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

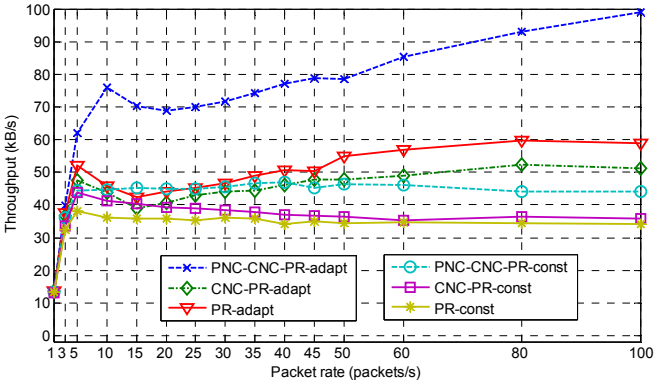

Fig. 4 Throughput comparison between different transmission mechanisms.

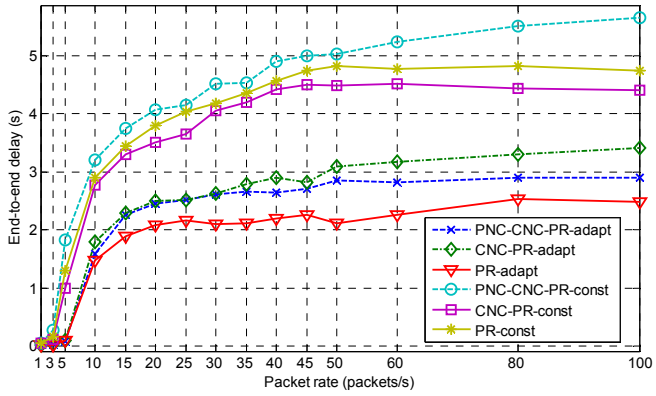

Fig. 5 End-to-end delay comparison between different transmission mechanisms.

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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References

[1] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: physical-layer network coding," in *Proc. ACM MOBICOM 2006*, Sept. 2006, pp. 358–365.

[2] A. Akhtar, M. Nakhai, A. Aghvami, "On the Use of Cooperative Physical Layer Network Coding for Energy Efficient Routing", *IEEE Transactions on Communications*, vol. 61, no. 4, April 2013, pp. 1498-1509.

[3] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: analog network coding," in *Proc. SIGCOMM 2007*, Aug. 2007, pp. 397–408.

[4] M. Khabbazian, F. Kuhn, N. Lynch, M. Medard, and A. ParandehGheibi, "MAC design for analog network coding," *MIT Computer Science and Artificial Intelligence Laboratory Technical Report*, Aug. 2010.

[5] S. Wang, Q. Song, X. Wang, and A. Jamalipour, "Distributed MAC protocol supporting physical-layer network coding," *IEEE Transactions on Mobile Computing*, vol. 12, no. 5, May 2013, pp. 1023–1036.

[6] A. Argyriou, "Coordinating Interfering Transmissions in Cooperative Wireless LANs", *IEEE Transactions on Wireless Communications*, vol. 10, no. 11, Nov. 2011, pp. 3804–3812.

[7] F. Wang, Q. Song, S. Wang, L. Guo, and A. Jamalipour, "MAC protocol supporting physical-layer network coding with overhearing," in *Proc. IEEE GLOBECOM 2013*, Dec. 2013, pp. 5128-5133.

[8] M. Gast, *802.11 Wireless Networks: The Definitive Guide, Second Edition*. Sebastopol: O'Reilly Media, Inc., 2005.

[9] A. Argyriou, "Wireless network coding with improved opportunistic listening," *IEEE Trans. on Wireless Communications*, vol. 8, no. 4, Apr. 2009, pp. 2014–2023.
[10] F. Wang, Q. Song, S. Wang, and L. Guo, "Rate and Power Adaptation for Physical-Layer Network Coding with *M*-QAM Modulation", in *Proc. IEEE ICC 2014*, Jun. 2014, pp. 5519-5524.

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