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Towards an end-to-end delay analysis of wireless multihop networks

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ABSTRACT

In wireless multihop networks, end-to-end (e2e) delay is a critical parameter for quality of service (QoS) guarantees. We employ discrete-time queueing theory to analyze the end-to-end (e2e) delay of wireless multihop networks for two MAC schemes, m-phase TDMA and slotted ALOHA. In one-dimensional (1-D) networks, due to the lack of sufficient multiplexing and splitting, a space–time correlation structure exists, the nodes are spatially correlated with each other, and the e2e performance cannot be analyzed as in general two-dimensional networks by assuming all nodes independent of each other. This paper studies an 1-D network fed with a single flow, an extreme scenario in which there is no multiplexing and splitting. A decomposition approach is used to decouple the whole network into isolated nodes. Each node is modeled as a GI/Geo/1 queueing system. First, we derive the complete per-node delay distribution and departure characterization, accounting for both the queueing delay and access delay. Second, based on the departure process approximation, we define a parameter to measure the spatial correlation and its influence on the e2e delay variance. Our study shows that traffic burstiness of the source flow and MAC together determines the sign of the correlation.

1. Introduction

With the growing demand for real-time applications over wireless networks, increasing attention is paid to the delay analysis of transmissions over error-prone channels. In multihop networks, like ad hoc, mesh, and multihop cellular networks, the analysis is more challenging than in single-hop networks due to the delay accumulation at each hop. Many factors affect the end-to-end (e2e) delay, including the routing algorithm, the MAC and packet scheduling algorithm and error-prone wireless channels. The analysis is unlikely to be tractable if all these factors are considered together. However, if there is only a single active path in the network, the two-dimensional (2-D) topology (Fig. 1a) can be reduced to one-dimension (1-D) (Fig. 1b) and routing could be ignored.

In the 1-D network, referred to as line network, there is no inter-flow interference, and the corresponding performance is an upper bound for general 2-D networks. On the other hand, it is easier to approximate 2-D networks than 1-D networks because in 2-D networks the delays are closer to be independent while in single flow 1-D networks the correlation cannot be ignored. The e2e delay is determined by the joint distribution of the successive delays of a packet traversing multiple nodes. In 2-D networks, with network-wide traffic integration, all nodes may be assumed to be independent and analyzed in isolation such that the joint distribution can be approximated in a product-form [1]. Generally speaking, the conditions to permit the"independence" assumption are: (i) the peak rate of each source does not exceed 5% of the total link capacity; and (ii) no more than 10% of the departing sources go to the same immediate downstream link [2], *i.e.*, large-scale multiplexing and splitting. However, in networks with convergecasting (*i.e.*, information gathering towards a central node Fig. 1a), the above conditions do not hold since there exists a space–time correlation structure. Then it is

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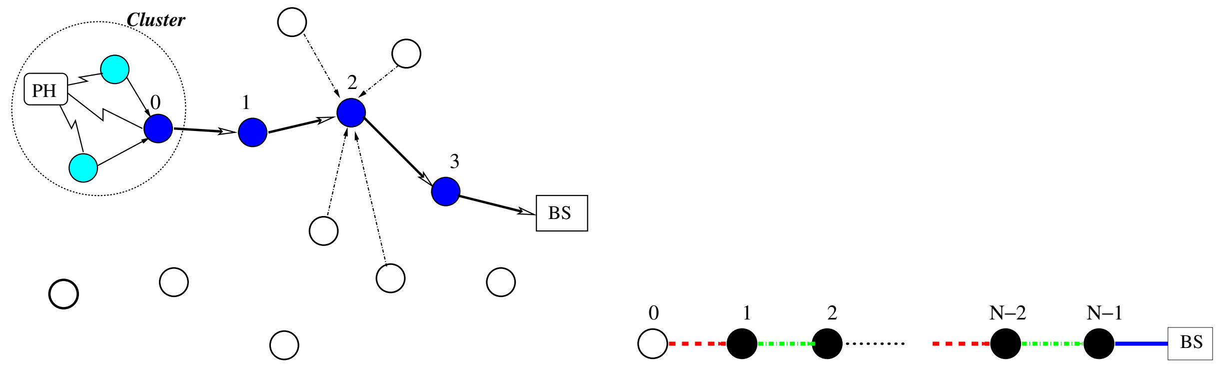

(a) General network (PH: phenomenon)

(b) Line network

Fig. 1. Wireless multihop networks.

difficult to derive the closed-form joint distribution. Specially, in an extreme case where all intermediate nodes are pure relays (Fig. 1b, which is a representative of the area closer to the base station in random networks with convergecasting), the departure process of node i is exactly the arrival to node $i+1$ and so forth and thus the space–time correlation is too strong to be ignored. Such correlations substantially complicate the e2e analysis.

The spatial correlation is mainly caused by the temporal correlation of the traffic flow, to which several factors contribute as well as the original traffic statistics. Here the *temporal correlation* is referred to as the correlation in two consecutive packet arrivals while the *spatial correlation* is the dependence between the activities of two nodes. Channel errors cause distortions to the traffic flow, which, in turn, change the temporal correlation. Such distortions may be further accumulated with multihop transmission [3]. The other factor is multiple access control (MAC) that schedules the node transmission order and may incur access delays, which certainly change the packet arrival pattern. Therefore, the study of the spatial correlation should take into account both the traffic statistics and the distortions caused by wireless channel errors and MAC.

1.1. Previous work

The throughput and single-hop delay of many MAC schemes have been comprehensively studied in the literature [4,5]. However, little work has been carried out on their multihop delay. Moreover, previous MAC studies usually assume that traffic is generated in a way that incurs no queueing delay, *e.g.*, a new node is generated to represent the newly generated packet; or new packets are generated only when the buffer is empty [5–7]. These models are simplified and unrealistic. In practice, new packets may be generated when the buffer is non-empty and thus experience a queueing delay. On the other hand, the study of queueing networks is concerned with the queueing delay only, ignoring the access delay [8–11].

Due to the presence of the queueing delay, queueing models are needed. If we assume independent wireless channel errors, the service time is geometrically distributed, and a single node can be modeled as a GI/Geo/1 system. In the literature, the queue length distribution of general GI/Geo/1 queues has been well studied [12]. However, to analyze multihop networks, the requirement for a departure process characterization arises. In the literature, only a few papers address the departure process when the arrival process has correlation in time, *e.g.*, [13]. Moreover, for non-Bernoulli and non-Poisson arrivals, it is known that the departure process is correlated with the queue length and arrival process [14], which results in cumbersome expressions [13,15] that prohibit a scalable e2e analysis. Closed-form solutions for the delay of wireless regular line networks with a single source (like Fig. 1b) are available only if the arrival is Bernoulli [9] or the channels are error-free [11]. For other cases, approximations are needed. [16] analyzed discrete-time tandem queueing networks with bursty and correlated input traffic by ignoring the correlation between nodes. An IEEE 802.11 wireless ad hoc network is modeled as a series of *independent* M/G/1 systems to obtain a delay distribution in product-form [17]. Similarly, in [18], the e2e delay variance of a two-node tandem network is derived by assuming that the two nodes are independent. The "independence" assumption usually holds for general network topologies with flow multiplexing. For line networks without multiplexing, such an assumption may lead to a very pessimistic or overly optimistic performance expression, especially in terms of delay variance.

1.2. Our contributions

This paper studies the e2e delay of a wireless line network (Fig. 1b) fed with a single source. We consider both the access delay and queueing delay. The e2e performance is investigated under two simple but typical MAC schemes, m-phase spatial TDMA [4] and slotted ALOHA. In TDMA, a node is scheduled to transmit once in m time slots, and nodes m hops apart may transmit simultaneously. In ALOHA, every node independently transmits with probability p_m whenever it has packets. TDMA (with nodes fully cooperative) and ALOHA (with nodes completely indepen-