The Effect of Cooperation at the Network Protocol Level*

(Invited Paper)

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ABSTRACT

There has been a great deal of attention on cooperative communication which exploits the spatial diversity among antennas belonging to multiple terminals. Most of the existing work focuses on the physical layer and shows how message relaying can improve the Shannon capacity region, outage probability, diversity order, etc. But it is possible to use relays in simple, innovative ways that depend on the protocol properties at the medium access control (MAC) and network layers. In this paper we build upon prior work on such relay use by considering sets of nodes in simple topology configurations in which reaching a common destination is accomplished through direct links as well as relayed transmissions. Each non-destination node generates its own traffic for the destination but the nodes that are closer to the destination have the capability and option to relay packets from nodes farther afield. Channel quality is modeled by a reception probability which injects the physical layer property into upper layer design and analysis. We consider bursty arrival processes and we characterize the stable throughput region and delay performance at each node. We show that a proposed cooperation strategy can lead to improved performance for both work-conserving and Time Division Multiple Access (TDMA) MAC protocols. The innovative elements in this work are the balance between own and relayed traffic at each node and the fact that the performance improvement is in part due to the concentration of the queues of failed packets into fewer virtual queues.

1. INTRODUCTION

Communication in wireless networks suffers from fading, shadowing, distance attenuation and interference from concurrent transmissions. These phenomena severely impair the quality and reliability of wireless communication. The advantage of multiple-input multiple-output (MIMO) systems has been widely acknowledged to combat these negative effects [1, 2]. However, due to hardware or size limitations, many real devices are equipped with a single antenna element. Typical examples include portable mobile devices and sensor nodes.

On the other hand, the wireless networks are distinguished from the wired networks in that in wireless networks, a single transmission may reach multiple receivers, which is referred to as the wireless multicast advantage [3]. As a result, nodes in different places of a network may obtain complete or partial information about the same message. Therefore, a class of techniques known as *cooperative communication* is emerging in which nodes share their antennas and coordinate their resources to create a virtual MIMO system [4, 5, 6, 7, 8]. Most of the work on cooperative communication focuses on the physical layer and on information theoretical considerations, where the objective is to characterize the Shannon capacity region under different assumptions. However, to characterize the Shannon rate region, one must assume that the symbol length and packet delay are allowed to approach infinity. Also these works usually assume that signals from the source and the relays are combined at the receiver for detection, receiver combining is not supported by any wireless hardware though. A recent work [9] provides the evidence that performance gains can also be achieved when cooperation is implemented at the network protocol level.

In this paper, we employ the network-level cooperation on a simple setting of a tandem network of nodes. We consider a single destination and multiple sources which form a tandem in the following sense: node 1 is the "farthest" node from the destination node $(N+1)$, and every subsequent node i is progressively "closer" to $(N+1)$. This distance notion can either be real distance as in free-space communication, or "virtual distance" that also includes the effects of different fading. Therefore node i is considered to have a better channel to $(N+1)$ than $(i-1)$ does. The channel quality is modeled by means of a packet erasure probability. Under this assumption, nodes "closer" to the destination have a higher probability to successfully deliver a packet to the destination. In addition, this model in principle allows any node to decode a transmitted packet, with different reception probabilities. Thus we provide the option to node i to relay packets of its predecessor nodes $1, 2, \ldots, (i-1)$ in lieu of its own packets if the transmission by these predecessor nodes to the destination is unsuccessful but correctly received by node i.

Packets of fixed length are generated at source nodes according to random stationary processes. Therefore we evaluate the impact of protocol-level cooperation by two performance metrics: stable throughput and average queueing

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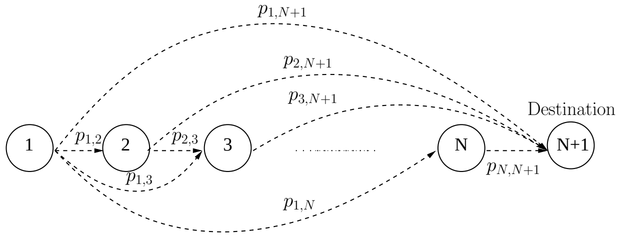

Figure 1: Wireless tandem network with probabilistic channel receptions. A total of N users communicate to the destination node $(N+1)$.

delay. Packet queues are defined to be stable if the probability that the queue length grows without bound diminishes to zero. In this sense, the stable throughput region is the set of all arrival rate vectors that can be stabilized by the network.

At the MAC layer, we study work-conserving policies and TDMA-based policies. The stable throughput regions under both work-conserving and TDMA-based cooperative policies are characterized. Further they are proved to strictly contain the non-cooperative stable throughput regions. In addition to the stable throughput, we derive the analytical expressions for the delay performance of the two-user case under both the TDMA-based policy and the priority-based policy (a special work-conserving policy). The analysis reveals that cooperation leads to reduced delay for both users. Moreover, it is shown that both the stable throughput and delay performance can be improved when the inter-user channel condition improves.

2. SYSTEM MODEL

We consider the tandem network shown in Figure 1. There are N users, numbered $1, 2, \ldots, N$, trying to communicate to a common destination node $(N+1)$ located at the right-most end of the tandem. Each source node i generates packets according to a Bernoulli process with rate λ_i. The Bernoulli processes are independent from node to node and i.i.d over slots. Packets generated by node i are denoted as class-i packets. We assume a channel with attenuation which also includes the effects of additive white Gaussian noise. When node i transmits a packet with power P, the probability that node j can decode the packet is given by:

$$p_{i,j} = \mathbf{P}\left[\frac{|h_{i,j}|^2 P}{N_0} > \gamma\right] > 0 \tag{1}$$

where $h_{i,j}$ is the channel gain from node i to node j, N_0 is the noise power level at the receiver j, and γ is the Signal-to-Noise Ratio (SNR) threshold required for correct decoding. The channel gain parameter can either be distance-dependent only as in free-space communication or it can include the effects of different types of fading represented by a random variable. Channels are independent, we also assume that nodes closer to the destination have a higher probability of successful delivery. Therefore, the reception probabilities shown in Figure 1 are such that $p_{N,N+1} > p_{N-1,N+1} > \cdots > p_{1,N+1} > 0$. We will use the reception probabilities $p_{i,j}$ throughout our work to evaluate the performance.

Intuitively, the relaying by nodes with a better channel to the destination is expected to yield performance gains. This intuition leads to the following cooperation strategy idea: when node i transmits a packet, all subsequent nodes from $(i+1)$ to $(N+1)$ can have some probability to decode the packet. If the destination $(N+1)$ successfully decodes the packet, it sends back an ACK, and every other node can hear it, so the packet exits the system; otherwise, if the destination doesn't decode the packet, but some nodes from the set $\{i+1, i+2, \ldots, N\}$ decode the packet, the node with the largest index among them (that is the node with the best channel to the destination among those that decode the packet) will keep the packet and take the responsibility to forward the packet, while all other nodes drop that packet. This can be done if any of i's subsequent nodes that decodes the packet generates an ACK, by checking all the ACKs, if a node finds itself to be the node with the largest index, it stores the packet, otherwise it drops the packet. Finally, if neither the destination nor any of i's subsequent source nodes decodes the packet, the packet remains at i's queue for retransmission. With this form of cooperation, except node 1 which only transmits packets generated by itself, every other node i, for $2 \leq i \leq N$, will forward some packets for all its predecessor nodes besides its own packets.

The evaluation of network performance requires the cross-layer interaction between the physical, MAC and network layers. At the MAC layer we separately consider two classes of multiple access policies: conflict-free work-conserving policy and Time Division Multiple Access (TDMA) policy. (a) Conflict-free work-conserving policy: a policy is *defined* to be conflict-free work-conserving if it satisfies the following two conditions: 1) It does not idle a time slot if there are packets in the system; 2) At most one backlogged node transmits in each time slot. So any channel access method is valid as long as the above two conditions are not violated. When a backlogged node i accesses the channel, it randomly picks up a packet from its queue and transmits. The packet can be its own packet, or a packet it accepts from any of its predecessor nodes. (b) TDMA policy: nodes access the channel via a TDMA-based schedule; each node is allocated a disjoint time fraction to utilize the channel. Let $\Omega = (\omega_1, \omega_2, \cdots, \omega_N)$ denote the resource-allocation vector for the N nodes, all feasible allocation vectors should satisfy $\Sigma_{i=1}^{N}\omega_i \leq 1$. Then the stable throughput region is obtained by taking the union of all stabilizable arrival rate vectors under any feasible allocation vector. At the beginning of node i's assigned time slot, i transmits a packet from its queue if it's backlogged. If i is empty, the slot is not utilized.

Together with the proposed cooperation strategy, we investigate the stable throughput and delay performance under the two cooperative communication policies.

3. RESULTS

3.1 Stable Throughput Region

In this section, we present the main results with respect to the stable throughput region. Analysis and proofs are removed for simplicity.

THEOREM 1. *$\Lambda = (\lambda_1, \lambda_2, \ldots, \lambda_N)$ is the Bernoulli arrival rate vector. The stable throughput region under both the conflict-free work-conserving and TDMA-based cooperative communication policies is the same, and is characterized by:*

$$\Re = \left\{\Lambda : \sum_{k=1}^{N} \frac{r_k}{1 - \prod_{i=k+1}^{N+1}(1 - p_{k,i})} < 1\right\} \tag{2}$$

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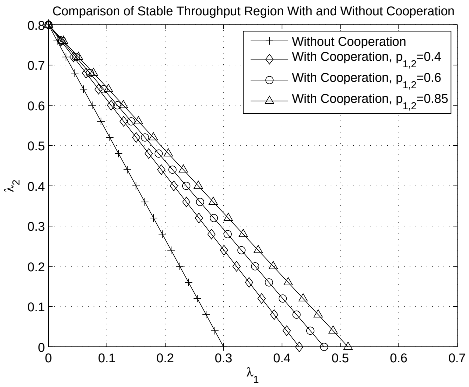

Figure 2: Comparison of stable throughput region under cooperative and non-cooperative policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

where

$$r_1 = \lambda_1$$

$$r_k = \lambda_k + \sum_{i=1}^{k-1} \frac{\left(p_{i,k}\prod_{m=k+1}^{N+1}(1-p_{i,m})\right) r_i}{1-\prod_{j=i+1}^{N+1}(1-p_{i,j})}, \qquad k \in [2, N] \tag{3}$$

THEOREM 2. *The stable throughput region of the cooperative system strictly contains the stable throughput region when cooperation is not used. The maximum stabilizable arrival rates of nodes from 1 up to $(N-1)$ strictly increase, while the maximum stabilizable arrival rate of node N stays unaffected.*

In Figure 2, we compare the stable throughput regions of the cooperative policies and the non-cooperative policies in the two-user case. In this plot, the reception probabilities of the user-destination channels are chosen to be $p_{1,3} = 0.3$, $p_{2,3} = 0.8$; while for the inter-user channel we study three channel conditions with reception probabilities: $p_{1,2} = 0.4, 0.6, 0.85$ (note that $p_{1,2}$ affects the performance of cooperative case only). The stable throughput region of the cooperative policies is found to strictly contain that of the non-cooperative policies, and the region increases as the inter-user channel condition improves.

3.2 Average Queueing Delay

It is known that delay analysis of more than two interacting queues is a very hard task [10, 11], thus we focus our effort on the case of two users. In Theorem 1, we establish that any cooperative work-conserving policy yields the same stable throughput region. However, the delay performance would vary for each different work-conserving policy. Therefore, in this section, we investigate the delay performance of the TDMA policy as well as a special work-conserving policy called the "priority-based policy". The priority rule prioritizes class-1 packets. The delay analysis relies on solving the moment-generating function of the joint stationary queue lengths as in [12], and closed-form expressions for the delay performance are derived under both cooperative policies. Analytical results and proofs are omitted for simplicity. In the following, we illustrate the delay improvement achieved by cooperation through a set of numerical results.

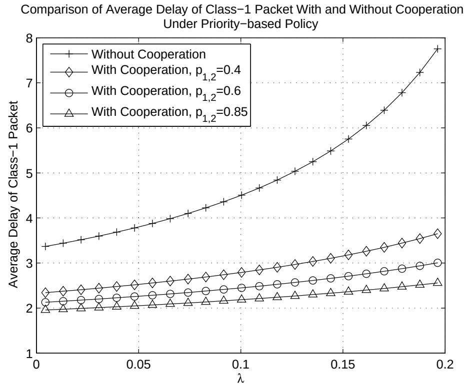

Figure 3: Comparison of class-1 packet delay under cooperative and non-cooperative priority-based policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

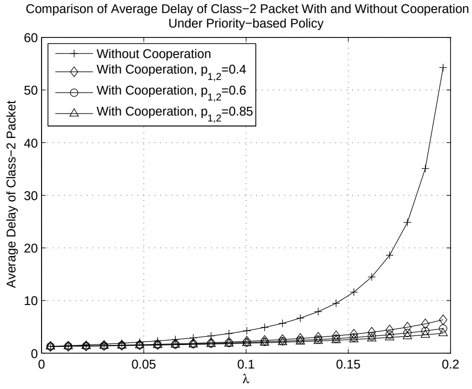

Figure 4: Comparison of class-2 packet delay under cooperative and non-cooperative priority-based policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

In Figures 3 and 4, we demonstrate the benefit of cooperation with respect to delay performance for class-1 packets and class-2 packets respectively, under the priority-based policy. The channel reception probabilities are chosen to be the same as those taken for stable throughput comparison in Figure 2. We let $\lambda_1 = \lambda_2 = \lambda$ and vary λ to obtain the shown plots. It is shown that when cooperation is used, both class-1 and class-2 packets experience lower average delay. Further as the inter-user channel quality improves, cooperation leads to more performance gains for both users.

Under the TDMA-based cooperative communication policy, when the network is stable, the analytical delay expressions are functions of the reception probabilities as well as the allocation vector (ω_1, ω_2). Among all allocation vectors that stabilize the system, we solve the optimal allocation vector (ω_1^*, ω_2^*) that minimizes the average delay over all packets. The achievable minimum overall average delay significantly decreases by following the cooperation strategy as shown in Figure 5.

Meanwhile, with (ω_1^*, ω_2^*), the average delay of class-1 and class-2 packets are compared with and without cooperation. It is seen that the delay for both the class-1 packets and class-2 packets improves over that of the non-cooperative case, as illustrated in Figures 6 and 7. Also a better inter-

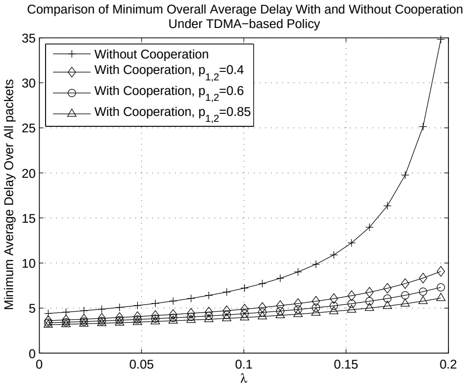

Figure 5: Comparison of minimum overall average delay under cooperative and non-cooperative TDMA-based policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

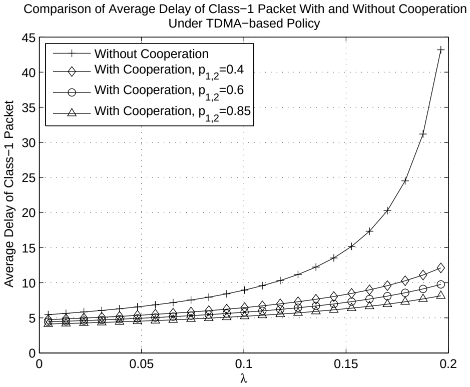

Figure 6: Comparison of class-1 packet delay under cooperative and non-cooperative TDMA-based policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

user channel helps reduce delay for the cooperative communication policy.

4. DISCUSSION

In this paper, we investigated the impact of user cooperation at the network layer in a tandem wireless network. Both performance metrics of stable throughput and delay improve for the work-conserving and TDMA MAC policies when cooperative relaying is used. The stimulating mechanism for cooperation is not addressed in this paper, but the performance gain for every user can serve as the motivation for cooperation.

The proposed cooperation strategy is simple and straightforward, but we would like to make the following comment regarding an important feature of this strategy: the cooperation strategy has the effect of concentrating packets from different sources into a single "virtual queue", i.e., node i can help in forwarding some packets for all its predecessor nodes from 1 up to $(i-1)$. Therefore, the packets stored at node i's queue are in general comprised of total i classes of packets. Given the option to schedule among multiple classes of packets, or even code over packets of different classes in a queue, the performance limit that can be approached must be an upper bound of the optimum achievable in non-cooperative case, where packets of different classes are separated in different queues. With multiple classes of packets in the same queue, it provides us the opportunity to exploit alternative cooperation strategies and inter-session network coding.

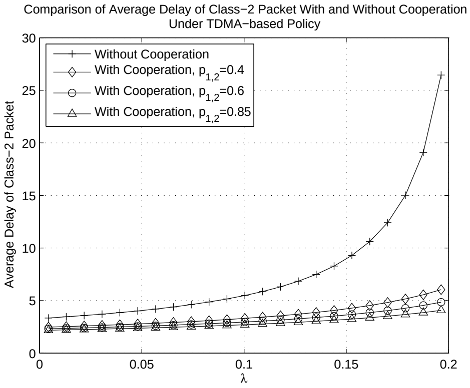

Figure 7: Comparison of class-2 packet delay under cooperative and non-cooperative TDMA-based policies, $p_{1,3} = 0.3$, $p_{2,3} = 0.8$, $p_{1,2} = 0.4, 0.6, 0.85$.

Another possible extension is to consider more general system models which allow simultaneous transmissions and multi-packet reception. With the capability to decode more than one packet at the receiver at the same time, random access policies may outperform the scheduled transmission policies. In our analysis, the wireless channel quality is simply characterized by a fixed channel erasure probability, i.e., the outcome of a transmission is a binary variable. This assumption is not practical and the channel qualities should be represented by the supportable data rates. Our focus can be on how to do joint rate and power control to achieve the optimal stable throughput region measured in bits/second. We leave all these considerations to the future work.

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