the energy efficiency of the system.

Index Terms—Medium Access Control (MAC); Nash Equilibrium; Network Coding; Green Communications; Zig Zag.

I. INTRODUCTION

The concept of data dissemination is becoming increasingly popular, since the distribution of digital content (video/audio files, images, etc.) constitutes the base of the information society. Furthermore, data dissemination in wireless networks provides fertile ground for exploitation of network coding techniques that accommodate the communication with higher robustness, diversity and enhanced Quality of Service (QoS).

Network coding (NC) [1] has been evolving as a quickly widespread technique that enables the intermediate nodes in a network to process the incoming information flows in order to enhance the system performance and provide the communication with a lightweight control information exchange. Recent developments in NC field focus on the physical part of the communication. In particular, analog network coding (ANC) techniques [2] have been introduced to exploit the packet collisions and achieve interference cancelation in wireless networks. In this context, ZigZag [3] was one of the fundamental works that had significant effect in the research community. Applying ZigZag, the decoding of the packets of two successive collisions becomes feasible, provided that the collision offsets $\Delta_1$ and $\Delta_2$ are different. In ZigZag, a collision offset $\Delta$ is defined as the interference-free chunk of the packet that is received in the beginning of non-aligned collisions. Therefore, the receiver can use the correctly received part of the data to decode the interfered bits of the collided packets.

In our previous work [4] we introduced a random-linear-network-coded game theoretic MAC protocol for data dissemination by adopting energy-based utility functions that intrinsically imply power awareness. We proposed a Dissemination Access Game to identify a state of balance (Nash Equilibrium Point - NEP) between saving energy and proceeding the dissemination in topologies where two source nodes have the greatest impact1 on the network. However, the recent advances in network coding domain have inspired us to adopt ANC techniques to exploit the potential benefits of the collisions in data dissemination schemes.

In this paper we propose an Analog-Network-Coding-aided Game Theoretic Energy Efficient Layout (ANGEL) for data dissemination in wireless networks. On the top of our former game theoretic derivations, we apply ZigZag coding techniques to turn the collisions of data packets into a benefit for the network performance. The contribution of our work is summarized on the following:

1) We propose a novel MAC protocol that exploits to the maximum the collisions in a wireless network.
2) We exploit the benefits of both digital and analog network coding to enhance the network performance.
3) We analytically evaluate the performance of our scheme.

The rest of this paper is organized as follows. Section II presents our system model, while in Section III we introduce ANGEL. The analytical model of our scheme is included in Section IV. The simulation scenario and the performance evaluation of our protocol are provided in Section V. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

We consider a wireless network topology with a Base Station (BS) that holds the total amount of information to be disseminated and a set of nodes interested in the available data set. Since not all the stations are inside the coverage area of the BS, the dissemination takes place in two phases: i) the BS broadcasts the data packets to the nodes inside its transmission range (so called inside or source nodes), and ii) the inside nodes that have already obtained the data forward the information to the nodes outside the range of the BS (so called outside, sink or destination nodes). Our system model is depicted in Fig. 1. We focus on the second phase of the dissemination, where we assume that there are two nodes that have received the whole information and a set of $L$ outside nodes that desire the disseminated data. The transmission

1Impact is defined as the number of innovative packets delivered in each transmission.
ranges of the two sources are partially overlapped with a subset of nodes located at the intersection of the coverage areas, while both source nodes affect the same number of sink nodes, thus having the highest impact on the network.

We further assume a slotted system where the node with the greatest impact transmits in every slot, since this technique has been proved to accelerate the dissemination process [5]. Apparently, the existence of two source nodes with the highest impact generates conflicting situations that are resolved using game theoretic techniques which enhance the system performance, as we have already demonstrated in our previous work [4].

Regarding the data transmissions, random linear network coding (RLNC) [6] techniques are used to facilitate the dissemination and eliminate the need of exchanging acknowledgment control packets. In addition, the nodes are able to perform ZigZag decoding techniques on the received packets, thus having benefit from the collisions incurred in the network. However, it is worth noting that the digital network coding techniques charge the communication with an extra overhead to the packets due to the network coding header which is necessary for the packet decoding, while the adoption of analog network coding techniques presupposes the acceptance of the assumptions in [3].

### III. Proposed Analog-Network-Coded Game Theoretic Energy Efficient Layout (ANGEL) for Data Dissemination

ANGEL is introduced to coordinate the transmissions of a set of nodes that broadcast the same content to a group of sink nodes carrying ZigZag decoding capabilities. Therefore, it can be perfectly applied to our model and, particularly, in the second phase of the dissemination.

First, in the beginning of each slot, the two source (inside) nodes select their transmission probabilities \( s_i \) by estimating the NEP of a non-cooperative game with complete information using energy-based utility functions. The application of energy-based functions guarantees the energy efficiency of the system, without compromising the completion time for the dissemination, as we have already shown in [4]. Accordingly, depending on the chosen probabilities, we have the following possibilities for a given slot:

1) **Idle slot**, if both nodes remain idle.
2) **Successful transmission**, if exactly one of the nodes transmits.
3) **Collision**, if both nodes transmit.

Upon a collision, the destination nodes initiate the ZigZag decoding procedure by transmitting a Negative Acknowledgment (NACK) message to the source nodes, after sensing the channel idle for SIFS (Short Inter Frame Space) period of time. The simultaneous transmission of NACK packets can be effectively handled by our protocol, since it has been recently proved that overlapping NACKs can be correctly recognized at the receiver side, given that the packets are identical. In particular, even in the presence of collisions, the Signal-to-Noise-Ratio (SNR) of the received signal may still be higher than a threshold, thereby allowing its correct recognition [7]. Back to our case, receiving the NACKs, the source nodes are informed that the packets have collided and retransmit the same coded packets in the next slot with transmission probability equal to one \( s_i = 1 \), thus resulting in a second, useful collision. Therefore, the sink nodes are able to extract both packets by applying ZigZag techniques to the two collision sets.

Data transmissions in ANGEL take place after a random DIFS (Distributed Inter Frame Space) time, uniformly distributed between SIFS and DIFS. In this way, it is ensured that collisions will not be perfectly synchronized, without trespassing the rule that control packets have higher priority compared to data packets. Moreover, ANGEL is backwards compatible with several CSMA standard protocols with the modification that the DIFS period in ANGEL is not used for actual sensing of the channel, since collisions are beneficial for our protocol.

For the sake of clarity, an example of frame sequence in ANGEL is depicted in Fig. 2. In particular, the protocol operates as follows:

1) At instant \( t_1 \), source 1 decides to transmit the network-
coded packet $A$ after a random $DIFS_1$ time. Source 2 decides to stay idle and, therefore, the destination nodes are able to extract packet $A$.

2) At instant $t_2$ source 1 remains idle, while source 2 transmits the network-coded packet $B$ after a random $DIFS_2$ time. Since there is only one transmission, the destination nodes are able to extract packet $B$.

3) At instant $t_3$ both sources 1 and 2 decide to remain silent, thus resulting in an idle slot in the system.

4) At instant $t_4$ both sources 1 and 2 decide to transmit the coded packets $C$ and $D$ after different random $DIFS$ times, $DIFS_1$ and $DIFS_2$, respectively.

5) At instant $t_5$ the destination nodes are not able to extract the received packets and, hence, they transmit a $NACK$ packet after sensing the channel for $SIFS$ period of time.

6) At instant $t_6$ the source nodes extract the received overlapped $NACK$s [7] and retransmit the same packets $C$ and $D$ after $DIFS_1$ and $DIFS_2$, respectively.

7) At instant $t_7$ the destination nodes are able to extract both packets $C$ and $D$ by using ZigZag decoding techniques to resolve the two consecutive collisions with different $\Delta$ offsets.

IV. PROTOCOL ANALYSIS

A. Completion Time

The minimum number of slots ($R_{ideal}$) in collision-free schemes, i.e. ideal scheduling among contention nodes, is simply calculated, since it depends on a set of known parameters, such as: i) the total number of the information data packets ($M$) ii) the number of $sink$ nodes ($L$), and iii) the impact of the $source$ nodes in the network ($J$). Therefore, it has already been proved in [5] that the ideal number of slots for the data dissemination can be expressed as $R_{ideal} = M \cdot \lfloor L/J \rfloor$.

On the other hand, in realistic MAC schemes, this ideal number is affected by the actual contention between the nodes, which results in collided and idle slots. Nevertheless, in ANGEL, the collisions can be exploited as a benefit for the network. Hence, the average number of slots needed to complete the data dissemination is given by $E[R] = R_{ideal}/(p_s + p_c)$, while the average total completion time can be represented as:

$$E[T_{total}] = E[R] \cdot ((p_s + p_{pos}) \cdot (DIFS + T_{tr}) + p_i \cdot \sigma + + p_{neg} \cdot (DIFS + T_c + SIFS + T_{NACK}))$$

(1)

In the above expressions, the terms $p_{pos}$ and $p_{neg}$ represent the probability of having a collision that can be resolved using ZigZag decoding and the probability of having an initial collision that can not be resolved, respectively. Moreover, the probabilities of having a successful transmission, a collision and an idle slot, are given by $p_s$, $p_c$ and $p_i$, respectively. The terms $T_{tr}$, $T_{NACK}$, $\sigma$, $T_c$ and $SIFS$ represent the duration of a network-coded data packet transmission, a $NACK$ packet transmission, an empty slot, a collision and a $SIFS$ period of time, while the $DIFS$ is used to denote the average random time, uniformly distributed between $SIFS$ and $DIFS$, that the sources wait before starting the transmission.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Conditional Probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>slot i</td>
<td>slot j</td>
</tr>
<tr>
<td>success</td>
<td>$p(succ_i)$</td>
</tr>
<tr>
<td>collision</td>
<td>$p(idle_i)$</td>
</tr>
<tr>
<td>idle</td>
<td>$p(c)_{i}$</td>
</tr>
</tbody>
</table>

In ANGEL, one slot is considered successful if exactly one node gets the channel access to transmit, collided if both nodes transmit simultaneously, and idle if both nodes remain idle. Therefore, we can write:

$$p(succ_i) = \sum_{k \neq l} s_k \cdot \bar{s}_l, \forall i \in N, (k, l) \in \{1, 2\}$$

(2)

$$p(col_i) = s_1 \cdot s_2, \forall i \in N$$

(3)

$$p(idle_i) = \bar{s}_1 \cdot \bar{s}_2, \forall i \in N$$

(4)

where $s_i \in (0, 1)$ is the probability of a node $i$ to transmit, as it has been estimated using game theoretic techniques, while $succ_i$, $col_i$ and $idle_i$ represent the fact that the random slot $i$ is successful, collided or idle, respectively.

Since the success of the transmission in one random slot depends on the status of the preceding slot, we need to use conditional probabilities in order to model our protocol. Hence, given the statistical independence of the events, we have:

$$p_s = \sum_{x \in \{succ, col, idle\}} p(succ|x_i) \cdot p(x_i), i \in N, j \in N^*$$

(5)

$$p_c = \sum_{x \in \{succ, col, idle\}} p(col|x_i) \cdot p(x_i), i \in N, j \in N^*$$

(6)

$$p_i = \sum_{x \in \{succ, col, idle\}} p(idle|x_i) \cdot p(x_i), i \in N, j \in N^*$$

(7)

where $i$ and $j$ are two consecutive slots and the conditional probabilities can be found in Table I.

B. Energy Efficiency

The energy efficiency of the system is represented by:

$$\eta = \frac{D_{useful}(\text{bits})}{\mathcal{E}_{cons}(\text{Joule})},$$

(9)

where $D_{useful}$ is the total amount of useful data delivered and $\mathcal{E}_{cons}$ denotes the total energy consumed.

In the context of ANGEL, the numerator has a determinist value, calculated as:

$$\hat{s}_i = 1 - s_i.$$

We use the notation $\hat{s}_i$ to denote the complementary probability of $s_i$, i.e. $\hat{s}_i = 1 - s_i$. 
where $M$ is the total number of packets, $\text{payload}$ is the useful packet payload and $L$ is the number of sink nodes.

On the other hand, the expected value of the energy consumption can be probabilistically estimated by exploiting our analysis in Section IV-A. In particular, we consider three different modes for the radio interface: i) Transmission mode, ii) Reception mode, and iii) Idle mode, while the power levels associated to each mode are $P_T$, $P_R$ and $P_I$, respectively. Furthermore, the relationship between energy and power is given by $E = P \cdot t$, where the terms $E$, $P$ and $t$ represent the energy, the power and the time, respectively. Having analyzed the ANGEL’s performance, we are able to derive a closed-form formula that describes the average energy consumption in the network:

$$E_{\text{cons}} = E_{\text{succ}} + E_{\text{idle}} + E_{\text{zigzag}}$$

where $E_{\text{succ}}$, $E_{\text{idle}}$ and $E_{\text{zigzag}}$ represent the energy consumed during the successful transmissions, the idle periods and the ZigZag procedure, respectively. Let us recall that the network consists of two source nodes, a set of $L$ sink nodes and a subset of $W \subseteq L$ nodes placed in the the coverage areas intersection of the two sources, thus experiencing the collisions. Therefore, considering the network topology, we have:

$$E_{\text{succ}} = p_s \cdot ((L+2) \cdot P_T \cdot \text{DIFS} + (P_T + J \cdot P_R + (L-J) \cdot P_I) \cdot T_{tr})$$

$$E_{\text{idle}} = p_I \cdot (L + 2) \cdot P_I \cdot \sigma$$

$$E_{\text{zigzag}} = p_{neg} \cdot ((L + 2) \cdot P_I \cdot (\text{DIFS} + \text{SIFS}) + (2 \cdot P_T + L \cdot P_R) \cdot T_c + (W \cdot P_T + 2 \cdot P_R + (L - W) \cdot P_I) \cdot T_{\text{ACK}}) + p_{pos} \cdot ((L + 2) \cdot P_I \cdot 2 \cdot \text{DIFS} + (2 \cdot P_T + L \cdot P_R) \cdot T_c)$$

where all the parameters have been already defined. The equations (12)-(14) are based on the following principles:

- All stations remain idle during the SIFS, DIFS and $\sigma$ times.
- All stations inside the coverage area of a transmitting node are in reception mode.
- All stations outside the coverage area of a transmitting node are in idle mode.

Therefore, we are able to estimate the average energy consumption, since all the variables are known and the respective probabilities can be found in Section IV-A.

V. PERFORMANCE EVALUATION

We have implemented a time-driven C++ code that simulates the operation of ANGEL. Monte Carlo simulations have been carried out to validate our analysis and further evaluate the performance of our proposed protocol. In this section, we present the simulation set up along with the experimental results.

A. Simulation Scenario

The network under simulation consists of five nodes in total, where two of them have already received the total amount of information broadcasted by the base station, while the rest three are sink nodes affected (i.e. placed inside the transmission range) by both sources (Fig. 3). Therefore, during the dissemination the two sources have the same impact in the network. In addition, as we have already mentioned, the nodes are capable of performing RLNC techniques to their buffered packets before forwarding them. In all our experiments, the number of packets to be disseminated is constant, equal to 256. However, the payload of the packets in each experiment varies among 64 and 1024 bytes. In our simulations we consider packet lengths of $\text{PHY} + \text{MAC} + N_{CH} + P$ bytes, where $\text{PHY}$ and $\text{MAC}$ are the physical and the MAC header, respectively, with $\text{PHY} = 192$ bits and $\text{MAC} = 224$ bits. $N_{CH}$ is the network coding header, while $P$ is the packet payload. The coding of the packets is performed over a finite Galois Field - $GF(2^8)$, since it has been proved to be sufficient for linear independence among the packets [8]. We have chosen to create 16 generations of 16 packets each, which results in $N_{CH}$ 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 has been selected equal to 20$\mu$s according to the IEEE 802.11g physical layer [9], while the transmission data rate is equal to 54 Mb/s. Regarding the power, Ebert et al. [10] have measured the power consumption of a wireless interface during the transmission and reception phase. Based on their work, we have chosen the following power levels for our scenarios: $P_T = 1900mW$, $P_R = P_I = 1340mW$. 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.

In order to evaluate ANGEL and highlight the promising benefits of analog network coding in wireless communication, we compare our proposed protocol with two alternative RLNC-aided protocols for data dissemination: i) a state-of-the-art game theoretic approach (GT) [4], where game theory is used to resolve the potential conflicting interests between the nodes, and ii) an IEEE 802.11-based protocol (BO-MAC), where the conflicts are resolved using congestion windows and back-off mechanisms. The simulation parameters are summarized in TABLE II.
B. Performance Results

Figure 4 depicts the performance results (both analytical and experimental) of the proposed ANGEL compared to the two RLNC-based solutions (game theoretic and backoff-aided) in terms of completion time. As it was expected, the completion time of the dissemination increases with the packet payload. However, it is clearly observed that applying analog network coding techniques in the network has a positive effect in the completion time under the same channel conditions. In particular, we are able to reduce the total completion time of the dissemination up to 75% and 300% over the game theoretic and the IEEE 802.11-based approach, respectively.

![Fig. 4. Completion Time of Data Dissemination](image)

Figure 5 presents the achieved energy efficiency of the three schemes discussed in this paper. The simulation results for ANGEL are almost perfectly matched to the theoretical ones, thus verifying and validating our analysis. Similar to the delay performance, the application of analog network coding techniques provides the network with higher energy efficiency. In Fig. 5, it is also observed that ANGEL is more energy efficient than the other two RLNC-based schemes. Furthermore, it should be noted that we achieve considerable energy gains especially for big packet payloads (i.e. payload > 512 bytes).

![Fig. 5. Energy Efficiency](image)

VI. CONCLUDING REMARKS

In this paper, an Analog-Network-Coding-aided Game Theoretic Energy Efficient Layout (ANGEL) for data dissemination in wireless networks was presented. Both analytical and experimental results have been provided to demonstrate that ANGEL significantly enhances the energy efficiency of the system without compromising the completion time for the data dissemination. Compared to other simple-digital-network-coding-aided game theoretic schemes without analog network coding capabilities, ANGEL provides a reduction up to 75% with regard to the dissemination completion time, while the enhancement regarding the energy efficiency of the network reaches 100% under certain conditions. In our future work we are planning to elaborate on conflicts between more than two source nodes in the network and study misbehavior issues in data dissemination schemes.

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