MAC Protocol Supporting Physical-Layer Network Coding with Overhearing

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***Abstract*—Physical-layer network coding (PNC) is a promising technique for improving the throughput of wireless networks. To implement PNC in practice, a suitable medium access control (MAC) protocol is needed. Existing works mainly focus on bidirectional PNC, where two nodes exchange their packets with each other. Considering the case where unidirectional flows exist, in this paper, we propose a distributed MAC protocol to support PNC with overhearing. The proposed protocol is compatible with conventional relaying methods, including conventional network coding and plain routing. It is based on the Request-to-Send/Clear-to-Send (RTS/CTS) mechanism and can be regarded as an extension to the IEEE 802.11 MAC protocol. Simulation results show that the proposed protocol can increase the throughput of networks with unidirectional flows, especially when the traffic load is heavy.**

***Index Terms*—Medium access control (MAC), overhearing, physical-layer network coding (PNC), relaying method selection, wireless networks.**

I. Introduction

Physical-layer network coding (PNC) takes full advantage of the superposition nature of electromagnetic waves and enables source nodes to transmit simultaneously, which increases network throughput [1]–[3]. In PNC, the (typically two [4]) source nodes transmit their packets simultaneously to the relay, the relay maps the superposed signal into a new signal and broadcasts the signal to the destinations. When using PNC with bidirectional flows, each destination is also a source for the other destination. In this case, the destination knows its previously transmitted packet and can decode the intended packet from the encoded signal. With unidirectional flows, the source and destination nodes do not overlap, hence the destination has to overhear the packet from its neighboring source node to decode the packet from the distant source node. A typical topology for the latter case is the "X" topology as shown in Fig. 1, where the source node s_i $(i = 1, 2)$ wants to send data to the destination node d_i via the relay r.

One major issue that arises with PNC is to develop a practical medium access control (MAC) protocol to support simultaneous data transmission. Some existing works have considered this issue, such as [5]–[8]. However, most works focused on the two-hop scenario and did not consider queuing issues or interactions between nodes that are interconnected in

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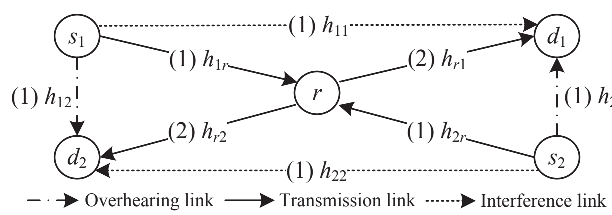

Fig. 1. Overhearing PNC in "X" topology. The number in the brackets indicates the communication phase.

a large multi-hop network. To make PNC applicable in general multi-hop networks, we proposed a distributed MAC protocol for PNC (named PNC-MAC) in [8], which is regarded as an extension to the IEEE 802.11 MAC protocol and is applicable for PNC with bidirectional flows. Noticing that unidirectional flows also exist in many wireless network applications, in this paper, we extend PNC-MAC to support unidirectional flows and overhearing. We name this protocol overhearing-supported PNC-MAC (OPNC-MAC) in our remaining discussions.

To support overhearing in OPNC-MAC, we face the following challenges:

1) As shown in Fig. 1, the signals sent from s_1 and s_2 in the first communication phase need to be respectively overheard by d_2 and d_1, and a superposed signal needs to be received by the relay r. Hence, the MAC protocol needs to ensure that there is no interference in the neighborhood of d_1, d_2, and r, and an appropriate collision avoidance mechanism is necessary.
2) Even if external interference is avoided, the simultaneously transmitting source nodes (s_1 and s_2) may interfere with the overheard signals at destination nodes (d_2 and d_1, respectively). Such self-interference causes the fact that relaying method selection only based on the network topology is inefficient [4], [9].
3) Because five nodes are simultaneously involved in the aforementioned PNC process (while only three nodes involved for PNC with bidirectional flows), it is more possible that packet loss occurs at a particular node, and actions need to be taken for such cases.

To tackle these challenges, the proposed OPNC-MAC is

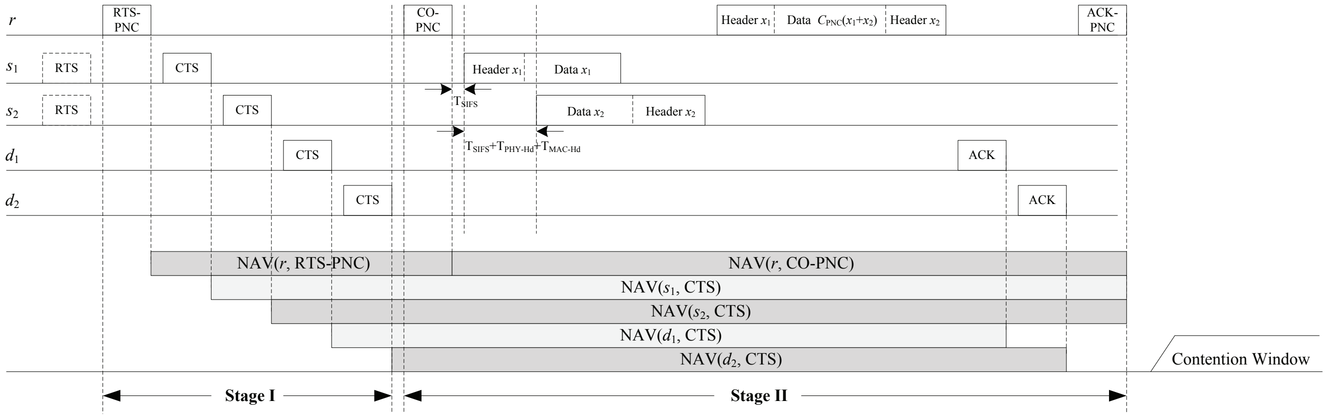

Fig. 2. Standard timing diagram of packet exchange in OPNC-MAC.

based on Request-to-Send/Clear-to-Send (RTS/CTS) with multiple CTSs from individual nodes, for channel reservation. Whether PNC should be performed is decided by a two-level process. The first level is a topology-based decision, and the PNC process is initiated when it is possible to perform PNC according to the network topology. The second level is a signal quality-based decision, i.e. making decision according to channel quality. If PNC is found inappropriate in the second level, or if not all nodes respond with CTSs, we switch back to conventional relaying methods, such as conventional network coding (CNC) and plain routing.

The remainder of this paper is organized as follows. Section II discusses the packet transmission process of OPNC-MAC and the first level of relaying method selection. Section III discusses the second level of relaying method selection and exception handling. The simulation results are given in Section IV. Section V draws conclusions.

II. Packet Exchange Process of OPNC-MAC

This section first describes the timing of OPNC-MAC. Then, the method of determining whether PNC should be initiated and the signal analysis of the PNC process with overhearing are discussed. The standard timing diagram of the packet exchange process in OPNC-MAC is shown in Fig. 2. We define T_{SIFS} as the short inter-frame space (SIFS) as in the IEEE 802.11 standard. Variables $T_{\text{PHY-Hd}}$ and $T_{\text{MAC-Hd}}$ respectively denote the time lengths of the physical-layer header and MAC-layer header. We assume that there exists an underlying routing protocol, which allows each node to be aware of the network topology within its two-hop range.

A. Initiating PNC Process

We use an RTS-PNC frame to start a PNC process. There are two cases where an RTS-PNC frame is broadcasted: 1) the relay r has the right to access channel and finds that there are PNC opportunities; 2) an RTS frame is received by r and r senses PNC opportunities. The first case is the same with the bidirectional PNC-MAC protocol in [8]. The second case extends [8] in a way that is similar with RTS/CTS of IEEE 802.11 MAC, i.e. either source node initiates data transmission and sends an RTS frame, but the relay replies with an RTS-PNC frame when it finds a PNC opportunity. Such an extension takes into account cases where the flows are unbalanced and information at r regarding whether there are PNC opportunities is not up-to-date. The sensing of PNC opportunities is based on a virtual queue at r, and the concept of virtual queues was introduced in [8] and a brief outline will be given in Section II-C. Once the relay r sends an RTS-PNC frame, the PNC process is initiated.

B. Timing of OPNC-MAC

The timing of packet exchange in OPNC-MAC has two stages as shown in Fig. 2. The stage I is the RTS-PNC/CTS stage. In this stage, after receiving the RTS-PNC frame, the received signal qualities and node statuses at s_1, s_2, d_1, and d_2 are delivered to r through CTS frames, which are used to further judge whether PNC is the appropriate relaying method, i.e. the second level of relaying method selection (details will be discussed in Section III). The stage II is the data exchange stage, where the involved nodes exchange data packets and receiving nodes acknowledge their receptions. The details of the two stages are described in the following.

In stage I, the relay r first broadcasts to all its neighbors an RTS-PNC frame, which contains the addresses of s_1, s_2, d_1, and d_2. The source node that has a shorter packet to send (which can be known by r from the virtual queue) is set as node s_1, for reasons described in the next paragraph. After receiving the RTS-PNC frame, all the involved four nodes (i.e. s_1, s_2, d_1, and d_2) separately respond to r with CTS frames.

In stage II, r broadcasts a coordination (CO-PNC) frame to coordinate packet transmissions of s_1 and s_2. CO-PNC contains information regarding whether PNC should be adopted. If PNC is used, after receiving CO-PNC, s_1 starts its data transmission after T_{SIFS}, and s_2 sends data after $2T_{\text{SIFS}} + T_{\text{PHY-Hd}} + T_{\text{MAC-Hd}}$ in a bit-reversed order, which means that the tail of data frame is transmitted at first and the header at last. Because the packet sent by s_1 is not longer than the packet sent by s_2, the time difference between the two data frames ensures that the headers of both packets sent by s_1 and s_2 can be successfully decoded by relay r [5], [8]. If the CO-PNC frame is successfully received, the destination nodes d_1

and d_2 are set in promiscuous mode to overhear the packets respectively sent by the source nodes s_2 and s_1.

The two signals sent by s_1 and s_2 are partly superposed at relay r. The relay r operates the superposed part of the signal with $C_{\text{PNC}}(\cdot)$, which can be either the amplify-and-forward (AF), denoise-and-forward (DNF), or decode-and-forward (DF) method of PNC [10]. The proposed OPNC-MAC can work well with these three methods and the DNF method is used in our simulations. After successfully overhearing packets, d_1 and d_2 are set in normal mode to reduce unnecessary overhearing. Then, the resulting partly coded packet is broadcasted to the destination nodes d_1 and d_2. After receiving the coded packet, the destination d_1 (or, correspondingly, d_2) attempts to decode the coded packet by using its overheard packet. If the destination d_1 (or, correspondingly, d_2) extracts its intended packet from the coded packet, it responds to r with an ACK frame. When at last one ACK frame is received, r sends an ACK-PNC frame to the acknowledged source node(s) and finishes this PNC round.

C. First-Level Relaying Method Selection

To sense coding opportunities and coordinate packet exchange, the relay r needs to know some information about the packets that need to be relayed by it. We use virtual queues to store this information.

The virtual queue in each node contains some essential information of the packets in the node's neighbors. Elements in the virtual queue contain four fields: 1) current node, i.e. the source node which currently holds the packet; 2) next hop, i.e. the second hop (the hop after the relay r) of the packet; 3) length of the packet; 4) staying time, i.e. the time that the packet has been staying in the current node. The relay r decides whether it should initiate PNC transmissions of its neighboring nodes or initiate to send its own packets, based on the packets in its actual and virtual queues. For more details, please refer to [8].

When PNC is not selected in the first-level judgment (i.e. RTS-PNC is not being sent), OPNC-MAC uses reliable broadcasting [11] if there is an opportunity to perform CNC, or conventional IEEE 802.11 MAC if no network coding opportunity exists.

D. Signal Analysis

When performing PNC, signal level issues need to be considered. We define z_n as noise and h_{n_i,n_j} as the channel gain from node n_i to node n_j, where n_i and n_j can be either s_1, s_2, d_1, d_2, or r. The signal sent by s_i is x_i. In the first communication phase, x_1 and x_2 sent by s_1 and s_2 are superposed at the relay. The received signal at the relay r can be written as

$$y_r = h_{s_1,r}x_1 + h_{s_2,r}x_2 + z_n \,. \tag{1}$$

The overhearing signals at d_1 and d_2 are

$$y'_{d_1} = h_{s_2,d_1}x_2 + (h_{s_1,d_1}x_1 + z_n)\,, \tag{2}$$

$$y'_{d_2} = h_{s_1,d_2}x_1 + (h_{s_2,d_2}x_2 + z_n)\,. \tag{3}$$

The direct transmission link without relaying (i.e. $s_i \rightarrow d_i$) is generally very weak, i.e. $h_{s_i,d_i}x_i$ has a small value, and we regard this signal as interference. Otherwise, s_i can directly transmit its signal to d_i without relaying.

In the second communication phase, r broadcasts the coded packet to destinations. The received signals at d_1 and d_2 are given by

$$y_{d_1} = h_{r,d_1}C_{\text{PNC}}(y_r) + z_n \,, \tag{4}$$

$$y_{d_2} = h_{r,d_2}C_{\text{PNC}}(y_r) + z_n \,. \tag{5}$$

From (1)–(5), it is easy to find that PNC may be not successfully executed when unavoidable self-interference is high at d_1 or d_2, or the bit-error-rate (BER) of the superposed signal is high at r. Moreover, in cases where overhearing links are in low quality, any type of network coding (including PNC and CNC) cannot be performed. Even when all the channels are good enough, it is also possible that some source nodes may have no packet to send but the relay assumes they have, due to obsolete information in the virtual queue which might be caused by packet losses. Therefore, it is necessary to design a scheme to decide whether to perform PNC based on the signal quality and handle cases where PNC cannot or should not be performed (although PNC is selected in the first-level judgment). We define such cases as exceptional cases.

III. Second-Level Relaying Method Selection and Exception Handling

This section proposes the second-level relaying method selection scheme and discusses how to deal with the exceptions. The selection is made based on signal quality, which is measured by the corresponding nodes and included in the CTS frames in stage I. The CTS frames also contain information on whether a source node has packets to send. When a source node indicates that it has no packet to send, we define such a CTS frame as invalid CTS; and we define all other successfully received CTS frames as valid CTS.

A. Second-Level Relaying Method Selection

When receiving four valid CTS frames, the relay r knows that the uplinks (i.e. $s_1 \rightarrow r$ and $s_2 \rightarrow r$) and the downlinks (i.e. $r \rightarrow d_1$ and $r \rightarrow d_2$) are good enough to perform plain routing. However, to determine whether it is possible to perform CNC, the relay r needs to know the BERs of the overhearing signals, which is dependent on the channel quality. Furthermore, to determine whether it is possible to perform PNC, the relay r needs to know the BERs of not only the overhearing signals but also the superposed signal at r, due to simultaneous transmissions in PNC. When the observed BERs are smaller than a given threshold, the corresponding relaying method can be adopted. Without loss of generality, in the following analysis and also in our simulations, we consider differential binary phase-shift keying (DBPSK) modulation [12], and receivers operate under the minimum distance decision rule. Based on the channel quality information in the CTS frames, the BER

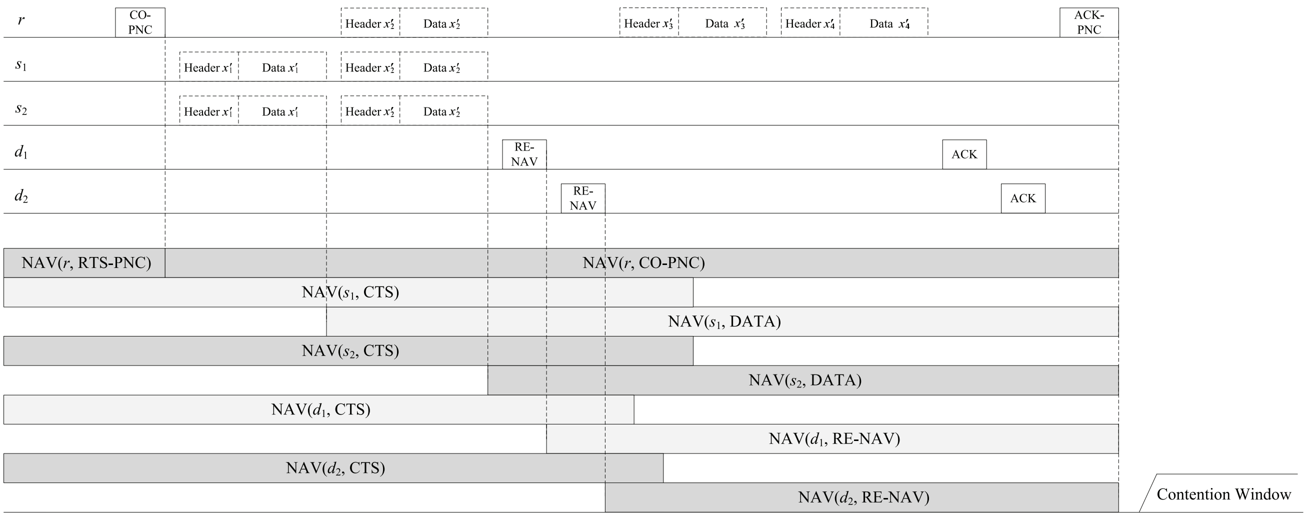

Fig. 3. Timing diagram of packet exchange in exceptional cases.

of the DBPSK modulation can be evaluated by [13]

$$P_{\text{e-DBPSK}} = 2Q\left(\sqrt{\frac{2E_s}{N_0 + IT_s}}\right), \tag{6}$$

where E_s is the received power energy per symbol, I is the total destructive interference power at the receiver node, N_0 represents the power spectrum density of noise, and T_s is the time length of each symbol. Let P_T denote the transmission power of nodes, we have $E_s = P_T \left|h_{n_i,n_j}\right|^2 T_s$.

When using the DNF method of PNC, the BER of the superposed signal received by r can be bounded by $P_{\text{e-DNF}} \leq 2P_{\text{e-DBPSK}}$ [8], and we use $P_{\text{e-DNF}} = 2P_{\text{e-DBPSK}}$ in our simulations. The BERs of the overhearing signals in PNC are calculated with (6), where I is the sum of the self-interference from the direct link and other interferences.

B. Handling Exceptional Cases

Generally, there are two main types of exceptions: 1) PNC is not the best choice for the current link conditions, i.e. PNC is found inappropriate based on the second-level judgement although being selected based on the first-level judgement; 2) the number of valid CTS frames received by r is smaller than four. In both cases, we need to switch back to CNC or plain routing (PR) in stage II of the packet exchange process.

All the possible exceptional cases are shown in Table I, and we use Fig. 3 to show how to handle these exceptions. Note that stage I is the same in all cases, which is not presented in Fig. 3 due to space limitation. The Valid-CTS column in Table I lists the nodes from which valid CTS frames have been received. As shown in Fig. 3, x'_1, x'_2, x'_3, and x'_4 denote timeslots, which may be used by different nodes or may not be used, based on different exceptional cases. The RE-NAV frame shown in Fig. 3 is used to reset the network allocation vector (NAV) when PNC is not selected and we need more than two timeslots for data exchange, because the duration of the CNC and some plain routing processes are longer than that of PNC. That is, the previous NAV setting for PNC in stage I is not suitable for the exceptional cases in stage II.

TABLE I
EXCEPTIONS AND THE CORRESPONDING RELAYING METHODS

Valid-CTS	x'_1	x'_2	x'_3	x'_4	Relaying method
s_1, s_2, d_1, d_2	$s_1 \to r$	$s_2 \to r$	$r \to s_1, s_2$	—	CNC
s_1, s_2, d_1, d_2	$s_1 \to r$	$s_2 \to r$	$r \to s_1$	$r \to s_2$	PR
s_1, s_2	$s_1 \to r$	$s_2 \to r$	—	—	—
s_1, s_2, d_1	$s_1 \to r$	$s_2 \to r$	$r \to d_1$	—	PR
s_1, s_2, d_2	$s_1 \to r$	$s_2 \to r$	$r \to d_2$	—	PR
s_1, d_1, d_2	$s_1 \to r$	$r \to d_1$	—	—	PR
s_1, d_1	$s_1 \to r$	$r \to d_1$	—	—	PR
s_2, d_1, d_2	$s_2 \to r$	$r \to d_2$	—	—	PR
s_2, d_2	$s_2 \to r$	$r \to d_2$	—	—	PR
s_1, d_2	$s_1 \to r$	—	—	—	—
s_1	$s_1 \to r$	—	—	—	—
s_2, d_1	$s_2 \to r$	—	—	—	—
s_2	$s_2 \to r$	—	—	—	—
d_1, d_2	—	—	—	—	—
d_1	—	—	—	—	—
d_2	—	—	—	—	—

When four valid CTS frames are received, and CNC is selected, r encodes and broadcasts the two received packets instead of sending them separately. Therefore, three timeslots in CNC are used as shown in Table I. Otherwise, plain routing is selected and all the data packets are sent one by one. If only two valid CTS frames are received from s_1 and s_2, then x'_1 and x'_2 are used by s_1 and s_2, and r stores the two packets in its own actual queue, and forwards them in its next channel occupation. In the cases of "s_1, s_2, d_1" and "s_1, s_2, d_2", r informs the two source nodes to send their packets, and forwards the corresponding packet to the destination, from which the valid CTS frame is received. The other packet will be stored in the actual queue of the relay. The transmission here is scheduled based on the principle of never delaying packets [14]. When receiving valid CTS frames from one source node and one or two destination nodes, the packet will be sent to the relay from the source node and then forwarded by the relay if the valid CTS frame is received from the corresponding destination node. In the worst cases that no valid CTS frame is received from source nodes, no timeslot is used, this round of packet exchange is finished immediately, and a new round of channel contention is initiated.

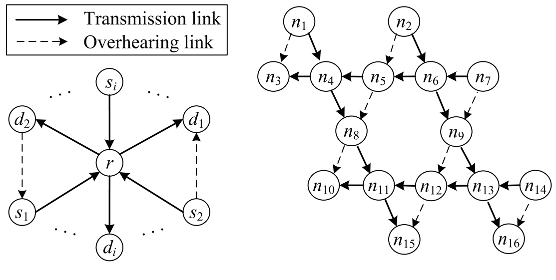

Fig. 4. Simulation topologies: (a) wheel topology, (b) #-shaped topology.

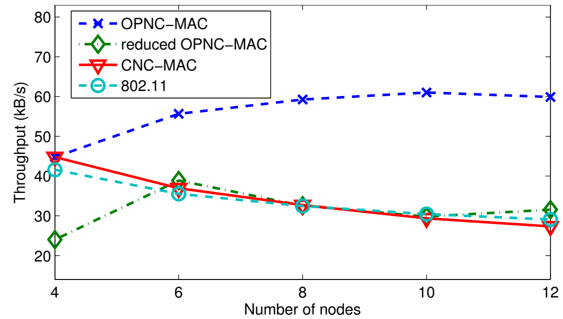

Fig. 5. Throughput vs. number of nodes in the wheel topology.

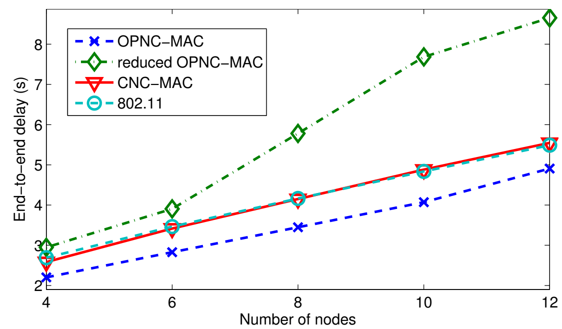

Fig. 6. End-to-end delay vs. number of nodes in the wheel topology.

IV. Simulation Results

We evaluate the performance of the proposed OPNC-MAC with our simulator jointly developed with MATLAB and C. We consider two topologies with unidirectional flows in the simulations: a wheel topology and a #-shaped topology, as shown in Fig. 4, to take into account both single relay and multiple relay cases. We consider these two special topologies because, to achieve a good performance in more complicated networks, PNC needs to be incorporated with power control and coding-aware routing [4], which is beyond the scope of this paper. We compare the performance of the proposed OPNC-MAC with that of OPNC-MAC with reduced functionality (referred to as reduced OPNC-MAC), MAC protocol for CNC with reliable broadcasting [11] (referred to as CNC-MAC), and conventional IEEE 802.11 (i.e. plain routing). In the reduced OPNC-MAC, two main functions of OPNC-MAC are removed: one is the second-level relaying method selection based on signal quality; the other is timeslot extension (to more than two timeslots) in the exceptional cases.

We use the IEEE 802.11 direct-sequence spread spectrum (DSSS) physical-layer with 1 Mbps data rate. The BER threshold used to select relaying methods in the second level is set to 10^{-3}. The transmission power is set to 3 dBm, the background noise density is –174 dBm/Hz with 6 dB noise figure. The selected source nodes send User Datagram Protocol (UDP) packets, and the packet size is 1000 bytes. The wait-for-PNC timeout (the time that the nodes should wait for transmission request from the relay when there are PNC opportunities, which is for avoiding contending with the relay and is defined in the same way as in [8]) is set to 0.1 s. The receiver's clear channel assessment (CCA) sensitivity is set to –100 dBm. The channel power gain is $|h_{n_i,n_j}| = 1/D^4_{n_i,n_j}$, where D_{n_i,n_j} is the distance between nodes n_i and n_j in meters. Each simulation is run 50 s with 10 different random seeds to obtain overall performance.

A. Wheel Topology

As shown in Fig. 4(a), in the wheel topology, nodes communicate with each other through the same relay node r. The sources $s_1, s_2, \cdots, s_i, \cdots$ and destinations $d_1, d_2, \cdots, d_i, \cdots$ are placed in a circle centered at r. The distance between r and each end node is 150 m. The source node s_i and its destination node d_i are opposite nodes, and cannot communicate with each other directly. The angle between two source-destination edges (e.g. the angle between $s_i \rightarrow d_i$ and $s_j \rightarrow d_j$) is a random value between 0 and 2π, and is changed every second. The source nodes are backlogged, i.e. they always have packets to send.

Fig. 5 shows the throughput under different number of nodes in the wheel topology. It can be observed that the throughput is approximately constant when OPNC-MAC is performed. The reason is that the relay node r coordinates the transmissions of the source nodes. Therefore, there are no contentions between these source nodes (also due to the wait-for-PNC mechanism [8]) and the throughput can be constant. We can also observe that when the number of nodes is four, the throughput of the reduced OPNC-MAC has the worst performance, which is due to ineffective first-level judgment. However, when more nodes exist, the reduced OPNC-MAC can achieve a slightly higher throughput than CNC-MAC and IEEE 802.11, because the increased spatial diversity due to the presence of more end nodes makes the first-level judgment more effective, and the coordination by r also reduces unnecessary channel contentions. It can be also observed that the CNC-MAC has a smaller throughput than IEEE 802.11 when the number of nodes is more than eight. The main reason is that coding method selection based on network topology (i.e. the first-level judgment) is inefficient even in such simple networks. The average throughput gain of OPNC-MAC over CNC-MAC is 1.65. When there are twelve nodes in the circle, the corresponding throughput gain is 2.19 because of the intense channel contention when using CNC-MAC.

Fig. 6 shows the end-to-end delay under different number of nodes. It can be observed that the delay of OPNC-MAC is the lowest. The long delay of reduced OPNC-MAC is because the first-level judgment may choose PNC as the relaying method

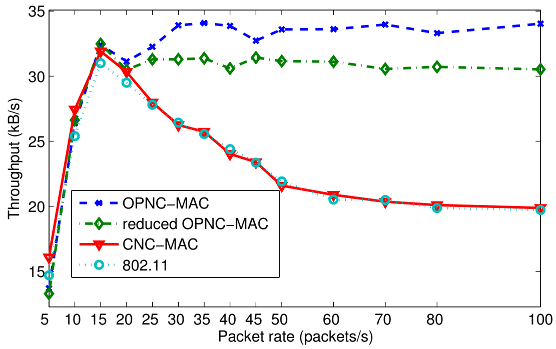

Fig. 7. Throughput vs. packet rate in the #-shaped topology.

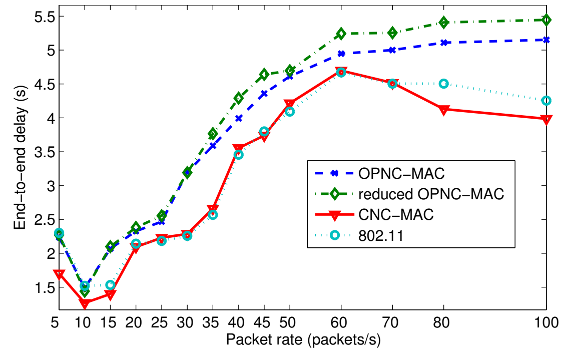

Fig. 8. End-to-end delay vs. packet rate in the #-shaped topology.

when PNC is unsuitable.

B. #-Shaped Topology

The #-shaped topology has 16 nodes as shown in Fig. 4(b). The distance between a node and its neighbors is 175 m. Four flows are configured in the topology, which are $n_1 \rightarrow n_{15}$, $n_2 \rightarrow n_{16}$, $n_7 \rightarrow n_3$, and $n_{14} \rightarrow n_{10}$.

Figs. 7 and 8 show the throughput and end-to-end delay under different packet rates. It is observed that the maximum throughput gain of OPNC-MAC over CNC-MAC is 1.54 and the average throughput gain is 1.23. OPNC-MAC outperforms the reduced OPNC-MAC especially under a high packet rate, with a maximum throughput gain of 1.21. The highest throughputs of CNC-MAC and IEEE 802.11 are achieved when the packet rate is 15 packets/s. Further increasing the packet rate decreases their throughputs, which is caused by intense channel contention. The throughput of OPNC-MAC stays similar when the packet rate is at or higher than 15 packets/s, because that the inherent operation mode of OPNC-MAC (i.e. r coordinates packet transmissions) reduces unnecessary channel contention. One important conclusion from our simulations is that OPNC-MAC is able to maintain a significant throughput gain, especially for a high offered load.

The end-to-end delay of the #-shaped topology is shown in Fig. 8. It can be observed that the end-to-end delays of OPNC-MAC and the reduced OPNC-MAC are slightly higher than those of CNC-MAC and IEEE 802.11. The reason is that, the #-shaped topology is actually composed of four "X" topologies and some of the shared nodes (i.e. n_5, n_8, n_9, n_{12}) in any two neighboring "X" topologies may become bottleneck nodes. The contention occurring at the bottleneck nodes results in unsuccessful PNC operations, and the relays have to switch to other relaying methods at the cost of delay.

V. Conclusions

In this paper, we have proposed OPNC-MAC, which extends PNC-MAC for bidirectional flows [8] to support overhearing and unidirectional flows. The proposed OPNC-MAC protocol selects the appropriate relaying method based on two-level judgment, i.e. topology level and signal level. The simulation results indicate that OPNC-MAC brings throughput improvement over conventional schemes that do not support PNC, while maintaining a reasonable delay. This demonstrates that OPNC-MAC is beneficial for networks that require high and stable throughput performance.

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References

[1] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical-layer network coding," in *Proc. ACM MobiCom*, Sep. 2006, pp. 358–365.
[2] P. Popovski and H. Yomo, "Wireless network coding by amplify-and-forward for bi-directional traffic flows," *IEEE Commun. Lett.*, vol. 11, no. 1, pp. 16–18, Jan. 2007.
[3] Y. Huang, S. Wang, Q. Song, L. Guo, and A. Jamalipour, "Synchronous physical-layer network coding: a feasibility study," *IEEE Trans. Wireless Comm.*, Apr. 2013, accepted for publication.
[4] S. Wang, Q. Song, X. Wang, and A. Jamalipour, "Rate and power adaptation for analog network coding," *IEEE Trans. Veh. Commun.*, vol. 60, no. 5, pp. 2302–2313, Jun. 2011.
[5] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: analog network coding," in *Proc. SIGCOMM 2007*, Aug. 2007, pp. 397–408.
[6] A. Argyriou and A. Pandharipande, "Cooperative protocol for analog network coding in distributed wireless networks," *IEEE Trans. Wireless Comm.*, vol. 9, no. 10, pp. 3112–3119, Oct. 2010.
[7] A. Argyriou, "Coordinating interfering transmissions in cooperative wireless LANs," *IEEE Trans. Wireless Comm.*, vol. 10, no. 11, pp. 3804–3812, Nov. 2011.
[8] S. Wang, Q. Song, X. Wang, and A. Jamalipour, "Distributed MAC protocol supporting physical-layer network coding," *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 1023–1036, May 2013.
[9] F. Wang, S. Wang, Q. Song, and L. Guo, "Adaptive relaying method selection for multi-rate wireless networks with network coding," *IEEE Commun. Lett.*, vol. 16, no. 12, pp. 2004–2007, Dec. 2012.
[10] K. Lee and L. Hanzo, "Resource-efficient wireless relaying protocols," *IEEE Trans. Wireless Comm.*, vol. 17, no. 2, pp. 66–72, Apr. 2010.
[11] A. Argyriou, "Wireless network coding with improved opportunistic listening," *IEEE Trans. Wireless Comm.*, vol. 8, no. 4, pp. 2014–2023, Apr. 2009.
[12] M. Gast, *802.11 Wireless Networks: The Definitive Guide*. O'Reilly Media, Inc., 2005.
[13] R. Gallager, *Principles of Digital Communications*. Cambridge: Cambridge University Press, 2008.
[14] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "XORs in the air: Practical wireless network coding," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 497–510, Jun. 2008.