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Modeling of Collision Probability for Maximum Backoff Stages during Association Process in Wireless Regional Area Networks

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Abstract: Cognitive radio (CR) technology has addressed the problem of spectrum scarcity in recent years. IEEE 802.22 Wireless Regional Area Network (WRAN) operations are based on this technology. A WRAN cell follows fixed point to multi-point topology consisting of base station (BS) and a number of customer premise equipments (CPEs). A collision occurs when more than one CPE attempt to associate with the BS at the same time. Probability of collision depends on size of initial Contention Window and number of CPEs. An estimation of this probability has significance for prediction of system performance beforehand during design stage of WRAN. To estimate it, a mathematical model is presented. It is based on accuracy assessment of a trend curve drawn as a mapping of varying number of contending CPEs. Numerical results confirm the effectiveness of the proposed model.

Keywords: Cognitive radio, Customer premise equipment, Initial ranging process, Contention Window, Backoff stage.

1. INTRODUCTION

Usually, the allocation of radio spectrum is done statically for various wireless networking services such as mobile and public safety communications, Wi-Fi and TV broadcast. Dependence of modern society on usage of radio spectrum is ever increasing. Static allocation of spectrum on long term basis has certain advantages, like ease of management, but its utilization is not optimal. Utilization depends not only on space but also on time, which results in overutilization in some bands and under utilization in others (Kolodzy and Avoidance, 2002). The phenomenal success of unlicensed bands utilization has led the regulatory authorities to open more bands, whereas licensed bands such as TV bands are less utilized (McHenry, 2005). This unbalanced usage of spectrum triggered policy reforms (Final and Stations, 2009), which in turn led to the idea of cognitive radio (CR) (Liang *et al*., 2008; Humaira *et al*., 2014; Ahmadfard, *et al*., 2017). There are two main features that make CR technology attractive. One, it provides cognitive capability that refers to the ability of CR to sense and capture spectrum related information from its surroundings, i.e. the unused frequency bands. Two, it allows reconfigurability that refers to adaptation capability according to the radio environment. More precisely, the CR has the ability to utilize the unused licensed spectrum in an intelligent manner without interfering with the primary/licensed users who are the owners of these bands. The implementation of this idea is the development of IEEE 802.22 standard (IEEE 802.22-2011), also known as CR based Wireless Regional Area Network (WRAN). To protect incumbent (e.g. digital/analog TV or wireless microphone) from harmful interference caused by opportunistic users, IEEE 802.22 devices are required to sense the spectrum periodically and leave it on return of incumbent.

The main components of WRAN are base station (BS) and customer premise equipments (CPEs). In order to communicate with each other, CPEs have to associate with BS. The association process comprises of initial ranging, authentication and registration. Initial ranging is not trivial in WRANs as there is no predefined channel using which CPEs can connect with BS (IEEE 802.22-2011). The reason behind this is the sharing among CPEs and the incumbent, IEEE 802.22 channels. When a CPE is switched on, it scans all TV channels to determine the presence of incumbent and makes a spectrum usage report. The same mechanism of sensing is also carried out by the BS. It broadcasts on an unused frequency channel in the cell. If CPE locates that channel, it tunes itself to it for further communication. In order to synchronize with the BS, CPEs are involved in initial ranging process, when they adjust their timing offsets and effective isotropic radiated power (EIRP). During this process, multiple CPEs may contend for the channel as follows. Each CPE uses code division multiple access (CDMA) and a random number drawn from initial contention window (CW). Code is modulated with initial ranging channel, while a random

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number is used to schedule CPE for transmission by deferring same number of slots. If by chance, other CPEs schedule at the same slot, a collision occurs, to cope up which a binary exponential random backoff (BERB) procedure is invoked. Through BERB, size of CW is increased in backoff stages till a maximum limit, with an aim to avoid further collisions. In this paper we analyze the initial ranging process to derive a mathematical expression for collision probability. Our work can help BSs in finding the collision probability per backoff stage for a given number of contending CPEs with some initial CW sizes. The rest of the paper is organized as follows. In Section 2, a brief overview of WRAN is presented. Our proposed model is given in Section 3. Results are presented in Section 4. Finally, Section 5 concludes the work.

2. OVERVIEW OF IEEE 802.22 WRAN

The target application of IEEE 802.22 standard was to provide wireless broadband access in remote and rural areas. The objective was to attain a performance comparable to existing fixed broadband access technologies deployed in urban and suburban areas. For this purpose, TV bands are selected by Federal Communication Commission (FCC) as their frequencies have favorable propagation properties, i.e. distant users can be served easily (Akhtar, *et al*., 2016; Oh, *et al*., 2016; Wang, *et al*., 2017). Moreover, studies show that many TV bands remain unoccupied most of the time in many areas, as many household and business activities rely on cable and satellite (Jiang, *et al*., 2014; Han, *et al.*, 2015; Hoyhtya, *et al*., 2016). WRAN devices can operate on TV bands ranging from 54 MHz to 862 MHz, consisting of very high frequency (VHF) and ultra high frequency (UHF) bands with the objective of causing no interference to the incumbents. Also, IEEE 802.22 standard supports various TV channel bandwidths of 6/7/8 MHz. The average coverage area of WRAN cell is 33 sq. km, which can be extended up to 100 sq. km depending upon weather condition.

IEEE 802.22 network has point-to-multipoint wireless interface as shown in Fig. 1. BS manages its own cell as well as the functions of all associated CPEs. It transmits in downlink to control access to medium and admission of CPEs, and Quality of Service (QoS) while keeping the security measures, whereas CPEs respond back in uplink. It also manages incumbent protection through distributed sensing. During this process, BS instructs CPEs to perform measurements of different TV channels and send back reports. If a channel is used by the incumbent, then IEEE 802.22 devices vacate the channel and resume their transmission on another unused channel.

Fig. 2 depicts the pattern of TV channel occupancy by incumbents over time and frequency. It is evident that both CPEs and BS have random behaviors while using TV channels, which affects the Physical and MAC layers of IEEE 802.22 stack.

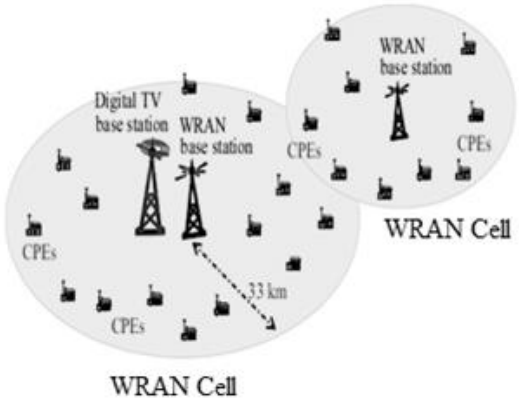


Fig. 1: An IEEE 802.22 deployment configuration.

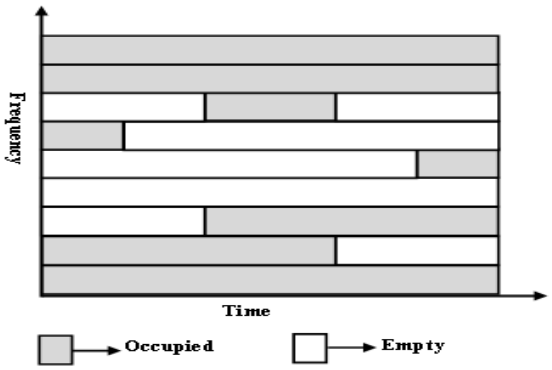


Fig. 2: An example of a TV band occupancy.

WRAN applications support multiple access both in downstream and upstream directions. Downstream transmission is regulated by time division multiplexing (TDM) and upstream is organized by orthogonal frequency-division multiple access (OFDMA), which is a multicarrier modulation that enables signal to be controlled in time and frequency domains (Karthipan, *et al*., 2016). An opportunity is a two dimensional slot of time and frequency. Transmission occurs in both directions during these slots. IEEE 802.22 MAC supports a superframe structure. At the beginning of every superframe, BS broadcasts superframe control header (SCH) and preamble on each channel, which is used for communication in the cell. Any CPE which intends to associate with BS can get the required information from SCH necessary for association. A superframe consists of 16 MAC frames and it lasts for 160 milliseconds. MAC frame structure is given in Fig. 3, which shows that the frame comprises of downstream

subframe and upstream subframe. The downstream subframe contains only one protocol data unit (PDU) while upstream subframe consists of multiple PDUs, with each one transmitted from a different CPE. In addition, upstream subframe has different parameters like initial ranging window, bandwidth request window, etc. Initial connection establishment, spectrum usage report, frequency of operation and service capacity etc. are few features of IEEE 802.22 MAC that differentiates it from other standards like 802.11 and 802.16.

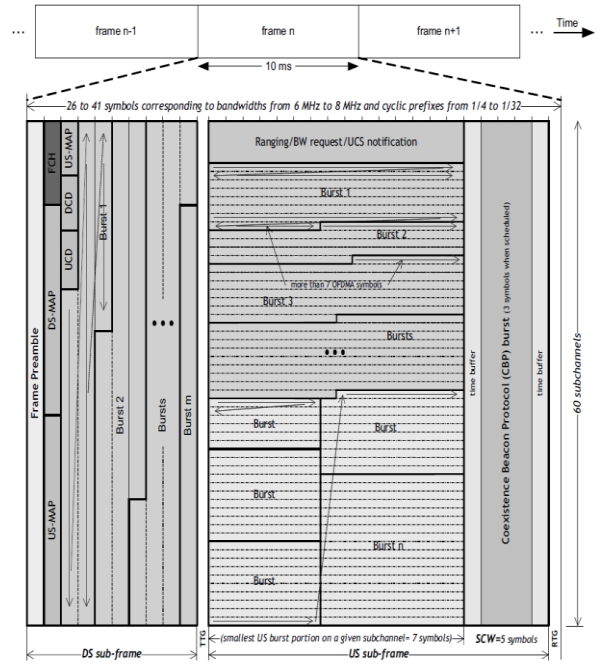


Fig. 3: The MAC frame structure.

3. PROPOSED COLLISION MODEL

A collision occurs when at least two CPEs attempt to transmit simultaneously. Given that network has n CPEs of which i transmit simultaneously, the probability of this event is $p^i(1-p)^{n-i}$, where p is the probability of transmission of one CPE in an arbitrarily chosen slot. A backoff counter drawn randomly from Uniform distribution $\mathrm{U}[0, CW]$ has $\frac{1}{CW+1}$ chances. This value can be taken as probability of transmission per slot, $p = \frac{1}{CW+1}$. Take $W = CW + 1$ and generalize to CW stages separately, let W_j and p_j denote respectively CW and p in stage j. The probability of network collision in stage j, $P_c(j)$, is computed by aggregating cases of all $i = 2, \cdots, n$ and for each considered i, taking all combinations of n chooses i (Humaira *et al*., 2015).

$$P_c(j) = \begin{cases} 0 & n = 1 \\ \sum_{i=2}^{n} \binom{n}{i} p_j^i (1-p_j)^{n-\mathrm{i}} & n > 1, \end{cases} \quad (1)$$

where $W_j = 2^j(W_0 + 1) - 1, 0 \le j \le m$ with m as the last stage of CW and W_0 is the initial CW at first backoff stage.

In IEEE 802.22 WRAN cell, each CPE has 5 retries to associate with BS while entering in initial ranging process, therefore, $m = 5$. We need to observe the collision probabilities up to 5 backoff stages in order to derive compact analytical expression for $P_c(j)$ in term of W_0. Denote this $P_c(j)$ as $\tilde{P}_c(j)$. To observe the dependence of collision probability on number of CPEs and backoff stages, graphs are plotted on logarithmic scale in Fig. 4 with $W_0 = 32$, n taken from $\{5, 10, 20, 40, 80\}$ and backoff stages taken from $\{1, 2, 3, 4, 5\}$.

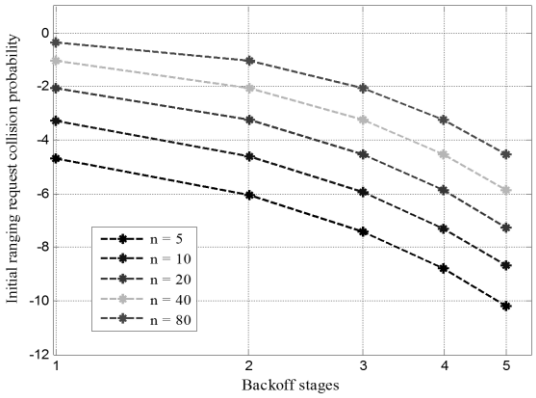


Fig. 4: Initial ranging request collision probability varying with number of contending CPEe and backoff stages.

The trends in graphs (Fig. 4), is approximated by straight lines, so that slope intercept formula $Y - \beta = pX$ is applied as

$$\ln \tilde{P}_c(j) - \beta = p \ln W_j, \quad (2)$$

where $Y = \ln \tilde{P}_c(j)$, $X = \ln W_j$, β is a small shift in collision probability that is considered as y-intercept, p is the slope of curve. We approximate $p = -2$ for different CW sizes and different n (see Table 1, in which for brevity we show results for n taken only from $\{5, 10\}$. Other values of n show similar trend.).

Solving (2), $\tilde{P}_c(j)$ can be computed as

$$\tilde{P}_c(j) = (2^j W_0)^p e^{\beta}, \quad (3)$$

where e^{β} is the offset to be determined and

$m = \frac{\log P_c(j)|_{Y_1} - \log P_c(j)|_{Y_2}}{X|_{X_1} - X|_{X_2}}$, $\forall (X_i, Y_i) \in (X, \log P_c(j))$.

To find e^{β}, we use the following equation of straight line,

$$\frac{X - X_1}{Y - Y_1} = \frac{X_2 - X_1}{Y_2 - Y_1}. \quad (4)$$

For y-intercept, $X = 0$, so that (4) takes the form

$$Y = Y_1 - X_1 \frac{Y_2 - Y_1}{X_2 - X_1}. \quad (5)$$

Now $e^{\beta} = \log^{-1}(Y)$, therefore, $e^{\beta} = \log^{-1}\left(Y_1 - X_1 \frac{Y_2 - Y_1}{X_2 - X_1}\right)$. Using Table 2, we apply least square method (Humaira *et al*., 2015) to obtain a simple expression for e^{β} as

$$e^{\beta} = a + bn = e^{a}\, n^{b}, \qquad (6)$$

where a and b are constant to be determined.

Table 1: Ranging request collision probabilities with slopes for various backoff stages. $X = \log W_j, Y = \log P_c(j)$.

n	W_j	X	$P_c(j)$	Y	p
5	32	3.4657	0.0092	-4.6885	-1.9027
	64	4.1588	0.0024	-6.0322	-1.9386
	128	4.8520	0.00060	-7.4171	-1.9979
	256	5.5451	0.00015	-8.7955	-1.9886
	512	6.2383	0.00003	-10.178	-1.9943
10	32	3.4657	0.0372	-3.2914	-1.7589
	64	4.1588	0.0101	-4.5952	-1.8809
	128	4.8520	0.0026	-5.9522	-1.9577
	256	5.5451	0.00067	-7.3045	-1.9509
	512	6.2383	0.00016	-8.6804	-1.985

Table 2: $e^{\beta} = \log^{-1}\left(Y_1 - X_1 \frac{Y_2 - Y_1}{X_2 - X_1}\right)$ with varying n.

n	X_1	X_2	Y_1	Y_2	e^{β}
5	4.8520	6.2383	-7.4171	-10.178	9.4490
10	4.8520	5.5451	-5.9522	-7.3045	33.5729
20	5.5451	6.2383	-5.8781	-7.2530	167.5239
40	5.5451	6.2383	-4.5282	-5.8781	529.1206
80	5.5451	6.2383	-3.2339	-4.5189	1148.253

Using the formulas given in (Humaira *et al*., 2015), the values of a and b are computed at $W_0 \in \{32, 64, 128, 256, 512\}$ (see Table 3).

Table 3: Values of a and b.

W_0	a	b
32	-0.5013	1.7828
64	-0.7264	1.8820
128	-0.8876	1.9861
256	-0.8384	1.9735
512	-0.8285	1.9711

Denote the average values of a and b as $\hat{a}$ and $\hat{b}$ respectively, we have
$\hat{a} = -0.73845$, $\hat{b} = 1.906146$. This implies

$$e^{\beta} = e^{\hat{a}}\, n^{\hat{b}} = e^{-0.73845}\, n^{1.906146}. \qquad (7)$$

Finally, the estimated ranging request collision probability is expressed as

$$\tilde{P}_c(j) = (2^j W_0)^m e^{\beta}, \qquad (8)$$

where $e^{\beta} = e^{-0.73845}\, n^{1.906146}$, $W_0 \geq 32$ and $0 \leq j \leq 4$. For $W_0 < 32$, the behaviour of $\tilde{P}_c(j)$ for particular value of n is non-linear, which means that smaller CW sizes are insignificant for an increasing the number of contending CPEs.

4. RESULTS AND DISCUSSION

To compare the results of numerically calculated collision probability $P_c(j)$ with estimated collision probability $\tilde{P}_c(j)$, Figs. 5-9 are drawn with varying number of CPEs. For simplicity, $W_0 = 32$ and number of retries, $m = 5$ is allowed for all contending CPEs.

Fig. 5 shows the relationship between two collision probabilities when 5 number of CPEs contend to associate with the BS. At the first backoff stage, $m = 1$, the relative error of the approximation is 0.0267, which is slightly high but acceptable. Note that the relative error is equal to magnitude of the difference between the actual collision probability and the estimated collision probability divided by the magnitude of the actual probability. The relative errors are plotted separately in Fig. 10. At the second backoff stage, $m = 2$, the relative error drops to 0.0137. Similarly, at the third, fourth and fifth backoff stages, the relative error further decreases to 0.0109, 0.0063 and 0.0008 respectively. Overall, relative errors are decreasing with backoff stages.

When CPEs are increased from 5 to 10 (Fig. 6), the relative error changes from 0.0267 to 0.0110 for the first backoff stage. For higher backoff stages, the relative error is decreasing again. Additionally, for the same backoff stages, the relative error is less as compared to the case of 5 CPEs.

Fig. 7 shows the collision probabilities with 20 CPEs. At the first backoff stage, the relative error is 0.0095. At the second backoff stage, the relative error reduces about 69%. At the third backoff stage, the relative error reduces 41%. Similarly, the relative error further reduces 64% and 83% at the fourth and fifth backoff stages respectively.

Now, when CPEs are increased from 20 to 40 as shown in Fig. 8, the relative error is just 0.0085 at the first backoff stage, which further reduces to 0.0075 and so on and so forth. Finally, at the last backoff stage, $m = 5$, it is about 0.0002, which is almost negligible.

Finally we increase CPEs to 80 (Fig. 9). The relative error is reduced to 0.0060 for the first backoff stage. The reduction continues for higher backoff stages.

In Fig. 10, we compare the relative errors of varying number of CPEs, according to the graphs in Figs. 5-9. Our analysis is that the relative errors reduce with the number of CPEs and backoff stages. This implies that the accuracy of our proposed estimations get better with increasing CPEs.

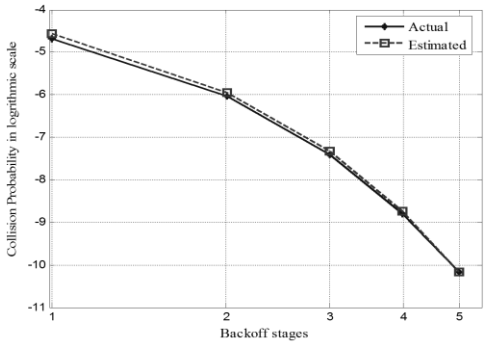


Fig. 5: Comparing our estimations with Numerical results of ranging request collision probabilities for 5 CPEs.

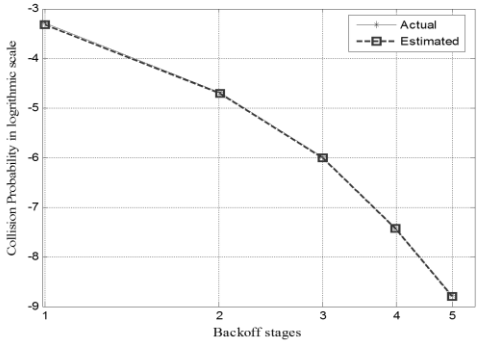


Fig. 6: Comparing our estimations with Numerical results of ranging request collision probabilities for 10 CPEs.

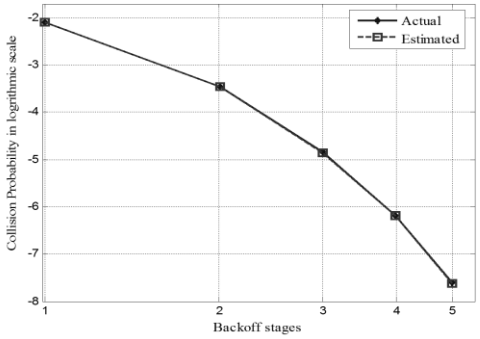


Fig. 7: Comparing our estimations with Numerical results of ranging request collision probabilities for 20 CPEs.

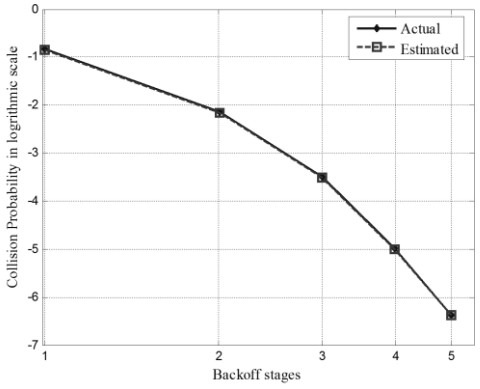


Fig. 8: Comparing our estimations with Numerical results of ranging request collision probabilities for 40 CPEs.

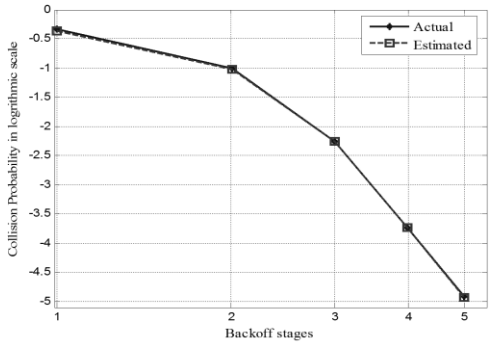


Fig. 9: Comparing our estimations with Numerical results of ranging request collision probabilities for 80 CPEs.

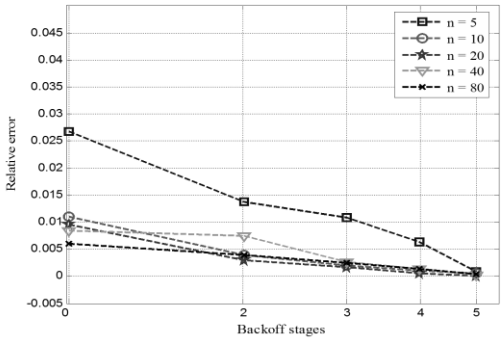


Fig. 10: Comparing relative errors of varying number of CPEs.

5. CONCLUSIONS

In this paper, we have presented a mathematical model for finding the collision probability at given initial Contention Window in wireless regional area network (WRAN). Accuracy level of the model is investigated on the basis of relative errors found by comparing it with numerically computed results. According to the results, our estimations have reasonably well accuracy, especially when CPEs are increased. It is believed that the proposed model can be effectively used to schedule CPEs such that Quality of Service (QoS) properties of applications can be predicted beforehand, thus allowing tuning of initial Contention Window such as to meet desired QoS requirements.

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