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On the performance of network coding and forwarding schemes with different degrees of redundancy for wireless mesh networks

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ABSTRACT

This work explores the throughput and delay that can be achieved by various forwarding schemes, employing multiple paths and different degrees of redundancy, focusing on linear network coding. The key contribution of the study is an analytical framework for modeling the throughput and delay for various schemes, considering wireless mesh networks where unicast traffic is forwarded and hop-by-hop retransmissions are employed for achieving reliability. The analytical framework is generalized for an arbitrary number of paths and hops per path. Another key contribution of the study is the evaluation and extension of the numerical results, drawn from the analysis, through system-level simulations. Our results show that, in scenarios with significant interference, the best throughput-delay tradeoff is achieved by single path forwarding. Moreover, when significant interference is present and network coding employs the larger packet generation size, it experiences higher delay than the other schemes. This is due to the inter-arrival times aggregating over all coded packets required to decode a packet generation.

1. Introduction

Meeting the increasing user demand for Quality of Service (QoS) in wireless multi-hop networks is a challenging issue due to their inherent limitations. Wireless networks are more error-prone and unreliable compared to their wired counterparts while wireless spectrum is limited. Moreover, transmissions on a specific link interfere with transmissions on neighboring links resulting in lower network performance [1]. Many studies have suggested utilizing different network paths in parallel in order to overcome wireless network limitations by aggregating their scarce resources. Multipath utilization for wireless networks however is a challenging issue due to interference. In wireless mesh networks for example where multiple multi-hop paths may be employed in parallel, receivers experience both inter- and intra-path interference. Adjusting the utilization of a specific link also affects the performance of neighboring links. This inherent interaction among links in a wireless environment makes modeling and controlling several parameters a complicated problem. Deriving accurate models for the performance of such networks and designing efficient multipath utilization schemes is a challenging issue.

In this study, we consider wireless mesh networks, where multiple paths are employed between a source and a destination node for forwarding flows that carry unicast traffic. Source and destination nodes are equipped with multiple interfaces and hop-by-hop retransmissions are assumed for achieving reliability. As far as redundancy is concerned, the forwarding schemes explored are: *single path* that employs zero redundancy and one path, *multipath* that employs multiple paths and zero redundancy, *multicopy* that replicates each packet on every path, and *network coding-based forwarding*. The main focus of this work is on, modeling and evaluating the throughput-delay tradeoff in this setup.

1.1. Related work

Utilization of multiple paths in parallel, in wireless networks, can provide a wide range of benefits in terms of, throughput [2], delay [3], and other performance metrics. Jointly employing multiple paths and redundancy, has been adopted by various schemes, aimed at increasing reliability [4].

The idea of using redundancy is central in channel coding theory. Several studies have employed diversity coding for link-, or path-error recovery. The work in [5] employs an M-for-N diversity coding scheme for fast recovery from link outages. The work of Tsirigos and Haas [6] considers diversity coding, and investigates the allocation of data to multiple paths that maximizes the probability of

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successful reception. The work of Tsirigos and Haas [7] extends the previous work, in the case where the failure probabilities are different for different paths, and when the paths are not necessarily independent. In our work, we consider forwarding schemes where redundancy is achieved by either employing multipath with network coding or, sending multiple copies of the same packet. We do not consider diversity coding.

Network coding is a generalization of the traditional store and forward technique. The core notion of network coding, introduced in [8], is to allow and encourage mixing of data at intermediate network nodes. Error correcting network coding is introduced in [9] as a generalization of classical error correcting codes. Several network coding related studies explore code design issues. Ahlswede et al. [8] are aimed at characterizing the admissible code rate region. The work in [10] suggests a coding scheme for both unicast and multicast traffic and also studies the coding delay in packet networks that support network coding. Booker and Sprintson [11] propose efficient algorithms for the construction of robust network codes for multicast connections. The work in [12] presents an approach for designing network codes, by considering path failures in the network instead of edge failures. The work in [13] explores a multipath transmission scheme employing network coding for providing better rate-delay trade-offs, being also adjustable according to QoS constraints. Our work explores the throughput-delay trade-off of various forwarding schemes, focusing on network coding that employs hop-by-hop and end-to-end coding.

There is a significant body of work concerning opportunistic routing in wireless mesh networks, with or without network coding. COPE [14], MORE [15] and MC^2 [16] investigate network coding with opportunistic routing in wireless networks with broadcast transmissions, focusing exclusively on the throughput improvements. ExOR [17] and ROMER [18] investigate opportunistic routing in broadcast wireless networks without network coding. Moreover, these works also focus on the throughput improvements, except [18], which also considers the packet delivery ratio. In our work, we consider flows carrying unicast traffic that are forwarded to the destination through multi-hop paths.

In [19], the authors discuss several issues that affect the performance, in terms of computational complexity, for practical network coding implementations including network coding parameters, such as, generation and field size, and also platform dependent and protocol related issues. CoMP suggested in [20] is a multipath online network coding scheme that is aimed at improving the performance of TCP sessions in multihop wireless mesh networks. The rate at which linear independent combinations are injected in the network depends on estimates of link loss rates. Oh et al. [4] suggest and evaluate through simulations, an adaptive multipath routing protocol that switches between single path, multipath with network coding, and multipath routing that replicates packets on all paths based on the observed channel loss conditions. Langberg and Medard [21] explore the advantage of network coding over standard routing for the multiple unicast network communication problem and show that under certain connection requirements it is bounded by three. The main difference of our work is that it relies on an analytical framework for modeling the throughput and delay of all these forwarding schemes. Moreover we provide simulation results in order to validate and extend the numerical results obtained. A network coding aware routing protocol is suggested in [22], that provides a better bandwidth estimate. The queueing behavior of network coding is explored in [23]. However, extending these results for a generic topology is a complicated issue. The relationship between forward error correction on the physical layer and random linear network coding on the network layer over simple network flows with end-to-end delay constraints is explored in [24]. Plain routing, analog and digital network coding are compared in a network where multiple terminals exchanging packets through a single relay in [25]. The impact of network coding on throughput and performance evaluation of network coding under different setups is explored in [26–29]. Several studies explore the utilization of network in the context of achieving reliability [30–32].

1.2. Contributions

Most of the theoretical results in network coding consider multicast traffic but the vast majority of Internet traffic is unicast. Applying network coding in wireless environments has to address multiple unicast flows, if it has any chance of being used. Especially for the case of multicast traffic, where all receivers are interested for all packets, intermediate nodes can encode any packets together, without worrying about decoding, which will be performed eventually at the destinations.

There are two key contributions in this work. The first contribution of the study is an analytical framework for modeling the throughput and delay of the aforementioned forwarding schemes. In the first part of the analysis, we express the throughput and delay for all forwarding schemes, for a simple topology, considering an erasure wireless channel where link error probability for each link is captured through the SINR model and demonstrate the complexity of generalizing for arbitrary topologies. In the second part of the analysis, the framework is generalized for an arbitrary number of paths and hops per paths, where link error probabilities are expressed through the SNR model. The second key contribution of this study is, the validation and extension of the numerical results, drawn from the analytical framework, through system-level (NS-2) simulations under realistic wireless settings.

The simulation results show that, in scenarios with significant interference, the best delay and throughput is achieved by forwarding schemes that moderate the parallel utilization of paths with the best throughput delay trade-off achieved by single path forwarding. In the presence of high interference, our analytical framework underestimates the rank of single path forwarding both in terms of delay and throughput. Moreover, when significant interference is present and network coding employs a large packet generation size, it experiences higher delay than all other schemes, due to the inter-arrival times aggregating over all coded packets required to decode a packet generation. Finally, in scenarios with lower interference, the suggested framework overestimates only the rank of network coding in terms of delay.

The rest of the paper is organized as follows. The system model considered, along with the analysis applied, are presented in Sections 2 and 3, respectively. Section 4 discusses numerical results for several wireless settings. In Section 5, the simulation setup employed is presented along with simulation results for several wireless settings. Section 6 evaluates the suggested analytical framework by comparing numerical and simulation results. Finally, the work is concluded in Section 7.

2. System model

A wireless acyclic network is assumed, where a single source sends unicast traffic to a single destination node, through multiple paths that consist of lossy links. The paths available between the source and the destination can be either node-disjoint, or share common nodes. They are assumed to be given by some multipath routing protocol [33]. Moreover, source routing is assumed, ensuring that packets of the same flow will be forwarded to the destination through the same path. As far as MAC layer is concerned, hop-by-hop retransmissions are assumed for achieving reliability, while time is slotted and packet transmission requires one time slot. When an error occurs at the transmission of a packet between two nodes, for example nodes i and $i+1$, node i retransmits the packet to $i+1$. Acknowledgements for successfully received packets are assumed to be instantaneous and error free. Nodes are also assumed to have multi-packet