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Generalized analytical expressions for end-to-end throughput of IEEE 802.11 string-topology multi-hop networks☆

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ABSTRACT

It is an effective approach for comprehending network performance is to develop a mathematical model because complex relationship between system parameters and performance can be obtained explicitly. This paper presents generalized analytical expressions for end-to-end throughput of IEEE 802.11 string-topology multi-hop networks. For obtaining expressions, a relationship between the durations of the backoff-timer (BT) decrements and frame transmission is expressed by integrating modified Bianchi's Markov-chain model and airtime expression. Additionally, the buffer queueing of each node is expressed by applying the queueing theory. The analytical expressions obtained in this paper provide end-to-end throughput for any hop number, any frame length, and any offered load, including most of analytical expressions presented in previous papers. The analytical results agree with simulation results quantitatively, which shows the verifications of the analytical expressions.

1. Introduction

Being highly flexible and infrastructure independent, wireless multi-hop networks have various potential applications such as sensor networks [1], vehicular ad-hoc networks (VANETs) [2–5], wireless mesh networks [6–8], flying ad-hoc networks [9], and underwater networks [10]. Basically, network nodes in ad-hoc networks operate individually, following the medium access control (MAC) protocol. The operation of network nodes, however, have interactions one another through the different MAC-layer interference, such as carrier sensing and frame collisions. The individual operations and interactions generates entire network dynamics. Because the relationship between individual operations and interactions is not simple, it is not easy to comprehend the network performance.

Mathematical models are effective for comprehending network performance because the effects of system parameters on network performance can be explicitly obtained. In addition, the statistical performance can be derived with low computational cost from mathematical models[11–37]. In this sense, the analytical expressions of network performance can be applied to protocol design [19,27,37] and/or performance optimizations [11–14,16,26,30–33].

As a fundamental and simple topology of multi-hop networks, string-topology networks are often selected for multi-hop network analyses [11–23]. Actually, many multi-hop-network analytical techniques were proposed from string-topology multi-hop network analyses. One of effective approaches for multi-hop network analyses is the use of airtime expressions, which are time-shares of network-node states [11–21]. It is possible to consider complicated interferences among network nodes by using airtime expressions [11–21]. However, such models are valid only for short-frame communications and cannot be applied to long-frame communications. Conversely, the analytical model in [15] is valid for long frame length. The results in [15] suggest that it is necessary to include the local-time duration relationship between back-off timer decrements an frame transmission in the mathematical model for expressing the network throughputs with any length frames.

☆ Part of this work has been published on the Personal, Indoor, and Mobile Radio Communications (PIMRC) [21]. The PIMRC manuscript considers only string topology network with one-way flow. The proposed analytical model in this paper is valid for the network throughput with asymmetric two-way flows, namely not only one-way flow but also two-way flows. Therefore, it is also possible to express the network throughput with multiple flows.

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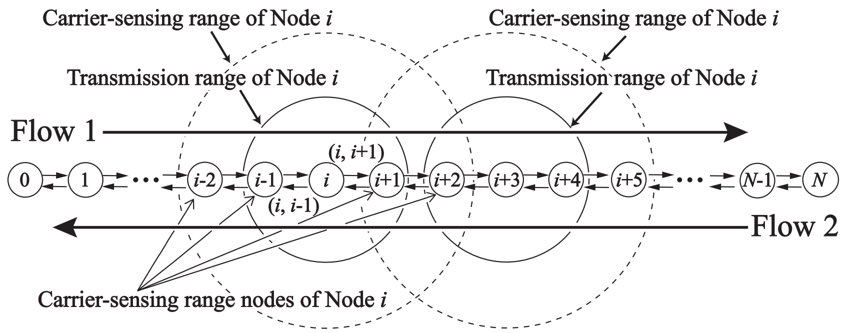

Fig. 1. *N*-hop string-topology network with two-way flow.

On the other hand, there are two situations, one- and two-way flows, in string-topology networks. In the previous mathematical models of two-way flows, it is assumed that the offered loads of one flow is the same as another flow [16,17]. Namely, there is no analytical expression of two-way flow topology, which valid for asymmetric traffics. For considering such asymmetric traffics, it is necessary to express the coexistence saturation and non-saturation flows. Additionally, there are difference-flow frames in a buffer of network nodes. Therefore, it is also necessary to establish a buffer queueing model according to the asymmetric traffics.

This paper presents generalized analytical expressions for end-to-end throughput of IEEE 802.11 string-topology multi-hop networks. Though the string-topology network is a fundamental and simple network topology, it is often used in various real applications. Additionally, analytical techniques proposed through the string-topology network can be extended to various network-topology analytical models. As the first step, we select the string-topology network as an analysis subject of this study. The presented analysis procedure includes two proposals: a local-time duration relationship of durations between backoff timer (BT) decrements and frame transmissions is expressed by integration of a modified Bianchi's Markov-chain model [21] and airtime expression; and the buffer states of network nodes are expressed by applying the queueing theory, which allows the coexistence of saturation and non-saturation flows. By including these ideas, it is possible to express end-to-end throughput for any hop number, any frame length, and any offered load analytically. The analytical predictions agree with simulation results quantitatively, which shows the verification of the obtained analytical expressions.

The rest of this paper is organized as follows: In Section 2, motivation and background of this paper are explained. We show an application-range comparison of string-topology multi-hop network analyses. In Section 3, analytical expressions for multi-hop networks for any offered load, any hop number, and any frame length are given. In Section 4, the validity of the proposed model is shown by comparisons between analytical predictions and simulation results. Section 5 discusses developments of the proposed analysis method, which is delay analysis and cross-topology network analysis. Finally, we conclude the paper in Section 6.

2. Motivation and background

2.1. String-topology multi-hop networks

Fig. 1 shows a string topology network, which is discussed in this paper. The string-topology network is fundamental and simple network in multi-hop networks. When the shortest path network is constructed, both source and end nodes are connected via multiple hops among vehicles on the spot in VANETs [2–5]. In this sense, vehicle-to-vehicle communications are often modeled by communications on string-topology multi-hop networks [2]. It can be stated that analytical expressions of string-topology multi-hop network performances are useful and valuable. Though the string-topology network has a simple network topology, it is not easy to comprehend network dynamics. This is because network nodes are interacted one another in spite of their individual operations.

2.2. Airtime expressions in analysis of multi-hop networks

It is a major purpose of the multi-hop network analyses is to obtain the analytical expressions of maximum throughput. Compared with the wireless local area network (WLAN) analyses, hidden-node problems increase the difficulty of multi-hop network analyses. Therefore, the expression of hidden-node collisions is an important and key technique for wireless multi-hop network analyses.

It is one of the effective approaches for multi-hop network analyses to use of the 'airtime' expressions, which are time shares of the network-node states [11–16,18–20]. Because the channel-access situation can be expressed using network-node airtimes, frame-collision probabilities induced by hidden nodes can be expressed in a simple form [11,12]. In the airtime expression approach, a long stretch of time in the interval of [0,*Time*] is considered. When s_i is the sum of the durations of the DATA frame transmission, ACK transmission, distributed interframe space (DIFS) and short interframe space (SIFS) for Node *i* in the interval of [0,*Time*], the transmission airtime, which is defined as the time share that Node *i* is in transmission state, by $x_i = \lim_{Time\to\infty} s_i/Time$ [11–16,18–20]. It is possible to express node operations in MAC layer with respect to each node by using airtime. Additionally, by averaging node states with airtime expressions, time shares that a node is in carrier-sensing state or channel idle state can be expressed by using the transmission airtimes of network nodes, which are explained in detail in Section 3.1. This means it is easy to express mutual interactions among network nodes by using airtimes. For example, frame-collision probabilities induced by hidden nodes can be obtained in a simple form by expressing the overlap durations of transmissions airtimes among hidden nodes [11,12].

It is assumed in [11–16,18] that all the nodes have at least one frame in the transmission buffer for obtaining the maximum throughput. Therefore, original airtime expressions cannot be applied to multi-hop network analyses in a non-saturated condition directly. For applying the airtime expressions to non-saturation condition, queueing theory is adopted for buffer-state expressions [20]. By defining "frame existence probability", which is defined as the probability that a node has at least one frame in time, network throughputs at non-saturated conditions can be modeled by using airtime expressions.