MAC Design of Uncoordinated FH-Based Collaborative Broadcast

Liang Xiao, Huaiyu Dai, and Peng Ning

***Abstract*—Uncoordinated Frequency Hopping (UFH) techniques are promising to address jamming attacks in wireless networks without requiring pre-shared secret keys, and its communication efficiency in the broadcast scenario can be significantly improved through node cooperation. In this letter, we take a first step to investigate efficient Media Access Control (MAC) strategies for the UFH-based collaborative broadcast, and derive closed-form expressions of the channel access probabilities for time-slotted systems to minimize the broadcast delay and to significantly reduce the energy cost. Numerical and simulation results are provided to verify our analysis and reveal some insights.**

***Index Terms*—Collaborative broadcast, frequency hopping, MAC, jamming, wireless networks.**

I. Introduction

JAMMING-RESISTANT broadcast is important for many safety-critical applications such as emergency alert broadcast and navigation signal dissemination [1]. As it is nontrivial to establish secret keys in dynamic wireless networks that are often challenged by node compromise, Uncoordinated FH (UFH) [1]–[4] techniques have been investigated to counteract jamming without pre-shared keys. In UFH, each message is split into short packets, which are then transmitted over randomly selected channels, independent of each other and only known to the sender. Such rapid channel switching over a large frequency range effectively thwarts the jamming attempts. Erasure coding and one-way authenticators based on bilinear maps have been proposed to enhance UFH [2], and some efficient packet verification methods were developed for it in [3]. In addition, the USD-FH scheme [4] can further improve system performance by conveying the hopping pattern with UFH and then transmitting the message with coordinated FH.

In spite of all these efforts, the communication efficiency of UFH may still be a bottleneck for practical applications. Our recent study on the Collaborative UFH-based Broadcast (CUB) exploits the node cooperation to further improve the communication efficiency [5]–[7]. The main idea is to have a set of nodes that already receive the message help broadcast it. Both the source and relay nodes send the message simultaneously and independently at multiple channels over various geographical regions, providing both the frequency diversity and spatial diversity to enhance jamming resistance and communication efficiency.

Due to the low communication efficiency of UFH and the multiple ongoing transmissions, an appropriate Media Access Control (MAC) mechanism is crucial for the success of the CUB scheme. In this letter, we take a step to explore effective media access control schemes for CUB concerning broadcast delay and energy consumption. In particular, we consider a time-slotted system, and derive the optimal channel access probabilities in several interesting cases. Numerical and simulation results are provided to verify our analysis and reveal some insights. The proposed MAC strategies can achieve the minimal broadcast delay or significantly reduce the overall energy consumption in the UFH-based anti-jamming broadcast without pre-shared keys. Although existing works on CUB cover important aspects such as the channel selection and ACK mechanism [5]–[7], so far as we know, this paper is the first to address the channel accessing issue. Moreover, many of our contributions also apply to multi-hop networks, and the proposed strategy has been shown to be robust against the parameter estimation error, which is highly desirable for practical implementations.

II. System Model

We mainly consider a single-hop radio network, where the source node aims at broadcasting a message to N identical nodes and all the nodes are within the communication range of the others. A single-hop network is amenable to analysis and of interest in its own right. Such a study can also shed some light on the single step of multihop propagation. The UFH technique is applied to counteract J reactive jammers [5], each with jamming probability p_J. Each node transmits (or receives) on a single channel randomly selected from C orthogonal channels, where C is large enough (greater than 100 as in a typical frequency hopping system) to provide strong jamming resistance. The broadcast message is divided into M short packets to defend reactive jamming, with each packet transmitted independently over one time slot.

In this study, we assume each relay node randomly and independently selects one out of C channels for potential packet transmission in each slot. We consider a time-slotted system, and investigate the optimal probability p that each relay will access the wireless media concerning broadcast delay and energy, assuming that the source node keeps transmitting during the broadcast. We mainly consider the energy consumption for a node to send and to receive a packet,

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denoted as E_t and E_r, respectively, and neglect other energy cost such as that on the signal processing in the baseband and IF band. The source node is assumed transmitting all the time.

III. Optimal Channel Access Probability

In this section, we analyze the optimal channel access probability p of relays in CUB in terms of broadcast delay and energy consumption, for two scenarios regarding the synchronization among the relays and the source: The first is the case with perfectly synchronous relays, where all the transmitters are synchronized both in time and in transmission content. The second case, referred to as asynchronous relays, is a more realistic scenario, where two or more transmissions on the same channel always lead to a failure in reception due to the difference in arrival time or transmitted packets. The broadcast delay is defined as the time duration from the beginning of broadcast till the time when all the nodes in the network successfully receive the entire message, while the overall energy consumption is defined as the sum of the transmit and the receive energy consumed by all the legitimate nodes during this process. In the following discussion, we assume there are n relays in the network at a given time, and this number may change over time.

A. Minimal Delay Strategy

We first consider the MAC strategy that achieves the minimal broadcast delay in CUB. Due to the low communication efficiency of UFH and the resulting long transmission delay even in the pairwise UFH communication, it is highly desirable to design a MAC strategy that minimizes the broadcast delay. As shown below, it turns out that in many scenarios of interest, all relay nodes only need to take a simple strategy, constantly accessing the channel.

Lemma 3.1: If the number of relay nodes in the network $n \leq C$, and the number of channels $C \gg 1$, the broadcast delay is minimized by the access probability $p = 1$, either with perfectly synchronous or asynchronous relays.

Proof: First we consider the successful packet reception rate p_a in a snapshot scenario with any given number of relays, n. For perfectly synchronous relays, a receiver can successfully receive a packet if choosing an unblocked channel selected by at least one transmitter (as no interference is incurred when two or more relays select the same channel). Therefore, as the source node transmits with probability one, the successful packet reception rate with n relays, p_a^{syn} is given by

$$p_a^{syn} = \left(1 - \left(1 - \frac{1}{C}\right)\left(1 - p\frac{1}{C}\right)^n\right)(1 - p_J)^J, \quad (1)$$

which monotonically increases with p.

Next, for asynchronous relays, a receiver can successfully receive a packet if exactly one transmitter accesses the receiving channel. Thus the successful packet reception rate becomes

$$p_a^{asyn} = \frac{np}{C}\left(1 - p\frac{1}{C}\right)^{n-1}(1 - p_J)^J. \quad (2)$$

Its derivative with respect to p can be written as

$$\frac{\partial p_a^{asyn}}{\partial p} = \frac{n}{C}(1 - p_J)^J\left(1 - \frac{p}{C}\right)^{n-2}\left(1 - p\frac{n}{C}\right). \quad (3)$$

Given $C \gg 1$, it can be shown that $p = \min(C/n, 1)$ maximizes p_a^{asyn}, i.e., $p = 1$ also maximizes p_a^{asyn} if $C \geq n$.

We now discuss the relationship between p_a and the broadcast delay. Similar to the analysis in [1], the probability for all the $N_r = N - n$ receivers to obtain all the M packets during the first k slots can be derived as

$$P[k] = \left(1 - (1 - p_a)^k\right)^{MN_r}, \quad (4)$$

and thus the average broadcast delay in terms of time slots is given by

$$T = \sum_{k=0}^{\infty}(1 - P[k])M = M\sum_{k=0}^{\infty}\left[1 - \left(1 - (1 - p_a)^k\right)^{MN_r}\right]. \quad (5)$$

It can be seen from (5) that the broadcast delay T monotonically decreases with p_a. This completes the proof. ■

Remark: Note that our proof above does not require the number of relays n fixed over time. In addition, Lemma 3.1 applies can actually be extended to the multihop scenario. In multi-hop networks, if the maximal number of one-hop neighbors, n is less than C, which holds in most FH systems, $p = 1$ is the optimal solution, regardless of the actually network size. We note that this MAC strategy for CUB is easy to implement, without requiring the transmitters to have the information such as n and the number of receivers in the communication range.

B. Energy Efficient Strategy

The overall energy consumption consists of the total transmission energy consumed by the transmitters including both the source node and relay nodes, and the energy consumed by the receivers. The average number of transmitters and receivers during a time slot are given by $N_t = 1 + np$ and $N_r = N - n$, respectively, and $1/p_a$ represents the average number of transmissions for a successful packet reception. Therefore, we define the effective energy consumption as

$$E_{eff} \triangleq \frac{E_t N_t + E_r N_r}{p_a} = \frac{E_t(1 + np) + E_r(N - n)}{p_a}. \quad (6)$$

Lemma 3.2: The overall effective energy consumption of CUB with perfectly synchronous relays is minimized by the access probability p^* that is the solution to Eq. (9) below. If $C \gg 1$ and $n < C$, this access probability can be well approximated by

$$p^* \approx \min\left(1, \frac{\sqrt{b^2 - 4ac} - b}{2a}\right), \quad (7)$$

where $a = n^2 - n$, $b = n\left(1 + \frac{E_r}{E_t}(N - n)\right)$, and $c = -C\left(1 + \frac{E_r}{E_t}(N - n)\right)$.

Proof: By incorporating (1) into (6), we can rewritten the energy consumption as

$$E_{eff} = \frac{E_t(1 + np) + E_r(N - n)}{\left(1 - \left(1 - \frac{1}{C}\right)\left(1 - p\frac{1}{C}\right)^n\right)(1 - p_J)^J}. \quad (8)$$

Taking the derivative with respect to p into zero, we obtain

$$E_t(1 - \epsilon) = (E_t(1 + np) + E_r(N - n))\frac{\epsilon}{C}\frac{1}{1 - \frac{p}{C}}, \quad (9)$$

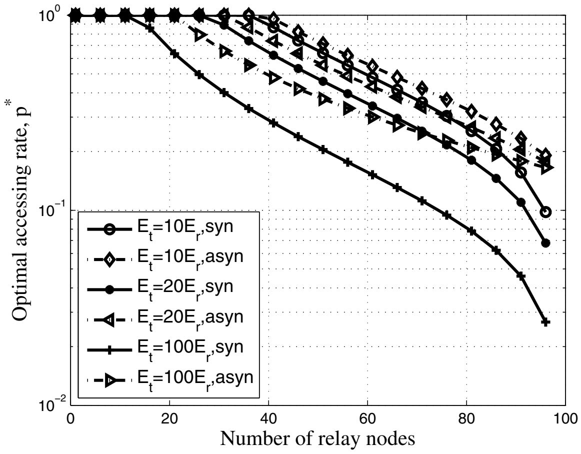


Fig. 1. The optimal channel access probabilities for energy-efficient broadcast, for both the synchronous and asynchronous relays, with $C = 256$ and $N = 100$, as given by Lemma 3.2 and Lemma 3.3.

where $\epsilon = \left(1 - \frac{1}{C}\right)\left(1 - \frac{p}{C}\right)^n$. If $C \gg 1$, as $p \leq 1$, we can use the following approximation

$$\epsilon = \left(1 - \frac{1}{C}\right)\left(1 - \frac{p}{C}\right)^n = \left(1 - \frac{1}{C}\right)\left(1 - \frac{np}{C} + o\left(\frac{p}{C}\right)\right)$$
$$= 1 - \frac{np}{C} - \frac{1}{C}\left(1 - \frac{np}{C} + o\left(\frac{p}{C}\right)\right) + o\left(\frac{p}{C}\right) \approx 1 - \frac{np}{C}. \quad (10)$$

By combining (10) and (9), we obtain after simplification the following,

$$p^2\left(n^2 - n\right) + pn\left(1 + \frac{E_r}{E_t}(N - n)\right) - C\left(1 + \frac{E_r}{E_t}(N - n)\right) = 0. \quad (11)$$

Since $0 \leq p \leq 1$, (11) yields the result given in (7). ■

Lemma 3.3: The overall effective energy consumption of CUB with asynchronous relays is minimized, if the access probability satisfies (7).

Proof: By incorporating (2) into (6), we have

$$E_{eff} = \frac{E_t(1 + np) + E_r(N - n)}{\frac{np}{C}\left(1 - p\frac{1}{C}\right)^{n-1}(1 - p_J)^J}. \quad (12)$$

By taking $\frac{\partial}{\partial p}E_{eff} = 0$, we have after simplification

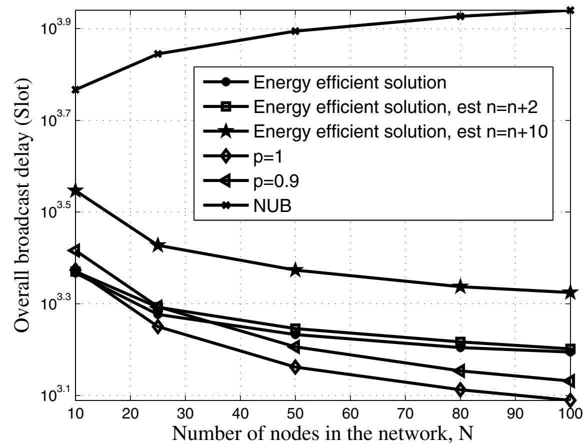
$$E_t np\left(1 - p\frac{1}{C}\right) = \left(E_t(1 + np) + E_r(N - n)\right)\left(1 - p\frac{n}{C}\right), \quad (13)$$

which can be further simplified as

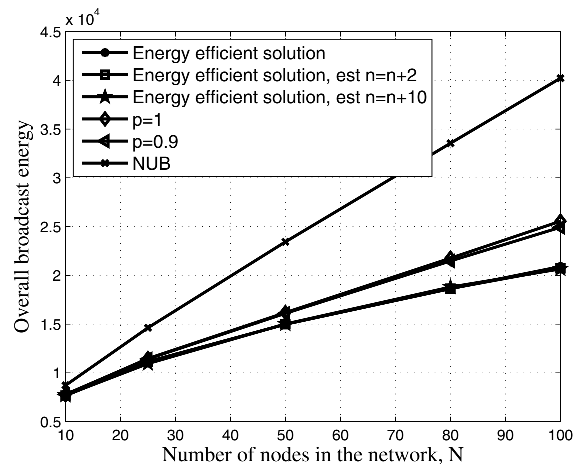
$$p^2\left(n^2 - n\right) + pn\left(1 + \frac{E_r}{E_t}(N - n)\right) - C\left(1 + \frac{E_r}{E_t}(N - n)\right) = 0, \quad (14)$$

the same as (11). Therefore, the solution is also given by (7). ■

Remark: Note that (7) provides the most energy-efficient solution for asynchronous relays and the sub-optimal solution for synchronous relays, as an approximation to (9). As illustrated in Fig. 1, this approximation is quite accurate especially the number of relays is not large. It is also shown that when the set of relays is small, all the relay nodes send packets with probability 1. On the other hand, when there are a large number of relay nodes, the access probability decreases to save the energy, since otherwise the probability of confliction outweighs the successful reception rate. Moreover, p^* decreases relatively slowly with the number of relay nodes, n, indicating that the solution is robust against small estimation error of n; this point is further verified through simulation below. Finally, if the relative transmission cost is higher, i.e., the ratio of the transmit power over receive power is larger, the optimal access probability deceases for better energy efficiency.



(a) Average broadcast delay.



(b) Average energy consumption.

Fig. 2. Broadcast performance vs. network size, for the broadcast of $M = 7$ packets, with $C = 128$, $E_t = 1$ and $E_r = 0.1$, against $J = 10$ responsive-sweep jammers each with jamming probability $p_J = 0.0313$.

IV. Simulation Results

In this section, we evaluate the performance of the two proposed MAC strategies for CUB through simulation, where a message consisting of $M = 7$ packets is broadcast to $N = 100$ nodes over $C = 128$ channels with perfect relay synchronization, against $J = 10$ responsive jammers each with $p_J = 0.0313$. For comparison, we also consider Non-cooperative UFH-based Broadcast (NUB), a CUB protocol with $p = 0.9$, and the energy efficient CUB with inaccurate parameter estimation, where the relay number is estimated to be $\hat{n} = n+2$ or $n+10$. The energy consumption for a node to send and to receive a packet are set as $E_t = 1$ and $E_r = 0.1$, respectively.

As shown in Fig. 2, the CUB scheme with the proposed MAC strategies can well resist 10 responsive jammers, due to the UFH scheme, as well as the node cooperation that leads to both the frequency and spatial diversity gains. Moreover, the collaborative broadcast with $p = 1$ achieves the fastest broadcast and also significantly reduces the energy cost compared with NUB (the second vs. the first curve from the top in Fig. 2 (b)). When reducing the channel access probability from $p = 1$ to $p = 0.9$, the broadcast delay increases but the overall energy consumption decreases, indicating a tradeoff between broadcast delay and energy consumption. If knowledge of n and N is available, the energy-saving scheme requires the least energy consumption, at the cost of some increase in broadcast delay. It is also observed that the energy saving of the proposed energy-efficient strategy is more prominent in larger networks, where the channel access probability of relays should be reduced as their number increases.

It is interesting to note that an estimation error of n up to 10 leads negligible degradation in terms of energy consumption (the bottom three curves in Fig. 2 (b)). A closer look into the simulated broadcast process reveals that the whole broadcast process can be roughly divided into two stages. In the first stage, all relay nodes keep on transmitting all the time (see Fig. 1), and the number of receiving nodes is large. When the relays accumulate to a critical number, the broadcast process dramatically speeds up. In the second stage, both the time duration and the number of transmitters and receivers are significantly reduced. Therefore, the energy consumption is dominated by the first stage, for which the MAC behavior does not change much in the presence of small to medium estimation errors. This observation also indicates that in practice the implementation of the energy-efficient schemes does not crucially rely on the real-time accurate estimate of the network parameters.

Similar trends have been observed for other values of J and asynchronous relays, which are not shown here in the interest of space.

V. Conclusion

In this work, we have investigated efficient channel accessing strategies for Collaborative UFH-based Broadcast in wireless networks. Our results indicate that in many interesting scenarios (where $C \gg 1$ and $n < C$), the relays should aggressively access the wireless media if broadcast delay is of paramount concern. Such an approach is even optimal in terms of energy consumption when the network size is small. However, the channel access probability should be gradually reduced to save energy as the network grows; the corresponding closed-form expressions have been derived, and shown robust to the estimation error of the relay number. Our analysis is well supported by simulations.

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