MAC Protocol for Wireless Cooperative Physical-Layer Network Coding

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***Abstract*—In this paper we present a cooperative medium access control (MAC) protocol that is designed for a physical layer that can decode interfering transmissions in distributed wireless networks. The proposed protocol pro-actively enforces two independent packet transmissions to interfere in a controlled and cooperative manner with the help of a relay. To enable distributed, uncoordinated, and adaptive operation of the protocol, a relay selection mechanism is introduced so that the optimal relay is selected dynamically and depending on the channel conditions. The most important advantage of the protocol is that interfering transmissions can originate from completely independent unicast transmissions from two senders. We present simulation results that validate the efficacy of our proposed scheme in terms of throughput and delay.**

***Index Terms*—Wireless networks, physical layer network coding, interference, cooperative communications, MAC protocol.**

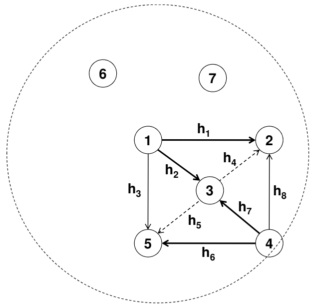

Fig. 1. Ad hop network topology that demonstrates physical layer network coding with cooperative relaying through node N_3. The solid lines indicate the concurrent broadcasting of packets from N_1 and N_4, while the dashed lines indicate the forwarded mixed packet from N_3.

I. INTRODUCTION

In wireless networks, where several nodes share the medium, the phenomenon of interference is avoided with mechanisms that orthogonalize transmissions. The classic examples of such mechanisms include frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and finally random access protocols like carrier sense multiple access with collision avoidance (CSMA/CA). However, besides channel orthogonilization, there have been several additional techniques throughout the years that attempt to combat this effect [1]. In more recent years, there is a trend to exploit interference in order to increase the network capacity [2], [3]. This technique is usually referred to as physical layer network coding (PLNC) and we can first identify it in [2], although not with this term. With PLNC network capacity is increased since concurrent interfering transmissions are allowed. Nodes listen to transmissions and then forward the unprocessed analog signals to destination nodes where various algorithms for interference cancelation can be applied in order to retrieve the signal of interest [3], [4]. The removal of an interfering signal is possible with PLNC when this signal is known at the receiver. A scenario where this might be the case is in multihop networks when the receiver had transmitted in the past the required signal in the form of a complete packet.

By removing the assumption of a known signal at a receiver, we investigated the potential improvement of PLNC in the sum-rate of a simple relay network with two completely independent senders/receivers and one relay in [4]. One of the main results was that if two packets, that originate from different senders, and are directed towards different receivers, interfere partially or entirely in the time domain, the subsequent forwarding of the mixed packets can work in favor of both unicast transmissions by increasing the total sum-rate. In this paper we take this result and we attempt to utilize it in more practical networks where several nodes that have independent traffic flows contend for the medium. We consider an extended and more realistic wireless ad hoc network where issues like channel estimation, medium access, and relay selection must be addressed.

To the best of our knowledge, the aforementioned problems have not been considered in any related works. One reason is that the topic of MAC protocol design for a communication layer that supports PLNC has not been studied so extensively. The most closely related work to this paper was performed by Boppana and Shea that proposed the overlapped CSMA protocol [5]. The main task of that protocol is to estimate the level of secondary interfering transmissions that another primary transmission can sustain given its perfect knowledge of the signal that intends to cause the interference. This protocol requires significant signaling overhead in order to propagate RTS/CTS messages at least two hops and notify the secondary sender whether it is allowed to proceed or not. Also the work by Zhang *et al.* [6] proposed a similar idea. Very recently the work by Khabbazian *et al.* presented in [7], proposed the design of a probabilistic MAC based

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on PLNC but only on a theoretical level. Finally, a practical MAC protocol that is based on CSMA/CA and is designed for a system that supports PLNC was presented by Yomo and Maeda in [8]. However, the proposed protocol only works when there is bidirectional traffic between two nodes and not in the more general scenario that we consider in this paper.

II. System Model and Overview

In this paper, we study wireless ad hoc local areas networks. Since the proposed protocol optimizes the cooperative transmission for a single hop, this relaxation with respect to the network structure, is possible. Fig. 1 presents a small network that is used throughout this paper for explaining several aspects of the presented algorithms. In this paper we assume that the core of the MAC functionality corresponds to the IEEE 802.11 MAC protocol that operates under the distributed coordination function (DCF) [9]. Nodes contend for the channel and when the backoff timer expires they use the request-to-send (RTS) and clear-to-send (CTS) floor acquisition mechanism for contacting the intended destination node. This very popular way of randomizing channel access with CSMA/CA ensures that there is only one node that completes successfully the RTS/CTS message exchange and obtains access to the channel. Now the RTS is received by potential relay nodes, that indicate their ability to act as relays for the impending transmission, with a special purpose signaling that we describe in later sections. From previous message exchanges, the relays also collect information about channel estimates in their neighborhood, while they subsequently estimate whether another node can transmit concurrently with the node that just exchanged the RTS/CTS. The aforementioned tasks are accomplished with the *cooperative channel information exchange algorithm* and the *rate estimation algorithm* that are processes that are executed continuously and in parallel with the normal protocol operation. In Fig. 1 for example N_3 estimates, according to the latest channel statistics, that N_4 can also transmit at the same time with N_1, while N_6, N_7 might have similar estimates. If interfering transmissions cannot be allowed by any relay, node N_1 proceeds with its transmission either cooperatively with the help of N_3 (named COOP transmission mode) or directly. Assume now that N_3 allows the two transmissions from N_1 and N_4 to take place concurrently. This task is accomplished with the *cooperative PLNC MAC* (CPLNC-MAC). Because of the broadcast nature of the channel the two packets/signals will interfere in several physical locations: nodes N_2, N_3, N_5, N_6, and N_7. In this way, both N_2 and N_5 have a locally interfered version of the signals that they simply cannot decode. The relay that has been selected with the previous algorithms, forwards its own version of the locally interfered signals to the two destinations. The destinations use then the two versions of the same interfered signals for recovering their respective packet with a *PLNC signal decoding algorithm*. The algorithm decodes symbol-by-symbol the interfered packets and it was presented in [10], [4]. This transmission mode is named *PLNC with overlapped transmissions* (PLNC-OL).

III. Channel and Rate Estimation of Cooperative and Interfering Transmissions

A secondary overlapping transmission should be selected to interfere *iff* the PLNC-OL mode will increase the sum-rate not only when compared to the direct transmission, but also when compared to a COOP transmission that employs amplify-and-forward (AF) [11], [12]. To do so it must be evaluated analytically, and more importantly during run-time, which type of cooperation is the most efficient. The only issue is that this decision can only be made by the relay since it is the only node in the network configuration that can obtain all the necessary information for doing so.

A. Channel Estimation and Information Exchange

It is clear from the introductory description that estimating the channel is necessary both for the decoding algorithm executed at the destinations, but also for the rate estimation. In this paper, channel estimates are obtained after averaging a number of measurements done for each symbol in the preambles and postambles of each control or data packet exchanged at the MAC layer [4]. Since the estimation of the channel from preamble/pilot-based schemes is a well known technique [1], we do not delve into this topic further. However, for testing if a potential PLNC-OL transmission is indeed the optimal choice for transmitting a packet, all the involved channels must be estimated. For example in Fig. 1 all the channel transfer functions shown with the letter h must be estimated in order to be able to test if the specific PLNC-OL transmission is efficient (a subset of them in case of COOP). Therefore, a significant number of messages should normally be exchanged even in the simple network of Fig. 1. In this paper all the necessary channels are estimated by leveraging the transmission of existing control messages in order to avoid additional traffic.

The main characteristic of the channel estimation algorithm is that it leverages the existing RTS/CTS mechanism as many cooperative protocols do [12], [11] and in addition the *clear-to-cooperate* (CTC) message that is introduced in this paper. The precise rules for overhearing and channel estimation are as follows: (1) The first requirement is that all nodes should overhear RTS messages regardless of whether the transmission is intended for them or not and estimate the channel between the transmitting node and themselves. (2) All nodes should overhear the CTC message transmissions of their neighbors. Each node should maintain a data structure that it should contain the nodes and the associated relay that were involved in an overheard COOP or PLNC-OL transmission. To understand how this works consider the example in Fig. 1. In this figure N_2 overhears cooperative transmissions (the CTC message) between N_4 and N_5 with N_3 being the relay. In a symmetrical fashion, N_5 overhears the cooperative transmission from N_1 to N_2 with the help of N_3. (3) A node should piggyback in its outgoing CTS message the results of the channel estimation only for channels that are formed between another node and themselves, but only if both have used the same relay in the past. The $\mathbf{anfl}$ data structure contains monitored data from several past relayed transmissions. To continue our previous example when N_2 sends a CTS for responding to an RTS from N_1, it includes in the CTS response not only the estimate $\tilde{h}_1$, but also the estimate that it has for $\tilde{h}_8$ which was obtained from previous transmissions of RTS messages from N_4 (Recall a few lines above that N_4 and N_3 were included in the **anfl** data structure of N_2). One way to summarize this functionality is that in this way a relay can obtain the information for channels that it cannot directly estimate ($\tilde{h}_8$ and $\tilde{h}_3$ here).

B. Rate Estimation

In the general case of cooperative systems, the transmitter may select to use cooperative transmission when a desired rate is not met with a direct transmission. However, without loosing generality we assume that with the proposed protocol the optimal mode is always selected whether it is PLNC-OL, COOP, or Direct. Now consider that the channel bandwidth is W, the transmitter power P, additive white Gaussian noise (AWGN) with zero mean and variance σ^2, and $\gamma_i = |h_i|^2$. If we assume Rayleigh block fading channels where the attenuation is considered constant throughout the transmission of a single frame then the SNR between two nodes in our system is given by $SNR = \frac{P\gamma}{\sigma^2}$. The estimated rate of the Direct transmission mode is then:

$$\widetilde{R}_{DIR} = W \cdot log_2(1 + \frac{P\gamma_1}{\sigma^2}). \quad (1)$$

On the other hand, the estimated rate of the cooperative transmission COOP that occurs in two orthogonal time slots for the example in Fig. 1 will be [11]:

$$\begin{aligned} \widetilde{R}_{COOP} &= \frac{W}{2} \cdot min\{log_2(1 + \frac{P\gamma_2}{\sigma^2}), log_2(1 + \frac{P\gamma_1}{\sigma^2} \\ &+ \frac{P\gamma_2\gamma_4 g^2}{\sigma^2(1+\gamma_4 g^2)})\} \end{aligned} \quad (2)$$

If we consider the overhead of the complete protocol we design in the next section, the cooperative scheme will be more efficient when it is

$$\frac{L}{\widetilde{R}_{COOP}} + T_{OVHD,COOP} < \frac{L}{\widetilde{R}_{DIR}}. \quad (3)$$

The aforementioned condition can also be interpreted as follows: The COOP transmission mode is more efficient when the time duration of the cooperative transmission is shorter from the direct transmission based on the estimated rate, plus the associated protocol overhead (T_{OVHD}) that is incurred by the cooperative protocol.

Now we present the estimated sum-rate of the PLNC-OL transmission from the present relay and for the unicast transmissions depicted in Fig. 1, i.e. $N_1 \to N_2$ and $N_4 \to N_5$. This sum-rate expression for two interfering transmissions incorporates the overheard information that is used for decoding the respective signals/packets at each receiver. This will be equal to [4]:

$$\begin{aligned} \widetilde{R}_{POL} = W \cdot \log_2 \Big(1 &+ \frac{P\gamma_1}{\sigma^2} + \frac{P\gamma_8}{\sigma^2} + \frac{P\gamma_2\gamma_4 g^2}{\sigma^2(1+\gamma_4 g^2)} \\ &+ \frac{P\gamma_4\gamma_7 g^2}{\sigma^2(1+\gamma_4 g^2)} + \frac{P^2\gamma_1\gamma_4\gamma_7 g^2}{\sigma^4(1+\gamma_4 g^2)} \\ &+ \frac{P^2\gamma_2\gamma_4\gamma_8 g^2}{\sigma^4(1+\gamma_4 g^2)} - \frac{P^2\gamma_4 Re(h_1 h_2^* h_7 h_8^*) g^2}{\sigma^4(1+\gamma_4 g^2)}\Big) \end{aligned} \quad (4)$$

The above formula is not a pre-requisite for the the operation of the proposed rate estimation algorithm and of course the entire protocol. Similar transmission modes like PLNC-OL could be utilized in conjunction with a suitable analytical rate expression. Also for the PLNC-OL mode to be more efficient than COOP in addition to inequality (3), the following condition must be true:

$$\frac{L}{\widetilde{R}_{POL}} + T_{OVHD,POL} < \frac{L}{\widetilde{R}_{COOP}} + T_{OVHD,COOP} \quad (5)$$

Relays use the previous rate estimation expressions for estimating the possible rate between for all the available channel estimates that they have stored for their neighbors. These results populate a data structure and in this case we name it **rate_estimates**.

IV. Cooperative PLNC MAC (CPLNC-MAC)

The two previous algorithms for cooperative channel information exchange and rate estimation are essential for the operation of our system but they do not affect directly the channel access mechanism. Now we describe the third central component of the complete system that is the CPLNC-MAC protocol. The proposed protocol does not affect the contention and channel access mechanism but only the cooperative packet transmission procedure.

A. Basic Protocol and Busy Tones

The $tx\_data()$ subroutine in the pseudo-algorithm of Fig. 2 depicts the actions executed at a sender when it desires to transmit a data packet. Let us assume that an RTS/CTS message exchange has finished (line 5 in the previous subroutine) and several relays have updated the **rate_estimates** as we explained in the previous section. Then the potential relays indicate their ability to relay a transmission by using busy tones that are transmitted after a time duration equal to T_{SIFS} after the end of the CTS transmission[1]. Note that busy tones are also transmitted in the same channel while there is no separate control channel. The conditions for transmitting busy tones are the following: A busy tone is transmitted from a relay candidate in the first slot after T_{SIFS}, if the relay desires to indicate that the PLNC-OL mode is efficient for improving the rate of the system by combining the indicated transmission with another transmission. This is indicated in line 5 of the $relay\_overhear()$ subroutine in Fig. 2. When

[1]For being compatible with the basic RTS/CTS message exchange of existing devices the transmission of the busy tone may be delayed for the duration of one slot. This will allow a legacy node to start transmitting a data frame before any relay indicates its intention with busy tones (see Fig. 3).

```
tx_data(D, payload)
1: execute_backoff()
2: dsts = {D}
3: tx_phy(RTS, dsts, payload), wait(T_SIFS)
4: if rx_phy() == CTS then
5:    wait(T_SIFS),check_channel(T_s)
6:    if busy tone received? then
7:       dsts = {Relay_opt^PLNCOL, D}
8:    else
9:       wait(T_s), check_channel(T_s)
10:      if busy tone received? then
11:         dsts = {Relay_opt^COOP, D}
12:      end if
13:   end if
14: end if
15: for all slots until N do
16:    check_channel(T_s)
17:    if rx_phy() == CTS||CTC then
18:       wait(T_SIFS), tx_phy(DATA, dsts, payload)
19:    end if
20: end for
relay_overhear(S, D)
1: update rate_estimates, channel_estimates
2: wait(T_SIFS)
3: if (R~^COOP > R~^DIR) then
4:    if (R~^PLNC > R~^COOP) then
5:       tx_phy(busy_tone)
6:    else
7:       wait(T_s), tx_phy(busy_tone)
8:    end if
9:    relay_backoff(R~, N), tx_phy(CTC, dsts)
10: end if
```

Fig. 2. Pseudo-code of the main functionality of the proposed cooperative CPLNC-MAC protocol at the sender and the relay.

no busy tone is transmitted after T_{SIFS} plus T_s, this means that this transmission cannot use the PLNC-OL mode jointly with another transmission based on the latest estimate by the relay(s). On the other hand, the first slot after CTS plus T_{SIFS} remains idle, and a busy tone is transmitted by a relay in the second slot, when the rate can be improved by enabling the COOP mode (again depicted in the $relay\_overhear()$ subroutine in Fig. 2). Similarly with before, several potential relays can transmit a busy tone. The optimal one has again to be selected in a similar way as in the case of PLNC-OL.

Finally, if no busy tone is transmitted in any of the first two slots after T_{SIFS}, the Direct transmission mode is selected instead. In this last case, the node that obtained the channel and sent the first RTS will send directly the data packet waiting at most T_{SIFS} plus $2T_s$ after the CTS reception. This minor delay of two time slots is very short when compared to the overall performance benefits of the proposed scheme. Note that busy tones are used since other relay candidates might also transmit a busy tone in the same slot (e.g. nodes N_6, N_7), which means that at least one node can be used for PLNC-OL.

B. Relay Prioritization

The next question is the following: How does the system treat multiple relay candidates? From all the potential relay nodes, the one with the highest possible increase in the transmission rate should obtain the channel and be used as a relay. To solve this problem a separate round is introduced during which relays are allowed to contend for this role. Fig. 3 presents how two relays contend for the relaying opportunity. We named this process *the relay contention round* and it works as follows. After the relay nodes transmit their respective busy tones, they set the value of a special backoff counter. The contention slot counter at a relay is set in terms of slots as $T_{RBKF} = (2 \cdot N - \lfloor \widetilde{R} \cdot N \rfloor) \cdot T_s$, where N is the maximum value for the contention slots. The value of N depends on the maximum allowed delay and it should be configured for the complete network during the initialization phase. What this formula does is that it allocates a smaller number of slots for nodes that can achieve the higher rate with any transmission mode[2]. In this way the relay with the highest possible rate obtains the channel by minimizing the number of slots it has to wait before it transmits a CTC message. Other potential relays that overhear a transmitted CTC, can infer safely that another more optimal node will relay the impending transmission, and they simply stop the T_{RBKF} timer. Now, the overhead in time slots that the proposed protocol introduces can now be easily derived from Fig. 3 as follows:

$$T_{OVHD} = T_{RTS} + 2T_{CTS} + 3T_{SIFS} + 2T_s + T_{RBKF} \quad (6)$$

After the T_{RBKF} timer expires, the relay transmits a clear to cooperate (CTC) message towards both nodes that should transmit concurrently (line 9 in the $relay\_overhear()$ subroutine of Fig. 2). CTC is essentially a CTS message that contains two destination addresses and indicates to the senders that the concurrent transmission can take place after T_{SIFS} allowing thus a synchronized collision. From the perspective of the initial sender of the RTS, the process that checks the existence of CTC and the transmition the actual data packet is handled in lines 15-20 of the $tx\_data()$ subroutine in Fig. 2. The main advantage of the proposed protocol is that the receivers do not need to explicitly identify the PLNC-OL transmission since they know that signals that are received after the CTC will interfere. The only need by the receiving nodes is to check the CTC header and make sure that they are one of the intended destinations of the impending PLNC-OL. This means that they can employ the ML decoding algorithm that we describe in [4] directly after the reception of the interfered packets.

V. Performance Evaluation

The performance of the proposed system is evaluated through computer simulation in Matlab. We assume that nodes are randomly placed in a single cell and that pairs

[2]Note that $\widetilde{R}$ is the normalized estimated rate gain from any transmission mode and takes values between 1 and 2, with 2 denoting the maximum gain, i.e. two packets/slot.

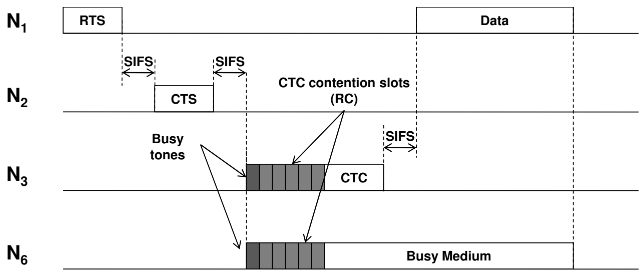

Fig. 3. Distributed optimal relay selection based on prioritization.

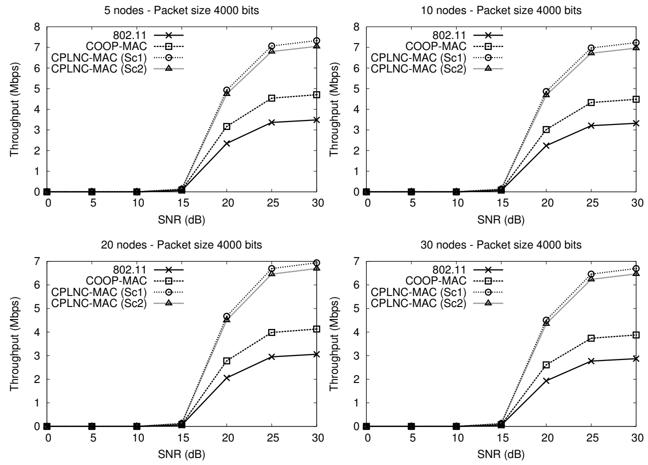

Fig. 4. Simulation results of the aggregate network throughput for different channel conditions and different number of nodes. Packet size of 4000 bits is used.

of backlogged nodes communicate to each other. We implemented CPLNC-MAC and IEEE 802.11 and we evaluated the performance in terms of MAC layer throughput (including the overheads) and packet transmission delay under different channel conditions. All nodes are assumed to be backlogged with traffic while results are obtained for 10,000 packet transmissions. The channel access timing parameters are similar with 802.11 (T_{SIFS}=16μsec, T_{DIFS}=34μsec). Regarding the lower layer parameters we assume a channel bandwidth of $W = 20$ MHz, while the same Rayleigh fading path loss model was used for all the channels. Our assumptions in this case include a frequency-flat fading wireless link that remains invariant per transmitted PHY frame, but may vary between simulated frames. The channel quality is captured by the average received SNR γ of the wireless link. Since the channel varies from frame to frame, the Nakagami-η fading model is adopted for describing γ [1]. This means that the received SNR per frame is a random variable, where we assume $\eta = 1$ for Rayleigh fading. The noise over the wireless spectrum is additive white Gaussian noise (AWGN) with the variance of the noise to be 10^{-9} at every node/link. Regarding specifics of CPLNC-MAC, the number of *different* PLNC-OL and COOP transmissions that are monitored and kept in the data structure was 20 while the maximum number of backoff slots in the relay contention round was set to $N = 10$. For comparing our protocol, we also implemented a typical relaying scheme named COOP-MAC, that employs orthogonal cooperative transmissions without interfering signals [11].

Finally, we investigated the impact of traffic pattern changes. For the PLNC-OL mode, a change in the next hop of one of the unicast transmissions will affect the performance of the channel estimation and ML detection algorithms since they have to be executed for a different next hop destination. To this aim we devised *Scenario 1* where a source-destination pair is constant throughout the simulation, and *Scenario 2* where nodes were alternating their next-hop destination node after the transmission of 500 consecutive packets. This last scenario is one way to simulate the behavior of nodes that act as routers in multi-hop or mobile communication scenarios.

A. Throughput vs. Number of Nodes

In Fig. 4 we present the aggregate MAC layer throughput results in the complete network for different number of nodes and for different SNR of the wireless channel. The last parameter is important to be evaluated since it affects the performance of the ML detector that is executed at the receivers. The results are very representative of the performance of complete system we propose since they show that for a higher number of nodes the aggregate MAC layer throughput can remain very high. Therefore, the impact of having a high rate of enforced interfering transmissions when the number of nodes is increased, is mitigated by the proposed cooperative protocol and the associated signal recovery algorithm. It is also interesting to note that for the traffic *Scenario 2* (Sc2) the performance of the proposed scheme is barely impacted by the more frequent changes in the traffic flow. The number of nodes seems to have only minor impact in the performance of the CPLNC-MAC in *Scenario 2* when compared to *Scenario 1*. The reason for this performance difference is that as the number of nodes that contend for the channel is increased, the time period between two successive packet transmissions takes longer. This fact increases the time duration until the channel information exchange and estimation algorithm updates the available information of a node.

It is important to understand that with the proposed CPLNC-MAC the performance is always lower-bounded by the baseline COOP-MAC which means that it cannot become worse both theoretically but also practically. One way to explain this intuitively is to think that for low SNR the performance of ML detection is naturally not very good which in practice means that PLNC is not used frequently. However, even with the baseline 802.11 or COOP-MAC, the performance is also poor because of the higher bit error rate (BER) of every link.

B. Packet Transmission Delay vs. Number of Nodes

Results for the packet transmission delay versus the number of nodes can be seen in Fig. 5. Regarding the performance of the COOP-MAC protocol it reduces the delay when compared to IEEE 802.11 but only because it reduces the number of retransmissions. The lower BER corresponds to lower packet

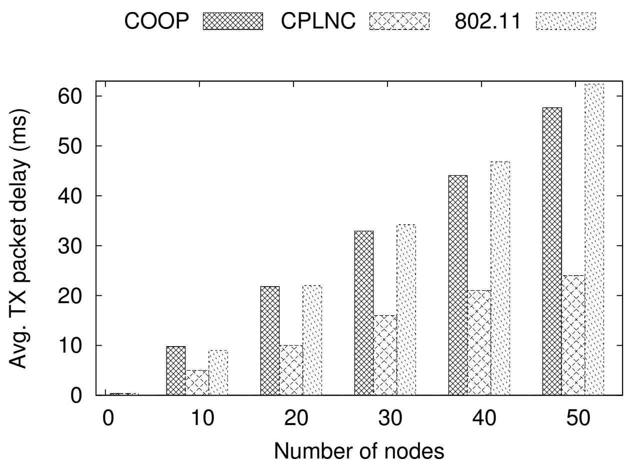

Fig. 5. Channel access delay for the three protocols under test.

error rate (PER) and eventually to a reduced number of retransmissions. On the contrary CPLNC-MAC combines the benefit that diversity provides in combination with the use of cooperative decoding, and also the benefit of transmitting two units of information in a single time slot. In our results in Fig. 5 the additional benefit of CPLNC-MAC over COOP-MAC is obvious but the delay is not exactly reduced by half as we would expect. Also note that as the number of nodes is increased with CPLNC-MAC, the rate at which the delay is increased has similar trend with the other two protocols. The explanation for these results is provided below. With the PLNC-OL mode a single packet is experiencing a higher transmission delay since it takes slightly longer to access the channel because of the altered protocol procedure. This is because the proposed protocol introduces an overhead even for the transmission of a single packet. However, if the average service time for each packet is considered, then the total delay for each packet is lower with CPLNC-MAC since it is serviced faster from the transmission queue. When a node sends an RTS before the data packet, our protocol is indirectly "fishing" for another suitable packet that could be transmitted from the HOL position in the queue of another node. Therefore, the average transmission time of packets in the complete network is theoretically reduced by half for fully backlogged nodes and without any protocol overhead. Of course in the case that nodes do not have packets to transmit, we expect that performance gains will be reduced.

VI. Implementation Issues

We do not expect implementation difficulties to arise for following reasons. First, the channel estimation is usually a process applied in existing WLANs while the relay only has to overhear RTS/CTS messages for performing this task. Second, in existing WLAN devices rate selection algorithms are also applied and are primarily vendor-specific. Third, the rate estimation algorithm requires a very small number of numerical calculations. Therefore, current hardware is capable of supporting these algorithms. The proposed decoder is basically a V-BLAST [1] decoder that is characterized by exponential computational complexity in both the number of transmitters and the size of the symbol constellation. In our system the number of transmitters is two and so the decoding complexity is similar to a 2x2 MIMO system [1]. This is the only algorithm that needs new hardware signal processing functionality at the PHY.

VII. Conclusions

In this paper we presented a cooperative MAC protocol that pro-actively enforces packets to interfere in distributed wireless local area networks. The protocol ensures that when two nodes desire to transmit packets to independent destinations, they coordinate with minimal overhead with a third relay node for concurrently transmitting over the wireless channel. The relay is responsible for ensuring that the desired packets can be decoded and recovered at the respective destinations by using analytical rate expressions. To enable distributed uncoordinated operation of the protocol, we introduce a relay selection mechanism so that the optimal relay can be selected in terms of ability to increase the achieved transmission rate. Performance results showed the efficacy of our proposed scheme in terms of both throughput and delay. In our future work we plan first to investigate in more detail the necessary protocol enhancements in multi-hop scenarios where more than two transmissions may interfere.

References

[1] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[2] M. Dankberg, M. Miller, and M. Mulligan, "Self-interference cancellation for two-party relayed communication," United States Patent 5596439, January 1997.

[3] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical-layer network coding," in *MobiCom*, 2006.

[4] A. Argyriou and A. Pandharipande, "Cooperative protocol for analog network coding in distributed wireless networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 2014–2023, October 2010.

[5] S. Boppana and J. M. Shea, "Overlapped carier-sense multiple access in wireless ad hoc networks," in *IEEE MILCOM*, October 2007.

[6] Z. Zhang, Y. Yang, and M. Zhao, "Enhancing downlink performance in wireless networks by simultaneous multiple packet transmission," *IEEE Transactions on Computers*, vol. 58, no. 5, pp. 706–718, May 2009.

[7] M. Khabbazian, F. Kuhn, N. Lynch, M. Medard, and A. P. Gheibi, "MAC design for analog network coding," MIT CSAIL Technical Report, Tech. Rep., 2010.

[8] H. Yomo and Y. Maeda, "Distributed mac protocol for physical layer network coding," in *International Symposium on Wireless Personal Multimedia Communications*, oct. 2011.

[9] "Part 11: Wireless LAN medium access control and physical layer (PHY) specifications," IEEE 802.11-1999 Standard, August 1999.

[10] A. Argyriou and A. Pandharipande, "Cooperative protocol for analog network coding in wireless networks," in *IEEE International Conference on Communications (ICC)*, May 2010.

[11] J. N. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, December 2004.

[12] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE Journal on Selected Areas in Communications, Special Issue on Cooperative Communications and Networking*, vol. 25, no. 2, February 2007.