A Distributed MAC Protocol for Cooperation in Random Access Networks

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Abstract—WLAN is one of the most successful applications of wireless communications in daily life because of low cost and ease of deployment. Whereas random access schemes used in WLAN guarantee the same probability for all users to access the channel, there still exists a significant throughput discrepancy between the users because of their positions in the network, especially if all users are constrained to the same energy consumption. Conversely, the farther users have to spend much more energy than the closer users to achieve the same throughput. In order to mitigate this discrepancy between spent energy and provided uplink rate, this work defines a new distributed cooperative MAC protocol for two-hop transmissions, called fairMACi. It dynamically selects the relaying nodes while it guarantees that all users spend the same amount of energy. Theoretical results show that fairMACi increases the minimum throughput that can be guaranteed to all users in the network and thereby improves fairness in terms of throughput. Monte Carlo simulations validate these results.

I. INTRODUCTION

The success of Wireless Local Area Network (WLAN) in day-to-day life is mainly due to the use of a simple distributed Medium Access Control (MAC) protocol. The carrier sense multiple access with collision avoidance (CSMA/CA) mechanism in distributed coordination function (DCF) guarantees in the long term the same opportunity of accessing the channel medium to each user in the network independent of his channel conditions [1]. Additionally, multirate capabilities of IEEE 802.11 have enabled WLAN hotspots to serve users with different channel conditions simultaneously. In the uplink, different channel conditions however result in a strong discrepancy of the experienced end-to-end throughput performance among the users depending on their position in the network. Users that are facing bad channel conditions indeed would have to spend significantly more energy than users with good channel conditions in order to achieve the same throughput. If strict throughput fairness between all users of the network is considered, this strategy leads to a severe throughput degradation for the best users as shown in [2]. Conversely, imposing the same energy consumption for all users significantly penalizes the throughput for the users facing bad channel conditions.

In the recent years, cooperation in wireless networks has drawn a lot of attention in order to mitigate throughput discrepancy between users in wireless networks. Based on the early results presented in [3], it was shown that cooperation among nodes for transmission has the potential to combat the fading characteristics of wireless channels [4]. In [5], [6], the authors illustrated that cooperation between two users can be beneficial for both users. More recently, distributed protocols were proposed to coordinate cooperation at the MAC layer, for instance rDCF [7] and CoopMAC [8]. Both protocols enable two-hop transmission as an alternative to direct transmission for WLAN. These protocols also coordinate cooperation on the PHY layer [9], [10]. The benefits of cooperation for the whole network have been analyzed in [11], [12]. However, most of the cooperative protocols proposed so far aim to optimize each packet flow separately. In [7], [8], [13], the authors proposed to select the best relay for each transmission separately. However, if one node is determined as the best relay for many nodes, its energy consumption will be very high compared to other nodes. In [14] we investigated distributed cooperative protocols for two users using DCF where both users were constrained to achieve same throughput with same energy consumption, i.e., full fairness. This was achieved by individual transmission power adaption for each user. Whereas large throughput gains were observed with this approach, the extension to scenarios with many users is unrealistic since the resulting transmission powers vary by orders of magnitude, which is incompatible with the typical characteristics of a power amplifier in a transmitter.

In this paper, we assume equal transmission power for all users. We propose the protocol fairMACi, which is designed to maximize the minimum throughput (min-throughput) achieved by any user in the network, assuming an equal energy constraint per user. For the uplink to a common access point (AP), the protocol enables cooperative transmission (Two-Hop or Decode-and-Forward) as an alternative to direct transmission. Along the lines of [15], fairMACi dynamically determines the relays when the source broadcasts its packet. Compared to DCF, fairMACi adds in the broadcast phase a flag (1 byte) to the control overhead in each packet. This flag contains
the current SNR value between the source node and the destination. Based on the SNR value, each node that can decode the packet decides to relay or not the information. The estimation of other nodes’ SNR and the maintenance of a “coopTable” with rate information of other nodes as in [8] is not necessary in fairMACi.

The remainder of the paper is organized as follows. In Section II, we describe the considered system setup and review the communication schemes Direct-Link, Two-Hop and Decode-and-Forward. The corresponding MAC protocols are defined in Section III. We analyze in Section IV the resulting min-throughput and discuss simulation results.

II. TRANSMISSION MODEL

We consider a network of \( N \) randomly distributed nodes that seek to transmit their data to a common AP. With each pair of nodes \( k, l \) of the network, we associate an achievable rate \( R_{k,l} \). We denote by \( R_k \) the maximum achievable rate of the direct link from node \( k \) to the AP. In our protocol described in the next section, we assume that node \( k \) knows the rate \( R_k \) or an estimate of it but none of the rates \( R_{k,l}, \forall k, l, k \neq l \). In comparison to CoopMAC [8], there is no need for each node to maintain a table referred as “coopTable”, which contains estimates of all rates \( R_{k,l} \). This assumption is fundamental for the implementation point of view since it considerably reduces the amount of information exchange between the nodes. We assume that the rates of the links remain constant during the implementation point of view since it considerably reduces the amount of information exchange between the nodes. We assume that the rates of the links remain constant during the transmission of a few consecutive packets. We assume continuous rate adaptation for all considered transmission schemes and identify the achievable rate \( R_{k,l} \) with the mutual information between sent and received signal as a function of the signal-to-noise-ratio (SNR) at the receiver \( l \), i.e.,

\[
R_{k,l} = \log(1 + \text{SNR}_{k,l}) \quad \text{[bits/s/Hz].} \tag{1a}
\]

\[
R_k = \log(1 + \text{SNR}_k) \quad \text{[bits/s/Hz].} \tag{1b}
\]

The SNR is defined as the ratio between the transmission power (which we assume to be the same for all nodes) and the noise power times the attenuation factor of the signal between \( k \) and \( l \) (or \( k \) and the AP, respectively). The noise is assumed to be complex symmetric additive white Gaussian.

Since we want to guarantee equal energy consumption for all nodes, we set all packets to the same size. We normalize it to one without loss of generality. The amount of information that can be associated with one packet depends on the corresponding transmission rate. The aim is to guarantee a minimum amount of information \( D \) per packet to all users in the network. We next recall briefly the three basic transmission schemes that we consider in this paper: “Direct-Link”, “Two-Hop”, and “Decode-and-Forward.” The three schemes are designed for two nodes \( k \) and \( l \) that seek to transmit messages to the AP. They will be the cornerstones when we design our protocol for more than two nodes in Section III.

1) Direct-Link: Each node transmits its data directly to the AP. Since the packet size is normalized to one, the maximum amount of information that node \( k \) can transmit to the AP within one packet is given by \( R^k_{\text{dir}} = R_k \). Although \( R^k_{\text{dir}} \) may be larger than \( D \) for some nodes \( k \), the choice for \( D \) is driven by the node(s) with smallest rate. Moreover, the nodes with rate \( R^k_{\text{dir}} \) larger than \( D \) can transmit the information \( D \) in the amount of time \( t_k = D/R^k_{\text{dir}} < 1 \). The remaining time \( 1 - t_k \) can be used to support the transmission of nodes with smaller rate as in the next two schemes.

2) Two-Hop: Assume node \( k \) cannot achieve the target rate by directly transmitting to the AP. Instead, node \( k \) may transmit its packet to some other closer node \( l \). Node \( l \) decodes the packet, then re-encodes it and transmits it to the AP. If node \( l \) has a “free” amount of time \( 1 - t_l \) at its disposal (as defined in the previous paragraph) for forwarding the packet, the maximum rate per packet at which node \( k \) can deliver data to the AP via the relaying node \( l \) is given by

\[
P_{2\text{hop}}^{k,l} = \min \{ R_{k,l}, (1-t_l)R_l \} \tag{2}.
\]

We denote by \( H_{2\text{hop}}^{k} = \{ l \mid P_{2\text{hop}}^{k,l} \geq D \} \) the set of nodes that can effectively help \( k \) to achieve the target rate \( D \) via Two-Hop.

3) Decode-and-Forward, [3]: This scheme is similar to the two-hop scheme but it exploits the broadcast nature of a wireless transmission. Although the AP cannot decode the transmission of node \( k \) if \( R_k < D \), it can listen to the transmission for “free”, record it and use it when the relaying node \( l \) will forward the message. The Decode-and-Forward scheme exploits this fact as follows. Instead of forwarding the whole packet as in the Two-Hop scheme, the relaying node \( l \) only forwards the part of data that is missing at the AP to decode the original transmission of node \( k \). The maximum rate for this scheme is given by

\[
P_{\text{df}}^{k,l} = \min \{ R_{k,l}, R_k + (1-t_l)R_l \} \tag{3}.
\]

This rate is a special case of [16, Prop. 2], since \( k \) remains silent when \( l \) is forwarding. By \( H_{\text{df}}^{k} = \{ l \mid P_{\text{df}}^{k,l} \geq D \} \), we denote the set of nodes that can help \( k \) to achieve the target rate \( R \) via Decode-and-Forward. The amount of data that node \( l \) has to forward is given by \( D - R_k \) and varies with \( R_k \). It is strictly less than in the Two-Hop scheme, where the amount of data to forward is always equal to \( D \).

III. MAC PROTOCOLS

In the previous section, we reviewed the two schemes Two-Hop and Decode-and-Forward that imply node cooperation (through the relaying node) and saw that they could increase the target rate \( D \) supported by the farther nodes. However, we did not address the problem of coordination, which consists for a farther node in selecting a closer node that can help. In this section, we introduce a new cooperative protocol, named fairMACi which dynamically selects a “good” relay node based on the current channel conditions. We shall show that this protocol increases the target rate \( D \) achievable by all nodes of the network while keeping the energy consumption constant over the nodes.

We are interested in maximizing the minimum throughput \( D \) achievable by all nodes, which occurs when the network is in saturation (all nodes are always backlogged). Under
this assumption, the DCF of IEEE 802.11 can be modeled as a simple CSMA scheme as shown in [1]. In the sequel, we therefore use this model. Additionally, we assume that the nodes are close enough to each other such that every node can sense ongoing transmissions of any other node. We also assume that the packet headers and the acknowledgments (ACK) are encoded at a rate sufficiently low such that they can be decoded by any node in the network, even when the corresponding data packet cannot be decoded. Finally, we neglect the collisions with ACKs, i.e., all ACKs from the AP will be detected and decoded correctly by all nodes in the network. Assuming the mechanisms at the physical layer described in Section II, we detail the three transmission schemes from the MAC layer perspective. CSMA with Direct-Link is used as reference for our new protocol fairMACi, which enables Two-Hop or Decode-and-Forward.

1) Direct-Link: When node $k$ seeks to transmit a packet, it competes for the medium according to CSMA: if $k$ senses the channel idle, it initiates a transmission with probability $r$. If no other node is transmitting meanwhile, the AP can decode the packet and sends an ACK in return. Otherwise, a collision occurs; no ACK is sent by the AP. Node $k$ declares its packet lost and will try to transmit again the same packet later.

2) Two-Hop fairMACi: The transmission of a packet via Two-Hop can be split into two phases, the broadcast phase and the relay phase. The relay phase happens only if the AP could not decode the packet at the end of the broadcast phase. Assume that node $k$ accesses the channel. Node $k$ starts to broadcast a packet $p_k$ at target rate $D$.

1a) In case of collision, no node can decode $p_k$ and $k$ competes again for the channel.

1b) If no collision occurs, all nodes within its transmission range successfully decode $p_k$ and record it.

1b1) If node $k$ is close to the AP ($R_k \geq l$), the AP successfully decodes $p_k$ and sends an ACK back to node $k$. All nodes receive the ACK and discard the recorded signal.

1b2) If node $k$ is far from the AP ($R_k < l$), the AP cannot decode $p_k$, but it stores $p_k$ and sends an ACK indicating that there was no collision. The transmission of $p_k$ enters the relay phase, which is described next.

After the broadcast phase, all nodes in $H_{2hop}^k$ decode $p_k$ successfully. Each node $l \in H_{2hop}^k$ forms a joint packet consisting of $p_k$ (amount of data equal to $D$) and own data (amount of data equal to $R_l - D \geq D$) and puts it in its packet queue. The header of the joint packet contains in addition the MAC address of $k$ and the packet number corresponding to $p_k$. The relay phase starts. All nodes compete for the channel. Assume that node $l \in H_{2hop}^k$ obtains the channel access and the joint packet containing $p_k$ is first in its packet queue. The relay phase begins when node $l$ starts to transmit this joint packet to the AP.

2a) In case of collision, all nodes in $H_{2hop}^k$ keep the joint packets with data $p_k$ in their queues and continue to compete for the channel.

2b) Otherwise, the AP sends an ACK to $l$ and $k$ for the successful reception of the joint packet. Under our assumptions, all nodes in the network can decode the ACK. All nodes in $H_{2hop}^k$ but $l$ remove $p_k$ from the corresponding joint packet in their packet queues; node $l$ removes the whole joint packet from its queue, and node $k$ removes $p_k$ from its queue.

3) Decode-and-Forward fairMACi: The MAC protocol for Decode-and-Forward is similar to the one for Two-Hop. However, nodes in $H_{dir}^k$ relay only the information of $p_k$ that is missing at the AP. This operation requires the knowledge of the information received by the AP during the broadcast phase. Under our assumptions, this information depends only on the rate $R_k$. This approach requires to add $R_k$ (or a quantized version of it) to the header of each packet $p_k$ sent by node $k$ as we suggested in the introduction. Alternatively, node $l$ can try to estimate $R_k$ by its own as proposed in [8]. With this modification, the protocol for Decode-and-Forward follows the lines of the Two-Hop protocol.

For Direct-Link, if node $k$ is very far from the AP, that is, if $R_{dir}^k < D$, node $k$ is not physically supported by the network. In this case, we assume that node $k$ remains silent forever.

In fairMACi, node $k$ broadcasts its packet at rate $D$ hoping that the AP can decode it or at least that some other node(s) in the network can relay the packet. If there is no such node in the network, a successful decoding of packet $p_k$ will never be acknowledged by the AP. To prevent node $k$ from flooding the network with additional transmissions, we impose that it broadcasts only up to $Q$ successive packets before receiving an ACK for the first one.

IV. THROUGHPUT ANALYSIS

We evaluate the three protocols introduced in the previous section with respect to fairness: under the constraint that all users spend the same amount of energy on the long term, we measure the unfairness resulting from variations in the data throughput provided to each user by the min-throughput, where the minimum is taken over all users in the network. High min-throughput indicates a low variance of throughput over the users, which corresponds to an increased degree of fairness. In our analysis, we assume large packets such that the size of ACKs and packet headers is negligible.

Assume that all nodes operate in saturation mode, i.e., they are backlogged and we do not need to consider packet arrival processes in our analysis. Also, assume that there is no degradation on the MAC layer, that is, on the long term all nodes have the same number of channel accesses and consequently transmit the same number of packets to the AP. This holds for Direct-Link, Two-Hop, and Decode-and-Forward, since forwarding is performed by forming joint packets of fixed size one: there is no difference in terms of competition for the channel between a standard packet and a joint packet. In addition, the same number of transmitted packets, the common transmission power, and the uniform...
packet size of one guarantee that each node spends the same amount of energy.

The effective min-throughput of the nodes can be calculated along the lines of [1]. Assume that \( N \) nodes compete for the channel. We slot the time into time slots of length \( \sigma \). If the channel is sensed idle during the current time slot, every node transmits in the next time slot independently with probability \( \tau \). After an idle time slot, the probabilities of successful transmission, idle state, and collision are given respectively by

\[
p_s = N(1 - \tau)^{N-1} \tau; \quad p_i = (1 - \tau)^N; \quad p_c = 1 - (p_s + p_i).
\]

A successful transmission or a collision take the amount of time one, and both are always followed by an idle time slot. The average effective min-throughput \( S(D) \) of each node is thus given by

\[
S(D) = p_s D / \{ N [(1 - p_i)(1 + \sigma) + p_i \sigma] \}.
\]

If a target rate \( D \) is physically supported by a network, \( S(D) \) gives an upper bound for the maximum effective min-throughput of the network. However, even if the considered target rate is physically supported, depending on the system configuration \( S(D) \) may not be achievable because of degradation on the MAC layer, as we discuss in subsection V-A and V-B.

V. NUMERICAL RESULTS

We apply our protocol to the 4 random topologies in Fig. 1 with 5, 10, 20, and 40 nodes. The node positions are uniformly distributed over the unit circle and normalized such that the node farthest away from the AP is at distance one. We assume free-space pathloss, i.e., the signal power is attenuated with the source-destination distance to the power of \( \gamma \) [17]. We set \( \gamma = 2 \). The transmit power is specified in SNR at the transmitting nodes and set to the same value for all nodes. The maximum number of unacknowledged packets is set to \( Q = 100 \). For all setups, 5 millions of packets are transmitted to the AP. The transmission probability is set to \( \tau = 0.001 \) and the normalized time slot length is set to \( \sigma = 0.002 \). We maximize the effective min-throughput gains compared to Direct-Link over the target rate \( D \) for Decode-and-Forward and for Two-Hop. The results are shown in Fig. 2 and in Fig. 3 respectively, as a function of the SNR. The effective min-throughput gains increase for both Two-Hop and Decode-and-Forward with the number of nodes in the network. This is intuitive since more nodes can be found in “good” positions for relaying in denser networks. The min-throughput gains for Decode-and-Forward are higher than for Two-Hop, which confirms the results from [14]. By investigating the dependency of our results on the parameters \( Q \) (maximum number of unacknowledged packets) and \( D \) (target rate), we identified two kinds of throughput degradation on the MAC layer.

A. First Kind of MAC Degradation

To prevent the nodes from flooding the network with retransmissions in fairMACi, we limited the number of unacknowledged packets to \( Q \). However, this can degrade the throughput on the MAC layer, since the random access in CSMA can lead to an unbounded number of unacknowledged packets. This degradation can be diminished by setting \( Q \) to a finite but large enough value. In Fig. 5 the effective min-throughput gain of Decode-and-Forward over Direct-Link is displayed as a function of \( Q \). In the considered example, bound (5) is already reached for \( Q = 17 \). Note that for a given value of \( Q \) and a network of \( N \) nodes, the maximum amount of additional memory needed by the relaying nodes is upper bounded by \( P \leq QN \).

B. Second Kind of MAC Degradation

The second kind of degradation occurs when the number of relaying nodes \( |H| \) is small compared to the number of the other nodes \( |C| \). The nodes in \( C \) are waiting for \( Q \) unacknowledged packets most of the time and are therefore unable to transmit new packets. This effect is illustrated in Fig. 6. For a random topology with 20 nodes, the target rate \( D \) is gradually increased. Consequently, the number of nodes in \( H \) decreases and the number of nodes in \( C \) increases. As long as there are enough helping nodes, the effective throughput gain follows the theoretical bound (5). After reaching a certain rate, the effective throughput gain rapidly decreases: although
the target rate is still physically supported by the network, at least one relay node starves, since the number of nodes that need help exceeds the number of relaying nodes. As the target rate farther increases, the effective throughput gain drops down to -100% , since there is at least one node in the network that cannot achieve the target rate by any scheme. The target rate is no longer physically supported by the network. The oscillating behavior of the curve is not random but depends on the topology. A future challenge is to determine the optimum operation point of fairMACi in a running network by choosing the target rate parameter $D$ properly.

VI. CONCLUSIONS

In this paper, we have proposed a new distributed cooperative protocol fairMACi for WLAN uplink transmissions that improves the min-throughput compared to the basic DCF under constant average energy per user. Our protocol supports Two-Hop and Decode-and-Forward transmissions. Since the maximization problem in terms of min-throughput guaranteed to any user in the network is equivalent to lower the variance of the individual throughput over the users, our protocol increases fairness in terms of throughput. For a random topology with 40 nodes, Decode-and-Forward provides min-throughput gains over Direct-Link of up to 50% and Two-Hop provides min-throughput gains of more than 25% for a large range of SNR. A possible extension of this work consists in finding a distributed target rate adaptation protocol that maximizes the min-throughput of fairMACi. Also, practical coding schemes should be addressed in order to determine if the theoretical gains observed in the present work are achievable in real networks.

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