

Cooperative Wireless Networks: From Radio to Network Protocol Designs

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Abstract

Cooperative communication has been shown as an effective way of exploiting spatial diversity to improve the quality of wireless links. The key feature of cooperative transmission is to encourage single-antenna devices to share their antennas cooperatively such that a virtual and distributed antenna array can be constructed and, as a result, reception reliability can be improved and power consumption can be reduced significantly. With a better understanding of such physical-layer technique, it becomes critically important to study how the performance gain of cooperative diversity at the physical layer can be reflected at the networking layer, thus ultimately improving application performance. This article presents an overview of the network performance in cooperative wireless networks.

I. INTRODUCTION

In the last few years, there have been a lot of interests in wireless ad-hoc networks as they have remarkable commercial and military applications. Such wireless networks have the benefit of avoiding a wired infrastructure. However, signal fading is a severe problem for wireless communications particularly

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for the multi-hop transmissions in the ad-hoc networks. In real application, without considering this issue, signals may not be received properly. In order to deal this problem, the use of diversity provides a good way to reduce signal interference. The multiple-input-multiple-output (MIMO) antenna can provide spatial diversity and multiplexing gain in wireless networks. It also represents a powerful technique for interference mitigation and reduction. Therefore, to meet the needs of future wireless communications, it is advantageous to equip the associated wireless ad-hoc networks with MIMO antenna capabilities.

Towards this goal, cooperative communication is studied as an alternative and low-cost way to achieve spatial diversity. The key feature of cooperative transmission is to encourage multiple single-antenna users/sensors to share their antennas cooperatively. In this way, a virtual antenna array can be constructed and as a result, the overall quality of the wireless transmission, in terms of the reception reliability [1], [2], energy efficiency [3] and network capacity [4], can be improved significantly.

Cooperative diversity has largely been considered by physical layer researchers and various cooperative transmission protocols have been developed at the physical layer to further increase the bandwidth efficiency of cooperative diversity. There have been intensive studies on the physical layer techniques of cooperative communication, we refer the interested reader to some state-of-art works [1], [2] for a preliminary understanding of cooperative transmission at physical layer.

On the way to the development of cooperative communication, there is a considerable need to understand its practical benefits and limitations, and its inter-dependence with networking functions. Especially, it becomes critically important to study how the performance gain of cooperative diversity at the physical layer can be reflected at the network layer, thus ultimately improving application performance. To be specific, it is of fundamental importance to understand: (1) how to bring the performance gain at physical layer up to the network layer and (2) how to allocate network resources dynamically through MAC/scheduling and routing so as to trade off the performance benefit of a given transmission (optimized by allocating many cooperating nodes) against network cost (power, interference, coordination overhead and delay), which are the major motivations of this tutorial.

The remainder of this paper is organized as follows. Section II introduces the physical layer technique of cooperative communication and the motivating example. In Section III, the cooperative routing on network layer is reviewed for the multi-hop scenario. Section IV examines the end-to-end performance

gains on throughput and delay of cooperative routing. Conclusion is given in Section V.

II. PHYSICAL LAYER COOPERATIVE TRANSMISSION

In cooperative networks, each node acts two roles in the network transmission: source node and relay node. Here, relay transmission is a main feature of cooperative communication.

Figure 1 (a) shows a classic cooperative network model which is well used in most of existing literature [1], [5] and we call it *cooperative link*. A cooperative link between the source (S) and destination (D) includes two different transmission channels. The dash line is direct transmission channel from the source directly to the destination, while the combined solid lines are relay transmission channels from the source through the relay (R) to the destination. A typical cooperative transmission can be divided into two stages (i.e., time slots). During the first stage, the source broadcasts its information where both relay and destination nodes are listening. During the second stage, the relay forwards the received information to the destination. Therefore, the destination node receives two copies of the same packets transmitted through different wireless channels. There are several cooperative signaling methods (e.g., amplify-and-forward and selected decode-and-forward) that can be applied on the relay node and all these methods are shown to be efficient to achieve full 2nd order of diversity from such cooperative transmission strategy. The main advantage of cooperative communication is significant improvement of reception reliability which becomes an important criterion to measure the performance of cooperative transmission.

In order to better understand the performance of cooperative transmission, we consider an example where both the conventional direct transmission and the selected decode-and-forward (DAF) cooperation scheme are applied, respectively, between a source and a destination node to guarantee a given quality-of-service (QoS) requirement. Assuming the channel model incorporates path loss and Rayleigh fading, we can have the transmission power of direct transmission link satisfying a given QoS requirement as

$$P_D = d_{s,d}^\alpha \left(\frac{2^R - 1}{\epsilon^{out}} \right) \quad (1)$$

where $d_{i,j}$ is the distance between the nodes i and j , α is the path-loss exponent, R is the given data rate in bits/s/Hz and ϵ^{out} is the given outage probability defined by the probability of channel capacity being smaller than the rate R .

As a contrary, the total transmission power (for simplicity, both source and relay power are assumed to be identical) of the cooperative link satisfying the same QoS requirement can be derived as [1]

$$P_{\text{DAF}} = 2\sqrt{\frac{1}{2}d_{s,d}^\alpha(d_{s,r}^\alpha + d_{r,d}^\alpha)\frac{(2^{2R} - 1)^2}{\epsilon^{\text{out}}}} \quad (2)$$

It is worth noting that for a fair comparison with direct transmission using only one time slot, cooperative transmission actually employs twice the data rate at $2R$, which is shown in Figure 1 that cooperative link transmits both packet 1 and 2 together, during two consecutive time slots, so that both schemes have the same effective data rate.

A careful reader may notice that the power consumption of the cooperative transmission is not only decided by the QoS factors (R and ϵ^{out}), but also the relative distance between the relay and the source-destination pair. To illustrate the main ideas, consider a three-node scenario where the relay node is located arbitrarily within the area defined by the circle whose diameter is the straight line between the source S and destination D. The distance between the nodes S and D is assumed to be $d_{s,d} = 20m$, the required data rate is $R = 1$ bits/s/Hz, the prefixed outage probability is $\epsilon^{\text{out}} = 0.01$ and the path loss exponent is set as $\alpha = 2$. For such system setup, the power consumed by direct transmission is $p_D = 46\text{dB}$, whereas the total power consumed by cooperative transmission is shown in Figure 2 as a function of the location of the relay node on the x-y plane. Recall that the nodes S and D are located at $(-10m, 0)$ and $(10m, 0)$, respectively, the cooperative transmission scheme can achieve its best performance if the relay node locates at the center of the circle.

All in all, there is a significant reduction in energy consumption when the relay is used to construct a cooperative link. Intuitively speaking, the larger reduction of power leads to less interference, thus conceivably increasing network capacity, reducing transmission delay, etc, which is a main motivation to bring such performance gains up to the network layer and will be reviewed in the following sections.

III. COOPERATIVE ROUTING ON NETWORK LAYER

With a better understanding of the physical-layer technique, it becomes critically important to study how the performance gain of cooperative diversity at the physical layer can be reflected at the networking layer, thus ultimately improving application performance. Our approach is to achieve that by tailoring the designs of network protocols for the new physical-layer techniques. For example, by encouraging nodes

to share their antennas, the transmission pattern could yield a new routing structure at the network layer, termed as cooperative links, which are different from the direct transmission links in the sense that besides the source and destination nodes for a transmission, intermediate nodes are also involved in relaying the transmitted signal between the two nodes.

The routing problem can be approached from physical layer, MAC layer up to application layer. Moreover, the cross-layer approach has been shown to be an effective way in the cooperative routing design. Recently, the route optimization problem is analyzed by using a probabilistic link model [6], which points out that the broadcasting nature of wireless communications should be utilized by routing protocols to achieve robustness at the networking level. Explicit results provided in [6] demonstrated that it is beneficial to construct an efficient route by considering the effect of physical layer technologies. Since cooperative transmission has been recognized as an effective technology to utilize such feature of wireless communications, various cross-layer routing protocols are developed for energy-constrained networks, where the cooperative transmission technique is used to form a virtual antenna array. For example, some energy concerned cooperative routing algorithms have been developed to further reduce the total transmission power of cooperative transmission. Recently, the braid routing [7] has been considered as an alternative to realize cooperative routing in practice.

Figure 3 shows an example of the cooperative routing generated by the distributed routing algorithm in [3]. There are 100 nodes uniformly distributed in $1000m \times 1000m$ topology with the source and destination nodes located at the top left corner (node 1) and the bottom right corner (node 100), respectively. Packets are transmitted in a hop-by-hop basis from the source to the destination. Setting a target outage probability for each transmission link (either using cooperative transmission or direct transmission), we generate the Distance-Vector (DV) routing which is the green dash line (located toward the upper right direction), whereas the combined red lines represent the proposed cooperative routing. For example, the cooperative link between node 1 and 19 uses node 26 as its relay. As shown in this figure, our proposed algorithm establishes a totally different route path compared with the DV routing algorithm. Furthermore, when compared with 9 hops and 10% end-to-end ϵ^{out} for the DV algorithm, the cooperative route generated by our proposed algorithm yields much better performance in terms of end-to-end reliability: 10 hops and 3% end-to-end ϵ^{out} . Moreover, motivated by the example in Section II, it is straight forward that the error

performance of proposed algorithm improves as the node density increases. This is so because for low node density, the chance for finding a good relay to form a cooperative link is low. As the total number of nodes increases, there are more chances to locate good relay for establishing cooperative routing, thus significantly improving the end-to-end reliability.

The improvement on the end-to-end reliability is not the only benefit that we can get from cooperative routing. From another aspect, the power consumption can also be reduced by cooperative routing. In [3], we devised new approaches of cross-layer optimization for cooperative networks, and proposed a joint physical-MAC distributed approach for power optimization, which has been shown to achieve more performance gain on energy saving. To be specific, by minimizing the total transmission power of cooperative link in (2), we can reduce 21.22% transmission power of cooperative link and achieve average energy saving of 82.43% compared to direct transmission link without violating the QoS requirement. This new method combines the physical and MAC layer mechanisms to identify the best relay in a cooperative and distributed way. Furthermore, implementing such a new method in cooperative routing, the end-to-end total power consumption of the same cooperative route in Figure 3 can be reduced by a couple of dB.

Through the above demonstration, it can be shown that using cooperative transmission can typically yield more efficient routes than the non-cooperative schemes. We actually can explore more insights from cooperative routing, especially the unique structure of the cooperative link gives us more inspirations on designing more efficient cooperative routing protocols to further improve the performance gain on network performance, which will be reviewed as follows.

IV. END-TO-END PERFORMANCE GAIN ON THROUGHPUT AND DELAY

In wireless networks, the broadcast nature of wireless transmission enables cooperation by sharing the same transmissions with nearby receivers and thus can help improve spatial reuse and boost network throughput along a multi-hop routing. The performance of wireless networks can be further improved if prior information available at the receivers can be utilized to achieve perfect interference subtraction.

The idea of employing multiuser detection (MUD) in wireless networks to increase spatial reuse and throughput has been proposed in [8]. Motivated by the fact that prior information available at the receiver

can be utilized to achieve perfect interference subtraction by using the MUD scheme and therefore invite more simultaneous transmissions along a multi-hop routing, we propose here to further exploit network throughput in cooperative networks by combining the MUD scheme with supplementary cooperation strategy.

A. Interference Subtraction

We first illustrate the idea of interference subtraction by using overlapped transmission in a four-node linear network, which is shown in Figure 4 (a). Without losing generality, the distance between adjacent node is unit one, the transmission range is also assumed to be unit one and the interference range is assumed to be twice the transmission range. Packets are transmitted one by one from the source (S) to the destination (D) using a regular TDM-schedule. As can be seen from the figure, the solid line is a transmission link from one hop to another and the dashed line is interference affecting neighboring receivers. Because of the interference at the receiver R1, a new packet P2 cannot be transmitted until P1 arrives at the destination D.

Motivated by [8], network throughput can be improved by employing simultaneous transmission and the scheduling scheme employing the overlapped transmission for the four-node linear network is depicted in Figure 4 (b). We observe that when R2 forwards packet P1, which is received by R1 in previous time slot, to node R2, node R1 can actually keep a copy of the transmitted message P1 locally, thus it knows the message being transmitted by node R2 and can apply the MUD with the stored prior information P1 to mitigate the interference caused by node R2, while node S is allowed to transmit the message P2 at the same time.

The performance of the scheduling schemes is measured in terms of network throughput at destination D. We assume time slots are equal length T and identical transmission power for all nodes. Since destination D successfully receives a message on an average in every two time slots, the average throughput for direct transmission with interference subtraction is $\frac{R}{2}$, rather than $\frac{R}{3}$ without interference subtraction, where R is the transmission data rate. Moreover, if we consider to use cooperative transmission in the same network scenario where path loss exponent $\alpha = 2$ and transmission power is 20dB, then with the same end-to-end outage performance, the scheduling scheme of cooperative transmission with interference subtraction has

shown better potential to improve network throughput by 24% over the scheme of direct transmission with interference subtraction and that potential can be further improved when implements supplementary cooperation with interference subtraction as will be examined in the following.

B. Supplementary Cooperation

Interference subtraction is only one way to improve the network throughput. We have focused so far the conventional cooperation strategy that the mutual information accumulation only happens at the destination node of each cooperative link. Actually, when we consider a cooperative route which is composed of multiple cooperative links, which is shown in Figure 4 (c), the relay node can also get full benefits from cooperation by taking advantage of the broadcast nature of wireless transmission to further reduce the decoding error. As depicted in Figure 4 (c) that in the $t + 1$ time slot, node R2 receives the second copy of P2 from relay R1. At the same time, relay R3 can actually overheard the same P2. That is so because the node R3 is within the interference range of node R1 and the same packet needs to go through all the nodes along the route. In essence, node R1, R2 and R3 can compose of another cooperative link called supplementary cooperation [9].

Consider the same example in the last subsection, the network throughput can be further improved from 24% to 42% when implements both interference subtraction and supplementary cooperation. In general, the results from above tell us that the supplementary cooperation with interference subtraction achieves the best performance. It is worth noting that the supplementary cooperation can be realized simply by taking the advantage of the broadcast nature of wireless transmission. Hence, compared with conventional cooperative transmission in Section II, there is no extra system overhead involved.

C. End-to-end Transmission Delay vs. Throughput

Having a large end-to-end throughput does not necessarily mean to have a small end-to-end transmission delay. Since the size of each packet and type of transmission schedule also play important roles in network performance. In order to evaluate the delay performance of cooperative transmission, we use the error exponent model [10] to formulate the random coding bound for cooperative protocols. Given a target block error probability ϵ that the receiver can successfully decode the message, the coding length N of a

packet is bounded by

$$N \geq \frac{\rho l - \ln \epsilon}{\rho \ln \left(1 + \frac{\text{SINR}}{1+\rho} \right)}. \quad (3)$$

where $\rho \in [0, 1]$ is a constant factor, l is the packet size in terms of information nats¹ and SINR is the Signal-to-Interference-Plus-Noise ratio at the receiver. Using this bound performance, we can evaluate the transmission delay of different cooperative protocols.

Moreover, in order to investigate the interference impact on network performance, we propose here to exploit delay performance in cooperative networks by implementing the same Multi-User Detection (MUD) scheme [8] under a more realistic network scenario which allows multi-node transmissions along the same route using space time reuse scheme (a regular TDM-schedule with reuse factor K).

Figure 5 shows the trade-off between the end-to-end transmission delay and the network throughput of the DAF protocol under a linear network scenario. In this example, we assume that total size of $L = 4 \times 10^4$ nats of data are transmitted via a 12 hops linear cooperative route, the normalized transmission power is 10dB, the path loss exponent is set as $\alpha = 3$ and the prefixed end-to-end reliability is $\epsilon = 10^{-3}$. The source node divide the total size of data into number of packets m to transmit using the TDM-schedule with reuse factor $K = 3$.

It is clear that as packet size ($l = L/m$) of the original data decreases, the end-to-end delay is reduced correspondingly. However, the network throughput is adversely affected by small packet size. Moreover, the interference subtraction can significantly improve the network performance.

V. CONCLUSION

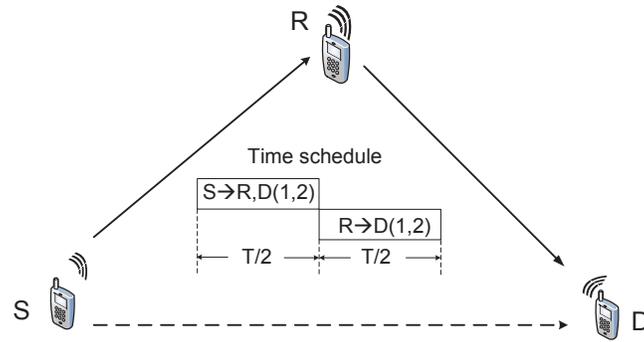
This tutorial describes cooperative wireless networks, especially on the performance of network layer. We have mainly analyzed and compared the performance of end-to-end reliability, energy consumption, throughput and delay of wireless cooperative communication. In our view, these benefits make cooperative wireless networks capable of combating radio unreliability and meeting future application requirements of high-speed and high-quality services with high energy efficiency. The acquired new insights on the network performance could also provide a precise guideline for the efficient designs of practical and reliable communications systems. Hence these results will potentially have a broad impact across a range

¹In order to simplify notation and analysis, we use information unit *nat* in this paper; $1 \text{ nat} = \log_2 e \text{ bit}$

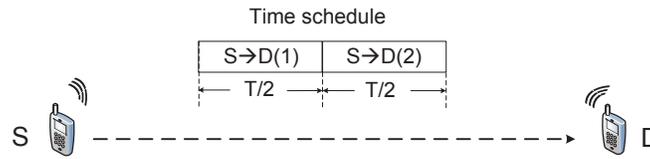
of areas, including wireless communications, network protocols, radio transceiver design and information theory.

REFERENCES

- [1] J. N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50(12), Dec. 2004.
- [2] A. Scaglione, D. Goeckel, and J. N. Laneman, "Cooperative communications in mobile ad-hoc networks: Rethinking the link abstraction," *IEEE Signal Process. Mag.*, vol. 23, pp. 18–29.
- [3] Z. Sheng, Z. Ding, and K. Leung, "Distributed and power efficient routing in wireless cooperative networks," in *Proc. IEEE International Conference on Communications (ICC)*, 2009.
- [4] A. Ozgur, O. Leveque, and D. Tse, "Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3549–3572, 2007.
- [5] I. M. Gerhard Kramer and R. D. Yates, *Cooperative Communications*. Now Publishers Inc., Hanover, USA, 2006.
- [6] E. Khandani, E. Modiano, J. Abounadi, and L. Zheng, "Reliability and route diversity in wireless networks," in *Proc. Conference on Information Sciences and Systems*, 2005.
- [7] V. Manfredi, R. Hancock, and J. Kurose, "Robust routing in dynamic manets," *Technical Report, University of Massachusetts, Amherst*, 2008.
- [8] H. V. P. C. Comaniciu, N. B. Mandayam, *Wireless Networks: Multiuser Detection in Cross-Layer Design*. Springer, 2005.
- [9] Z. Sheng, Z. Ding, and K. Leung, "Interference subtraction with supplementary cooperation in wireless cooperative networks," in *Proc. IEEE International Conference on Communications (ICC)*, 2009.
- [10] I. E. Telatar and R. G. Gallager, "Combining queueing theory with information theory for multiaccess," *IEEE J. Sel. Areas Commun.*, vol. 13, pp. 963–969, August 1995.



(a) An example of a wireless cooperative link



(b) A direct transmission link

Fig. 1. Comparison of two transmission models

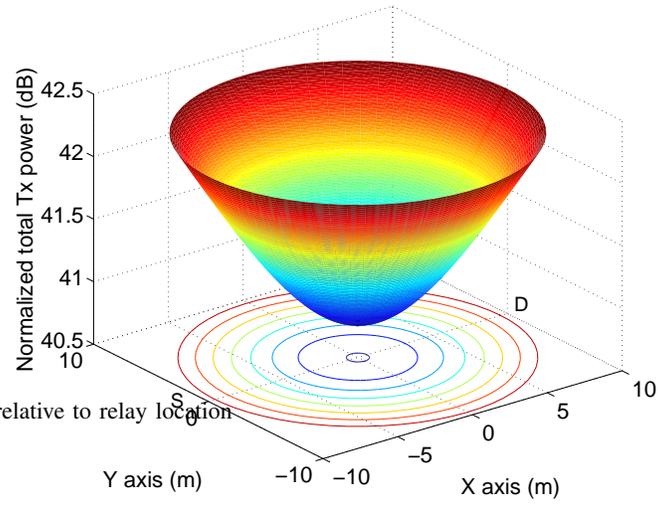


Fig. 2. Total transmission power relative to relay location

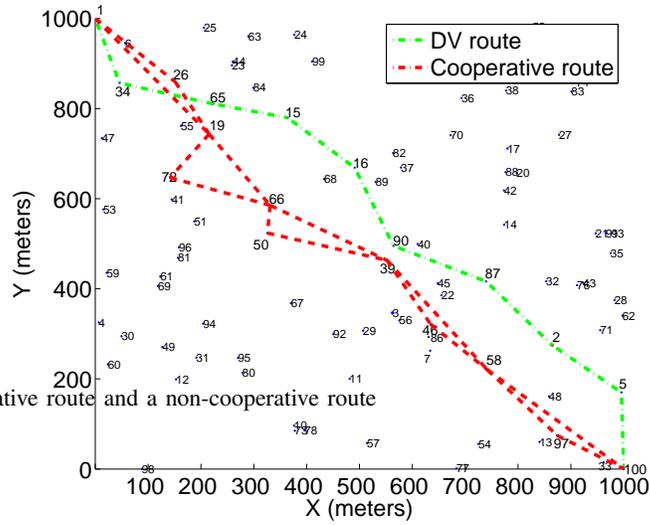


Fig. 3. Comparison of a cooperative route and a non-cooperative route

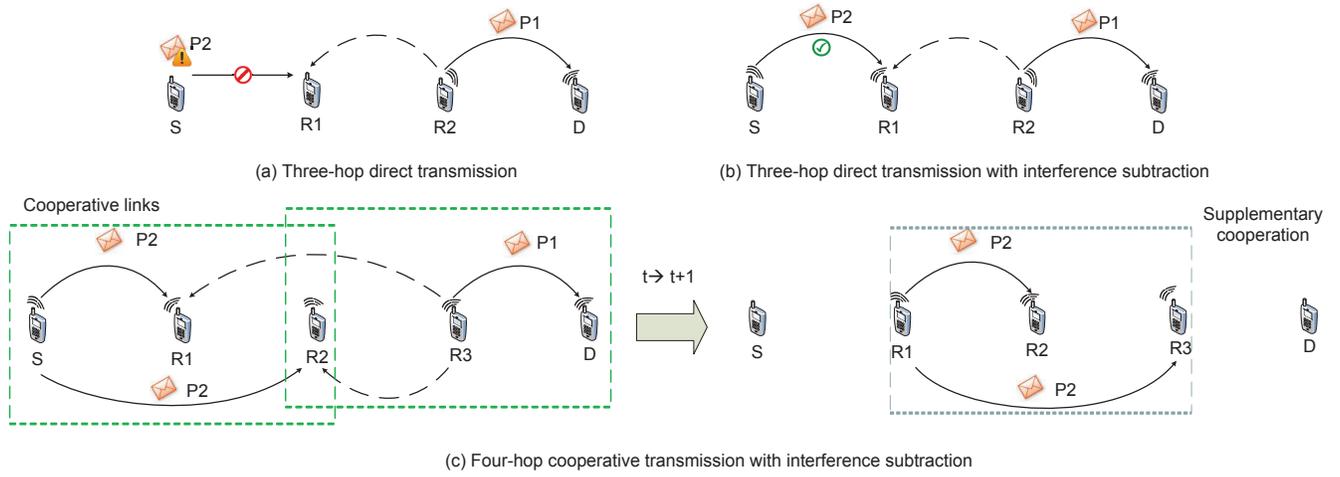


Fig. 4. An illustration of interference subtraction and supplementary cooperation

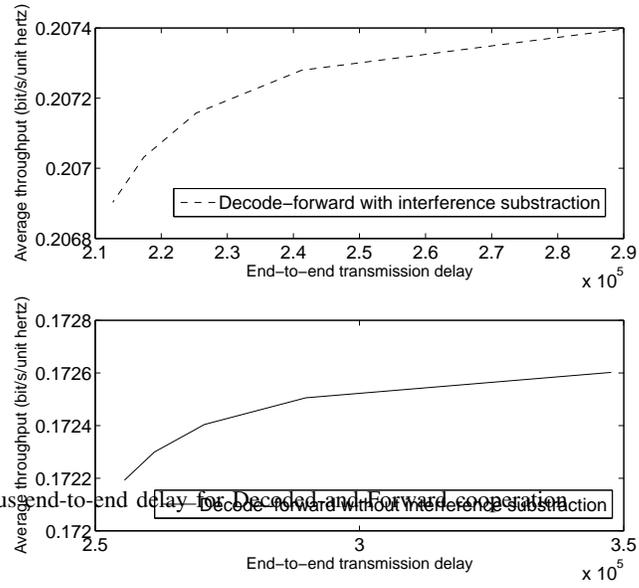


Fig. 5. Average throughput versus end-to-end delay for Decode-and-Forward cooperation



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