









### Data Exchange

Data packets are exchanged with the optimal rate and power, and receptions are acknowledged by the receiving nodes. The details of the process are described next.

A coordination (CO-PNC) frame is broadcasted by  $r$  to coordinate packet transmissions of  $s_1$  and  $s_2$ , which contains information regarding whether PNC should be adopted and the transmission rates and powers that should be used by  $s_1$ ,  $s_2$ , and  $r$ .

When CO-PNC is successfully received and PNC is adopted,  $s_1$  transmits its data frame at data rate  $R(s_1)$  after  $T_{\text{SIFS}}$ , and  $s_2$  starts its transmission after  $2T_{\text{SIFS}} + (L_{\text{PHY-Hd}} + L_{\text{MAC-Hd}})/R(s_1)$  and transmits in a bit-reversed order, which means that  $s_2$  sends the tail of its data frame at first and the header at last. The node holding the shorter packet sends first, and the two packets are transmitted at the same rate. As a result, a time difference between the two data frames ensures that  $r$  can successfully decode the headers of both packets sent by the source nodes [5]. If a destination has to overhear packets, it is set to the promiscuous mode after receiving the CO-PNC frame. After successful overhearing, this destination node switches back to the normal mode.

Relay  $r$  receives a partly superposed signal sent by  $s_1$  and  $s_2$ , and broadcasts the resulting partly coded packet to the destinations  $d_1$  and  $d_2$ . Then, each destination node attempts to decode the coded packet by using the copy of its overheard/own packet. If the intended packet is extracted from the coded packet by the destination, an ACK frame is responded to  $r$ . After receiving the ACK frames from the destination nodes, an ACK-PNC frame is broadcasted to the sources  $s_1$  and  $s_2$  by  $r$  to finish this PNC round.

If PNC is not selected as the relaying method, data exchange is performed with CNC or PR. When RTS-PNC has been sent for the current transmission round but PNC is not appropriate to use according to later judgments, the data exchange stage of the timing diagram in Fig. 3 is modified to accommodate CNC or PR [7]. Otherwise, when RTS-PNC has not been sent and CNC or PR is selected directly, the reliable broadcasting method as proposed in [9] is used for CNC and the conventional IEEE 802.11 MAC is used for PR.

### NAV Setting and Updating

The length of the NAV is carried in the duration field of each frame and used to reserve channel. When nodes other than  $s_1$ ,  $s_2$ ,  $d_1$ ,  $d_2$  and  $r$  receive the frames sent during the packet exchange process, they update their NAV timers and remain silent until the time specified by the NAV timers expire. Different NAV length carried by different frames is shown in Fig. 3.

Before the relaying method and transmission rates are decided (i.e. in the stage of preparing for PNC), the NAVs of the CTS frames are temporarily set as the case where the PR relaying method is used and all transmissions are at the lowest rate, to guarantee that the temporary NAVs are not shorter than the time of the whole transmission process.

In the data exchange stage, based on the selected relaying method and transmission rates, the NAV length in the CO-PNC frame is set to precisely cover the remaining time used for data exchange. Generally, the NAV length

will be shorter than that in the CTS frame.

In conventional MAC protocols, one node updates its own NAV timer when the NAV length specified by the received frame is larger than the current NAV setting. However, we cannot update the NAV setting in the same way for our PNC-supported MAC protocol discussed in this article because the NAV length may need to be reduced. To resolve this problem, each node maintains a NAV table, which is indexed by node address. Each entry in the NAV table is an individual timer representing the corresponding node. Every time when receiving a new packet, the corresponding entry in NAV table at the receiving node is updated with the latest NAV setting from the sender (no matter whether it increases or decreases the NAV length). The node does not transmit until all NAV timers in the table expire. Recall that the source and destination nodes initially set the NAV length to the largest possible value in their CTS frames. These can be shortened subsequently in data frames and ACK frames, where the NAV lengths are set precisely to the time needed for transmission. This is possible because the relaying method has been determined at this point. When using PNC, the headers of the partly superposed data frame can be separately decoded, hence  $s_1$  and  $s_2$  can specify their NAV lengths individually.

### PERFORMANCE EVALUATION

The performance of the cross-layer collaboration mechanism is evaluated on our discrete-event simulator which has detailed physical-layer modeling and supports all the operations in the physical, MAC, and network layers. The simulator is developed jointly with MATLAB and C. We consider the following mechanisms in the simulations: 1) supporting three relaying methods (including PNC, CNC, and PR) with constant transmission powers and data rates (named as PNC-CNC-PR-const); 2) supporting three relaying methods (including PNC, CNC, and PR) with adaptive transmission powers and data rates (named as PNC-CNC-PR-adapt); 3) supporting two relaying methods (including CNC and PR) with constant transmission powers and data rates (named as CNC-PR-const); 4) supporting two relaying methods (including CNC and PR) with adaptive transmission powers and data rates (named as CNC-PR-adapt); 5) only supporting PR with constant transmission powers and data rates (named as PR-const); 6) only supporting PR with adaptive transmission powers and data rates (named as PR-adapt). The rate and power adaptation method developed in [10] is used. A random topology is considered, where 14 random flows exist among 20 nodes that are randomly distributed in an  $800 \times 800$  m<sup>2</sup> area.

The throughput performances of these mechanisms are shown in Fig. 4. We can observe that the PNC-CNC-PR-adapt mechanism outperforms other mechanisms. It implies that the PNC-oriented cross-layer collaboration mechanism can significantly improve throughput via adaptive transmission and resource allocation based on traffic pattern and network conditions. We can also observe that the PNC-CNC-PR-const mechanism performs better than other mechanisms that also have constant powers and rates. It demonstrates that PNC can improve throughput, especially

with the efficient collaboration between physical layer and upper layers. We can also find that the CNC-PR-adapt mechanism has the lowest throughput among all the mechanisms with rate and power adaption, which is caused by unnecessary overhead for coding opportunity sensing [9].

The end-to-end delay performances of these mechanisms are shown in Fig. 5. We can observe that the end-to-end delays of the PNC-supported mechanisms are similar as or slightly higher than those of the PNC-excluded mechanisms. The reason is that unsuccessful PNC operations due to contentions at bottleneck nodes cause relaying method switching at the cost of delay. However, when we compare PNC-CNC-PR-adapt with PR-adapt, the throughput gain is much higher than the delay increases. We can therefore still conclude that PNC with adaptive rate and power control is beneficial, particularly for throughput-demanding applications, such as file transfer.

In summary, the performance gain in terms of delay using PNC-CNC-PR-adapt is much better than those of most other methods, while the throughput gain is definitely the best when PNC-CNC-PR-adapt is adopted

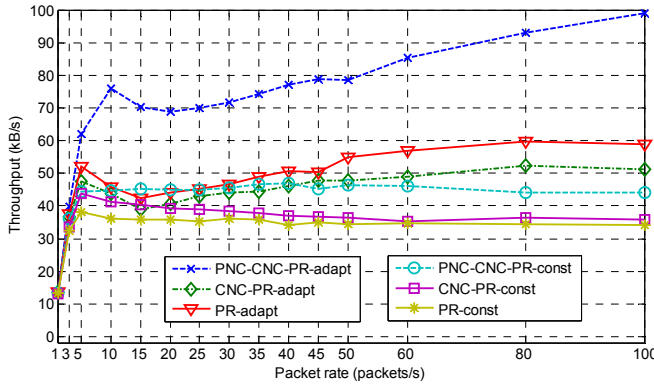


Fig. 4 Throughput comparison between different transmission mechanisms.

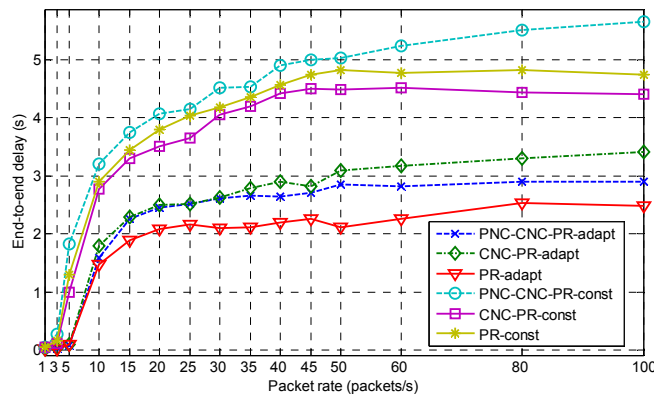


Fig. 5 End-to-end delay comparison between different transmission mechanisms.

## CONCLUSION AND FUTURE WORK

The emerging physical-layer techniques for cooperative communications are promising for improving spectrum resource utilization. In order to further explore the efficient

implementation of these techniques, in this article, we have taken PNC as an example and presented a MAC-centric cross-layer collaboration mechanism for PNC. By leveraging cross-layer coupling, the information collected from different layers is synthesized to help wireless nodes to coordinate efficiently and adaptively. The idea of cross-layer collaboration for PNC presented in this article can be applied to other similar physical-layer techniques and has the potential to advance the development of cooperative communications.

In future research, information and requirements in upper layers (e.g. application layer) should be considered to deepen the cooperation between nodes. Especially, cross-layer information exchange between the bottom three layers and the application layer should be reinforced so that users' preferences collected in the application layer can timely help the bottom three layers to optimize the cooperation via reasonable resource assignment and appropriate utilization of physical-layer techniques. Additionally, the tradeoff between performance and complexity in the cross-layer collaboration mechanism design for emerging physical-layer techniques should be considered. Efforts should be made to reach the design goal effectively by a simple way with low signaling overhead.

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