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Network-level performance evaluation of a two-relay cooperative random access wireless system☆

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ABSTRACT

In wireless networks relay nodes can be used to assist the users' transmissions to reach their destination. Work on relay cooperation, from a physical layer perspective, has up to now yielded well-known results. This paper takes a different stance focusing on network-level co-operation. Extending previous results for a single relay, we investigate here the benefits from the deployment of a second one. We assume that the two relays do not generate packets of their own and the system employs random access to the medium; we further consider slotted time and that the users have saturated queues. We obtain analytical expressions for the arrival and service rates of the queues of the two relays and the stability conditions. We investigate a model of the system, in which the users are divided into clusters, each being served by one relay, and show its advantages in terms of aggregate and throughput per user. We quantify the above, analytically for the case of the collision channel and through simulations for the case of multi-packet reception (MPR), and we provide insight on when the deployment of a second relay in the system can yield significant advantages.

1. Introduction

Cooperative communications have gained significant attention lately. Cooperation can take place in different communication layers, with the bulk of interest focusing on physical layer performance [2,3]. In that level, cooperation benefits are self-evident, since the explored systems typically belong to a single actor with interest to maximize a specific utility [4]. Promoting cooperation at higher layers, has also drawn significant attention due to the potential benefits from operators and users. Focusing on the purely network layer the benefits of utilizing cooperative techniques have been recently shown to be multi-fold, with respect to system performance in terms of throughput [5–10], reliability [11] and delay [8]. In that regard the use of dedicated relays has been introduced in may practical systems, such as wi-fi (known as range extenders) and in LTE.

1.1. Related work

The notion of cooperative communications was introduced by information theory with the relay channel. The relay channel is the basic building block for the implementation of cooperative communications, which are widely acknowledged to provide higher communication rates and reliability in a wireless network with time varying channels

☆ This work was presented in part in IEEE ICC 2013 [1].

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[3]. It was initially proposed by van der Meulen [12], and its first information-theoretic characterizations were presented in [13].

Recently, the study of the relay channel has gained significant interest in the wireless communications community. In [14] for the classic relay channel a protocol is presented for selection of reception and transmission time slots adaptively and based on the quality of the involved links. Considering full-duplex and half-duplex relaying [15] shows that if the numbers of antennas at source and destination are equal to or larger than the number of antennas at the relay, half-duplex relaying can achieve in some cases higher throughput than ideal full-duplex relaying. With beamforming and taking inter-relay interference [16] proposes two buffer-aided relay selection schemes. Interference cancellation is employed in [17] to allow opportunistic relaying selection maximizing the average capacity of the network. For a practical system, OFDMA based cellular resource allocation schemes are proposed in [18] for multiple relay stations (RS) with adaptive RS activation.

As mentioned, the majority of the works in this area focus on potential gains by cooperation on the physical layer. Recent works [5] and [6] suggest that similar gains can be achieved by network-layer cooperation. By network-layer cooperation they consider relaying to be taking place at a protocol level avoiding physical layer considerations. Random multiple access schemes in these works use the collision channel model with erasures, where concurrent transmissions will fail [6,19,20]. The collision channel however is not the appropriate model for wireless networks.

Random access with multi-packet reception (MPR) capabilities has attracted attention recently [21–24]. The seminal paper [21] was the first to examine MPR as an interaction between the physical and medium access control layers for a wireless random access network. In [22], the notion of MPR was introduced and two important theorems for the slotted ALOHA network with MPR are provided. They consider the effect of MPR on stability and delay of slotted Aloha based random-access system and it is shown that the stability region undergoes a phase transition from a concave region to a convex polyhedral region as the MPR capability improves in a two-user system. In [23], the authors specify a general asymmetric MPR model and the medium access control capacity region. In [24], the impact of a relay node to a network with a finite number of users-sources and a destination node is investigated. In this network the relay and the destination nodes have MPR capabilities. Analytical expressions for the characteristics of the relay node queue such as average queue length, stability conditions etc. were obtained. Finally, an overview of MPR-related research work covering the theoretically proved impacts and advantages of using MPR from a channel perspective to network capacity and throughput, the various technologies that enable MPR from transmitter, transceiver, and receiver perspectives and previous work on protocol improvement to better exploit MPR, is provided in [25].

1.2. Contribution

In this work, we provide a thorough study of the impact of using two relay nodes in a network to assist with relaying packets from a number of users to a destination node. We first investigate the system analytically, assuming the collision channel; then we move to assume that the system is MPR enabled and we conduct a thorough, system-level simulation study. Our common assumptions in both models are that (i) users have saturated queues and random access to the medium with slotted time[1]; (ii) the transmission of a packet takes the duration of exactly one time slot; (iii) the two relays are dedicated, i.e. do not have packets of their own, but assist the users by relaying their packets when necessary; (iv) the wireless link between any two nodes of the network is a Rayleigh narrowband flat-fading channel with additive Gaussian noise.

In the first part, we obtain analytical expressions for the arrival and service rates of the queues of the two relays, and for the stability conditions. In doing so we use the stochastic dominance technique [28] because the two queues are coupled (i.e., the service process of each queue depends on the other queue having a packet to send or not). We also look into a topology of the system in which the users are divided into two clusters. In this scenario, we consider that the users of one cluster do not interfere with the users or the relay of the other cluster, still, the relays are interfering with each other. This corresponds to the case of having the users in two distant areas. However, since the location of the users is captured by the link success probability, this scenario can cover any similar case, in which a system practitioner could leverage sophisticated clustering techniques to approach our results, even in an on-line fashion. In general, clustering can deliver results depending on the topology of the users [29]. For both scenarios (with and without clustering) we study the impact of the two relay nodes of the two cases on the aggregate throughput and the throughput per user when the queues of the two relays are stable. We show that the probabilities of the two relays to attempt transmission do not depend on each other when the queues are stable. The insertion of the second relay offers a significant performance gain (higher throughput) when the users are divided into clusters and each cluster is assigned to one relay, though in the general un-clustered scenario the gains are not as significant.

Under the MPR model, the transmission of a node j is successful if the received signal to interference plus noise ratio (SINR) is above a threshold γ_j. Here, due to queue coupling the stability analysis and the derivation of analytical expressions for the characteristics of the relays' queues such as arrival and service rates, are not tractable. We therefore conduct extensive simulations to provide a comprehensive insight into the performance of the two-relay system. We show that the use of two relays offers significant advantage in terms of aggregate and throughput per user compared to systems with one and no relay, for values of SINR threshold $\gamma > 1$. Under the clustering scenario employed in the first part we study the impact on the aggregate and throughput per user compared to the cases of no relay, one relay and two variations of two relay nodes' operation: a packet received

[1] Dealing with analytical performance evaluation of random access systems above three users with random arrivals is mathematically intractable. Specifically, assuming the sources saturated, the so-called saturated throughput can be obtained and is an inner bound of the stable throughput [26,27].