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Reliability and performance of general two-dimensional broadcast wireless network

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ABSTRACT

In this paper, an analytic model is built to study the medium access control (MAC) performance and reliability of general two-dimensional (2-D) IEEE 802.11 based wireless networks for one-hop broadcast communications. First, a semi-Markov process (SMP) model is introduced to capture the medium contention and backoff behavior and the impact of hidden terminal problem in IEEE 802.11 broadcast wireless networks in a more precise way. An M/G/1/K queue is used to model arrival and service of messages in an individual mobile terminal. To the contention for the shared medium, the SMP model interacts with the M/G/1/K queue through fixed-point iteration. Furthermore, based on the fixed-point solution, performance metrics including packet delivery probability (PDP), MAC-level and Application-level transmission delay, and MAC-level and Application-level packet reception ratio (PRR) are derived. The 2-D PDPs are derived through a coverage area computation for the impact of hidden terminal problem and concurrent transmissions to evaluate point-to-point reception probability, and then through integration of the reception probabilities over the circular intended range of the sending node. The analytical model takes into account IEEE 802.11 backoff counter process, hidden terminal problem, message inter-arrival interval, distinct transmission range, carrier sensing and interference ranges, and *Nakagami* fading channel with distance dependent path loss. Finally, as an example, the proposed analytic model is applied to a 2-D ad hoc network. The new model is validated through extensive simulations and new observations about the effects of network parameters on the performance and reliability are obtained.

1. Introduction

Wireless networks such as mobile ad hoc networks (MANETs) and wireless sensor networks deployed in desert battlefields, underwater, big square fields, and big forests can be abstracted or approximated as general two-dimensional (2-D) networks [1–4]. Broadcast services in such networks are provided widely in various wireless network applications such as safety applications in vehicle-to-vehicle communication [1,5], military battle field communication [6–8,3], and medical monitoring [9]. IEEE 802.11 based physical design and network protocols have been very commonly adopted in such wireless networks. These applications require highly reliable and real-time communications between mobile nodes under adverse environments. Modeling and analysis of IEEE 802.11 based 2-D broadcast networks plays an important role in the design and development of such networks for specific applications.

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1.1. Related work

There has been much research work on the performance analysis of IEEE 802.11 based wireless networks [10–12] and sensor networks [13]. These analyses started from Bianchi's original work in [12]. Then the work was extended to fit various different applications under different communication environments. However, most of the analytic models assumed either one-hop node spatial situations where nodes in the network can hear each other or one-dimensional Poisson node distribution. Several papers investigated the impact of the spatial distributions on the performance of networks [14,15]. However, analyses of broadcast services in the wireless networks are quite different from that in unicast systems [16]. For example, Hidden terminal area in broadcast networks is bigger than that in unicast network, and has to be evaluated in different ways [16]. Normally, the performance of broadcast networks is evaluated by simulations. In [17–20], analytical models are proposed to obtain *PRR* expressions in one-dimensional (1-D) IEEE 802.11 based broadcast ad hoc networks with hidden terminals. However, the impact of fading channel, if any, is approximated by a constant bit error rate (BER). Assuming spatially Poisson distributed nodes and saturated packet generation condition, *PRR* of beacon message broadcast in vehicular ad hoc networks is investigated in [18] taking into account the impact of *Rayleigh* fading. Unfortunately, very few network scenarios in real applications can be abstracted as 1-D models. However, extension of 1-D network reliability analysis to general 2-D network reliability analysis is not trivial. The precise computation of expected potential hidden terminal area given a random distribution of nodes in 2-D area is still claimed to be an open problem although some approximations have been made to approach the evaluation [16,21]. Recently, we conducted *PRR* analysis in a special type of 2-D ad hoc networks (two parallel lines approximate two opposite roads on highway) [22,23] and a general 2-D network with ideal communication environment [24]. An Markov chain model was proposed for the analysis of multi-hop unicast networks with *Rayleigh* fading channel in [25]. As of now, there is no work on the performance evaluation of general 2-D IEEE 802.11 broadcast networks taking real factors and adverse communication environments into account. Furthermore, MAC level or network level performance focusing on success of packet by packet transmissions, sometimes, is not sufficient to characterize the networks from application perspective [26,27]: the network 's ability for all intended mobile nodes to receive the broadcast messages within specified operation duration is more concerned about.

1.2. Our contributions

In this paper, we propose a new analytic model for the analysis of general 2-D and IEEE 802.11 based broadcast networks including all the mentioned features. Compared with the existing models for performance analysis of broadcast in the wireless networks, the main contributions of the proposed analytic model in this paper are: (1) Instead of calculating broadcast hidden terminal area directly, a new approach through integration of point-to-point packet delivery probability over intended 2-D area is proposed to derive the one-hop broadcast reliability and transmission delay accounting for IEEE 802.11 MAC, non-saturated packet generation, hidden terminal problem, and fading channel with path loss. (2) The impact analysis of distance related *Nakagami* fading on the performance is conducted; (3) Introducing semi-Markov process (SMP) model [28] interacting with M/G/1/K queue model facilitates the accurate evaluation of IEEE 802.11 broadcast and hidden terminal impact that is one of the major factors leading to the degradation of the reliability; (4) Application-level metrics are derived from the MAC-level performance and reliability; (5) Different from the existing *PRR* expressions, which are average metrics among all receivers within sender's transmission ranges, the new *PRR* in this paper are functions of the receivers' distances to the broadcast sender, which provides a deeper insight into the performance as the distances vary.

This paper is organized as follows. Section 2 presents a brief description of IEEE 802.11 broadcast MAC, broadcast hidden terminal problem, channel fading with path loss in wireless network environment, and assumptions under which the analytic model is built. Section 3 presents SMP analytic models and the fixed-point iteration algorithm. Consequently, performance metrics such as mean transmission delay, packet delivery probability, and packet reception ratio in both MAC-level and application-level are derived in the 2-D IEEE 802.11 broadcast wireless networks. Section 4 demonstrates and discusses the numerical results from the analytic model and the simulation. The paper is concluded in Section 5.

2. Description of wireless network broadcast and environment and assumptions

2.1. Distributed coordination function for IEEE 802.11 broadcast service

MAC layer of IEEE 802.11 [1] deploys a random access scheme for all associated devices in a cluster based on carrier sense multiple access with collision avoidance (CSMA/CA). In the 802.11 MAC protocols, the fundamental mechanism for medium access is the distributed coordination function (DCF). DCF is meant to support an ad hoc network without the need for any infrastructure elements such as an access point. Broadcast procedure of 802.11 MAC follows the basic medium access protocol of DCF. Broadcast of wireless network MAC occurs when a broadcast packet arrives at wireless network MAC layer from the upper layer and the MAC senses the channel status first and stores the status. Next, once an idle period is equal to DCF inter-frame space (DIFS) or extended inter-frame space (EIFS) (if previously received frame or packet contains error, before transmitting a frame, it has to defer EIFS duration. Otherwise, DIFS delay is deferred) is observed, MAC takes the next operation according to the stored channel status and the current value of its backoff time. If the current value of the