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# Performance analysis of contending customer equipment in wireless networks

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ABSTRACT

Initial ranging is the primary and important process in wireless networks for the customer premise equipments (CPEs) to access the network and establish their connections with the base station. Contention may occur during the initial ranging process. To avoid contention, the mandatory solution defined in the standards is based on a truncated binary exponential random backoff (TBERB) algorithm with a fixed initial contention window size. However, the TBERB algorithm does not take into account the possibility that the number of contended CPEs may change dynamically over time, leading to a dynamically changing collision probability. To the best of our knowledge, this is the first attempt to address this issue. There are three major contributions presented in this paper. First, a comprehensive analysis of initial ranging mechanisms in wireless networks is provided and initial ranging request success probability is derived based on number of contending CPEs and the initial contention window size. Second, the average ranging success delay is derived for the maximum backoff stages. It is found that the collision probability is highly dependent on the size of the initial contention window and the number of contending CPEs. To achieve the higher success probability or to reduce the collision probability among CPEs, the BS needs to adjust the initial contention window size. To keep the collision probability at a specific value for the particular number of contending CPEs, it is necessary for the BS to schedule the required size of the initial contention window to facilitate the maximum number of CPEs to establish their connections with reasonable delay. In our third contribution, the initial window size is optimized to provide the least upper bound that meets the collision probability constraint for a particular number of contending CPEs. The numerical results validate our analysis.



## 1. Introduction

Radio spectrum is a limited natural resource, the supply of which is now struggling to meet the seemingly ever increasing demand from consumers for mobile broadband data services. The reforming of spectrum, whereby bandwidth allocated to redundant or outmoded services is redeployed to new services is one means of providing bandwidth. This can now be seen in the allocation of bandwidth previously set aside for analogue TV to 4G mobile communications, following the introduction of digital TV services. The demand for mobile broadband data services may not simply be served by reallocating bandwidth, but may require some form of spectral sharing with incumbent services. A means of achieving this is through cognitive radio (CR), which builds on the concepts of Software Defined Radio put forward in the 1990s, whereby a service modifies its radio parameters within a given bandwidth, based on the transmission and reception environment in which it operates.

The IEEE 802.22 working group was formed in November 2004 to develop a first international standard based on a CR network. This was subsequently published in 2005 and accepted by the Federal Communication Commission. The basic purpose of this development was to provide broadband access in remote and rural areas by exploiting the unused TV band (Federal Communications Commission, 2008; 802.22-2011, 2011; P802.22a/D1, 2013; Chang-Jiang et al., 2013). Many other applications, such as real-time video streaming in home networks or automatic meter reading in the smart grid, can also be better supported. These systems can operate in the VHF/UHF, band ranging from 54 MHz to 862 MHz frequency, subject to non-interfering to the broadcast incumbents which may be digital or analog TV or wireless microphone. The main reason for TV band selection is twofold. The TV band is not

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always used in the geographical area of concern; it remains underutilized (Report of the spectrum efficiency working group, 2002; Nekovee, 2010; Beek et al., 2012; Mishra et al., 2013; Elshafie et al., 2014). The second reason is of having lower frequencies compared to other licensed bands, therefore, resulting in lower propagation path loss (Liang et al., 2008). Due to this feature, the spectral power density of the radio signal reduces slowly, which results in a high coverage area. The average coverage area is 33 km but it can be extended up to 100 km, subject to weather condition, which is larger than IEEE 802.11 based Wi-Fi and IEEE 802.16 based WiMAX (Li et al., 2008). It is the first worldwide wireless standard based on CR techniques for the opportunistic use of TV band on a non-interfering basis. A CR observes its spectral environment and modifies its transmission parameters accordingly (Li et al., 2008; Cordeiro et al., 2006; Masonta et al., 2013; Hsieh et al., 2012; Youssef et al., 2014; Wang et al., 2012). A number of techniques can be incorporated in a CR network for the awareness of its environment. The two techniques used with wireless networks for spectral awareness are geo-location/database service and spectrum sensing (802.22-2011, 2011). In geo-location, the location information about each device is identified. The database service provides a list of available channels and their respective allowable effective isotropic radiated power (EIRP), which can be transmitted without providing any harmful interference to incumbent/licensed users in any given geographical area and is officially incorporated by the local regulatory authority. In a situation where no database service is required, all channels are assumed to be available. Spectrum sensing consists of observing the TV band and identifying which channels are not occupied by the licensed users. The wireless network operates on one of these unoccupied channels called operating channel and, in the case of licensed user occurrence, the entire network shifts quickly its transmission to the other free available channel (P802.22a/D1, 2013; Kim and Shin, 2010; Min et al., 2011).

The wireless network is based on a master/slave architecture with a single base station (BS) managing more than one customer premise equipments (CPE) through Medium Access Control (MAC). The BS controls all the communication in the cell, i.e., there is no peer-to-peer communication directly between the CPEs. The IEEE MAC is strictly connection-oriented, which requires CPEs to establish connections with the BS before any data transmissions can occur. Connection is the key element that can be identified by 12 bits in which 9 bits are reserved for station ID (SID) and 3 bits are for flow ID (FID). The station being under the control of BS is uniquely identified by SID, which can be unicast station (single CPE) or multicast station (group of CPEs), whereas FID represents a specific traffic flow assigned to a CPE. The combination of SID and FID defines a connection identifier (CID) for the particular CPE. Based on time division multiplex, data are scheduled in the downstream direction, while in the upstream direction the channel capacity is shared by CPEs on a demand basis according to an orthogonal frequency division multiplex (OFDMA) scheme. CPEs may lie at different locations in the large network; some are near while some are far away from the BS. Therefore, their transmission delays and received powers are different. To attain orthogonality among the sub-carriers in the upstream link, it is necessary that the signals generated by all the active CPEs must arrive at the BS synchronously. If not, CPEs will cause interference with each other and at the end BS will not be in a position to recover the individual signal of each CPE. Therefore, synchronization is an important aspect that can be achieved through a ranging process in which the CPEs adjust their timing offset and EIRP so that at the BS their transmitted signals having equal powers synchronized to the mini-slot boundary of the BS. The basic functions of this process at the BS comprise: timing estimation, ranging codes detection, and power estimation. The ranging process is further classified into initial ranging and periodic ranging. Initial ranging is the primary process for the CPEs to access the network and establish their connections with the BS. Work on the initial ranging process has been extensively discussed in Morelli et al. (2009), Miao et al. (2010), Liang et al. (2010) and Sanguinetti and Morelli (2012) for IEEE 802.11 and IEEE 802.16 but little work has been found in the literature for the IEEE 802.22 standard (Afzal et al., 2014; Afzal et al. (2015a, 2015b)). The contributions of this paper are threefold. Firstly, a comprehensive analysis of initial ranging mechanism is provided and initial ranging request success probability is derived based on a number of contending CPEs and the initial contention window size. Secondly, the average ranging success delay is derived for the maximum backoff stages. Since, the collision probability is highly dependent on the size of the initial contention window and the number of contending CPEs, therefore, to achieve the higher success probability, the BS needs to adjust the initial contention window size. To keep the collision probability at a specific level for the particular number of contending CPEs, it is essential for the BS to schedule the required size of the initial contention window to facilitate the maximum number of CPEs to establish their connections with reasonable delay. Our third contribution is to optimize the initial window size and to provide the least upper bound that meets the collision probability constraint for a particular number of contention CPEs. This paper is organized as follows: Section 2 provides an overview of IEEE 802.22 network. An analytical model is then derived in Section 3 and numerical results are discussed in Section 4 before concluding remarks are presented in Section 5.

## 2. Overview of IEEE 802.22

The wireless regional area network (WRAN) consists of one BS and a number of fixed or portable CPEs having different quality of service (QoS) requirements. The cell follows fixed-point to multipoint topology with a master/slave architecture and can facilitate up to 512 CPEs after fulfilling the requirements necessary for the protection of the incumbent. No CPE is allowed to transmit without receiving appropriate authorization from a BS. The BS manages all the activities regarding modulation, coding etc. of its associated CPEs by MAC. There are two operational modes, i.e., normal mode and self-coexistence mode, defined in the IEEE 802.22 standard (802.22-2011, 2011). A WRAN cell works by default in normal mode and switches to self-coexistence mode if another WRAN cell is detected. This paper is focused on normal mode. During normal operation, a WRAN cell broadcasts a superframe preamble and a superframe control header (SCH) at the beginning of every superframe on its operating channel. Each superframe has a duration of 160 ms and is composed of 16 frames, each having a length of 10 ms. All transmissions can be organized into downstream (DS) and upstream (US) transmissions based on the direction of transmissions. The DS transmission is defined from the BS to CPE. Conversely, the US transmission is in the opposite direction. According to the IEEE 802.22 standard, the BS is responsible for scheduling both DS and US transmissions. All scheduling behavior is put into the MAC frame. The structure of a MAC frame can be divided into DS subframe and US subframe. The DS subframe is for DS transmissions. Similarly, the US subframe is for US transmissions. The first MAC frame contains superframe preamble, frame preamble, SCH, frame control header (FCH) and data payload as shown in Fig. 1. Its payload is reduced by two symbols to compensate for the superframe preamble and SCH.

The superframe preamble showing at the beginning of the superframe is for frequency and time synchronization purposes. The SCH carries the BS MAC address and other information necessary for the CPE to initiate a connection. To protect incumbents and to handle a self-coexistence situation, sufficient mechanism