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Performance Analysis of Hybrid Spectrum Sharing in Cognitive Radio Based Wireless Regional Area Network

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ABSTRACT

Cognitive radio (CR) network is the footstep and essential need of the new wireless emerging technologies like the Wireless Sensor Network (WSN), Internet of Things (IoT), Bluetooth, and Vehicular Ad Hoc Network (VANET). Due to tremendous progress in the number of wireless devices and their traffic, large scale use of these technologies may soon cause a shortage of spectrum as all these technologies use unlicensed bands. So, CR is a vital choice for their survival. In this paper, we address the Quality of Service (QoS) parameters related to spectrum sharing among multiple Customer Premises Equipments (CPEs) in the context of CR based Wireless Regional Area Network (WRAN) using trunking theory. For this purpose, an analytical framework is developed to obtain QoS parameters such as traffic intensity, the total number of users in the network, and time to associate with the base station (BS). For a progressive environment, particularly increase in the population of WRAN, we also analyzed channel access time and received signal strength (RSS) for CPEs. Two types of centralized trunked CR systems: (1) queued and (2) non-queued systems are investigated and this model can be helpful for the Base Station (BS) in scheduling the required number of channels depending upon Grade of Service (GoS) and the total number of users. The numerical results validate our model.

Keywords: *Cognitive radio, Internet of things, WRAN, Grade of service*

1. Introduction

The rapid increase in the growth of wireless technologies, mobile communications, big data, Internet of Things (IoT) and cloud computing has led to an increasing spectrum demand. Therefore, the increase in utilization of the limited radio spectrum bands is becoming one of the major challenges in the wireless communication domain. The most effective solution towards fulfilling this challenge is the big achievement in the development of a Cognitive Radio (CR) network [1]. The existing wireless spectrum is an insufficient resource and also extremely underutilized [2]. Secondary users (SUs) which are unlicensed users can access the CR systems opportunistically and must attempt to occupy the underutilized spectrum for better utilization. A dilemma can happen if an adolescent policy of spontaneous effort by various cognitive systems to exploit the identical spectrum is applied by these systems. To mitigate this problem, appropriate spectrum distribution is the main concern in CR technologies. Two types of spectrum allotment are employed in such kinds of networks: (1) Primary-secondary allotment, (2) Secondary-secondary allotment. In primary-secondary distribution, the primary consumers permit secondary consumers to exploit their spectrum under several circumstances. It is further subdivided into primary-secondary underlay distribution and primary-secondary overlay distribution [3]. In underlay pattern, the SU works on the primary user (PU) channel by assuring guarantee of no interference to PU according to an interference threshold, whereas in an overlay pattern, SUs are allowed by the PU to use their spectrum. In secondary-secondary distribution, secondary consumers exploit the spectrum platform on a few distribution policies [3].

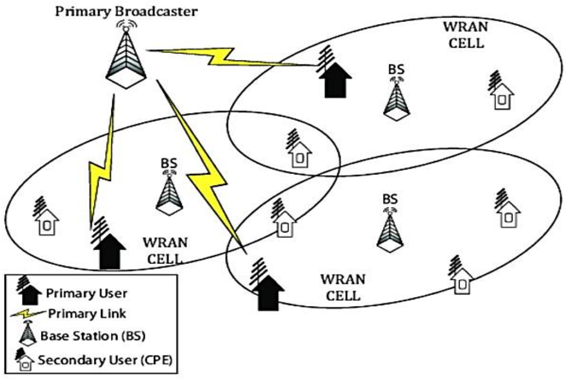

Fig. 1: Wireless regional area network [5].

To preserve the precious radio spectrum, the Federal Communication Commission (FCC) has proposed the IEEE 802.22 standard generally called wireless regional area network (WRAN) [4]. A WRAN cell follows master/slave platform with a single Base Station (BS) that can manage one or more customer premise equipments (CPEs) by applying the functionalities of medium access control (MAC) as shown in Fig. 1 [5]. The BS is responsible for controlling all the traffic in the cell/area. Moreover, there is no peer-to-peer communication directly among the CPEs. The licensed users are called incumbents which can be wireless microphone or digital-analog TV. The unlicensed users are called CPEs. The cell operates on unused sections of the UHF/VHF TV bands

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between 54 MHz to 862 MHz and its coverage area may range up to 100 square km subject to weather conditions [6]. The standard uses the orthogonal frequency division multiple access (OFDMA) with time division duplex (TDD) techniques to provide asymmetric traffic between downlink and uplink, higher trunking efficiency and channel repository [7]. IEEE 802.22.1 is a successive standard developed for avoiding interference due to low power applications and also improves the earlier standard with added features so that certain applications based on wireless local area networks can share the technology [8].

Trunked radio systems are the best option for bigger organizations requiring wide coverage along with flexibility, privacy and accessibility leading to avoid once of spectrum scarcity. In these systems, users are automatically connected to available radio channels on a need basis. To increase channel capacity, systems use the time-division multiple access (TDMA) scheme and share the radio spectrum either in a centralized or decentralized manner. Trunking used with CR is the way to access the free spectrum dynamically after sensing [9, 10]. Trunked radio systems can be classified into two categories [11]: (i) Blocked calls cleared (BCC) system, (ii) Blocked calls delayed (BCD) system. The BCC systems are memoryless systems having no queuing for the calls that are blocked, i.e., when no channels are available. On the other hand, BCD systems use queuing for holding the calls that are blocked, i.e., if a new CPE entering into the system finds all the channels busy, then it will be listed in a queue in which it has to wait for the service later on.

CR systems may depend upon trunking where a large number of users can access and share a limited number of channels from a pool of available channels when required. Most of the work based on trunking theory was focused on the performance of queues [12-14] while less work has been done on Quality of Service (QoS) parameters in wireless networks especially in CR networks [15-17]. In this paper, we discuss the QoS parameters related to spectrum sharing among multiple CPEs in CR based WRAN using trunking theory. For this, an analytical model is developed to obtain QoS of CPEs like accomplished traffic and time to associate with the BS. For an environment where the population of WRAN progressively increases, we analyze channel access time and received signal strength (RSS) for CPEs. Two types of centralized trunked CR systems namely queued and non-queued systems are considered and we call it hybrid spectrum sharing in CR network. The work presented in this paper focuses mainly on preempted CPEs to be kept in a queue and resume their communications whenever the channel becomes available.

CR Networks has become a hot topic in the wireless communication area for researchers to study. A lot of research work has been carried out in this field. Akyildiz et al. [18] worked on CR Network and defined its boundaries, challenges, and trends to improve the efficiency of spectrum usage. A CR Network can be called an adaptive intelligent network because of its features, i.e., automatic detection of available channels and change its transmission parameters to improve better connectivity without disturbing the licensed users. A survey on CR handoff methods and problems for industrial wireless sensor networks (IWSN) applications was presented by Oyewobi and Hancke [19]. Since IWSN is highly delay-sensitive application having necessary QoS requirements, handoff in CR has the potential to provide an effective solution to increase bandwidth, minimize delay, and interference-free communication. A detailed analysis of the initial ranging process in WRAN has been presented previously [20, 21] and ranging request collision probability was calculated depending upon contention window size and contending CPEs. For maximum back off stages, the average delay was derived. To reduce the collision probability to facilitate the large number of CPEs to become the part of the WRAN cell with reasonable delay, BS should decide and schedule the required initial contention window size. In our previous study [22], a discrete-time Markov chain model was developed for the registration process of CPEs with BS in WRAN, i.e., IEEE 802.22 network. Various evaluation parameters such as return time, association time, first passage time, etc. were computed. A contract theory based contention resolution scheme was proposed for contending CPEs to register with the BS in WRAN [23]. In a previous study [24], a fuzzy-logic based scheme was designed for WRAN to prioritize the backup and candidate channels lists based on the incumbent behavior. BS may be able to select the operating channel from the available channels. A two-stage spectrum sensing technique was proposed by Capriglione et al. [25] for dynamic spectrum access in the CR network. In the first stage, the occupied TV bands of incumbents were identified and in the second stage, the identified TV bands were further refined to achieve more accurate detection results. Chu et al. [26] presented a dynamic spectrum access scheme for the CR network having different types of traffic. PUs have a higher priority than the SUs. Blocking and dropping probabilities of SUs were also investigated. An M/G/1/K queuing model with pre-emptive resume priority was developed for the CR network to estimate optimal buffer size by Hoque et al. [27]. Different proactive decision handoff schemes such as switching spectrum handoff, non-switching spectrum handoff, and random spectrum handoff were performed to evaluate cumulative handoff delay and total service time for SUs. A subjective trust model was reported for the spectrum management of BS in the WRAN cell [28]. The trust values of CPEs based on their previous behaviors were computed and then propagated to BS, which would be utilized in the spectrum sensing decision-making process. Khan and Zeeshan [29] proposed dynamic channel selection schemes based on fuzzy logic for the CR-based smart grid communication network. The scheme employing IEEE 802.22 standard architecture is incorporated for selecting the most suitable channel from the available channels with the desired QoS requirements. In case, if the appropriate channel is not available, then the designed scheme helps in finding the best possible channel with the desired QoS requirements. In the aforementioned work, trunking is not considered. Yu et al. [30] incorporated the trunking theory in spectrum sharing approach for CRN to improve the traffic load of SUs under *GoS* constraints. In addition, literature shows that some researchers [12, 13] utilized the idea of trunking theory on the performance of queues but a little work has been found in the literature on QoS parameters in CR networks. With trunking, better spectrum efficiency can be achieved, as a large number of users are able to share a relatively smaller number of channels in a system.

2. Methodology

For non-queued trunked WRAN, assume that the call arrival rate follows the Poisson distribution. Initially, a limited number of channels are available in the trunking pool which may grow or shrink dynamically depending upon the sensing results of both BS and CPEs. For this system, traffic intensity is measured using the Erlang B formula, given in Eq. (1), which is also a measure of Grade of Service (GoS) of the system, used for call blocking probability.

$$\Pr[\text{blocking}] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C}\frac{A^k}{k!}} = \text{GoS} \tag{1}$$

where C represents the number of channels offered by the non-queued trunked WRAN system and A is the total traffic capacity. For queued trunked WRAN, the likelihood of an arriving call not having instant access to a channel (or being delayed) is calculated by the Erlang C formula, given as:

$$P_r[delay > 0] = \frac{A^C}{A^C + C!\left(1-\frac{A}{C}\right)\sum_{k=0}^{C-1}\frac{A^k}{k!}} \tag{2}$$

where C and A represent the number of channels and total traffic capacity in queued trunked WRAN system respectively. If traffic is uniformly dispersed among the channels, the traffic intensity per channel (Ac), is written as:

$$A_C = \frac{UA_u}{C} \tag{3}$$

where Au is per user channel capacity. In our proposed model, assume the total numbers of users including incumbent and CPEs are U and the number of incumbents is equal to the number of channels, then the number of CPEs (active or not active), i.e., CR Users, can be expressed as:

$$CR\ Users = U - C \tag{4}$$

For WRAN system represented in Fig. 1, the QoS parameters are investigated by calculating the distance of CPE from BS, delay for reaching a signal from a CPE to BS, path loss faced by the signal from CPE, call blocking probability as well as the probability of a call being delayed for CPE to get an association with the BS. Suppose that, BS is at (0, 0) and (xi, yi) be the position of ith CPE, where i = 1, …, n in WRAN cell, then the Euclidean distance (d) is represented as:

$$d = \sqrt{\sum_{i=0}^{n}\left|x_i - y_j\right|^2} \tag{5}$$

Suppose, sender and receiver are in the line of sight with each other. Using the time of arrival method, we calculate the relative distance of CPEs (R_t) from the BS, which is given as:

$$R_t = c \times t \tag{6}$$

Here $c = 3 \times 10^8$ is the speed of light (speed of packet) and t is time to reach a signal from sender to receiver. To measure exact or more accurate distances (D) between a sender and receiver, the internal delay is a significant parameter that should be estimated. For simplicity, let the internal delay be *Int_d*. It includes processing delay, queuing delay in case of queued systems, propagation delay, and transmission delay which can be expressed as:

$$Int\_d = dprocess + dqueue + dtransmit + dprop \tag{7}$$

where *dprocess*, *dqueue*, dtransmit, *dprop* represent processing delay, queuing delay, transmission delay, propagation delay respectively. Now, D from BS to CPE can be written as:

$$D = c \times (R_t - InI\_d) \tag{8}$$

Let P_t, P_r be transmitter strength and receiver strength respectively, path loss can be estimated as:

$$\frac{P_t}{P_r} = \frac{(4\times\pi\times D)}{\lambda} \tag{9}$$

where $\lambda = \frac{c}{f}$ is the wavelength and f is the frequency of the signal.

3 Numerical Results and Discussions

To evaluate the proposed model, many simulations are performed using the Matlab/Simulink environment. Using expressions given in Eqs. (2) to (9), we calculate the value of traffic capacity, total users, distances from CPEs to BS, and path loss. Since the trunked WRAN may be queued or non-queued system, so we have two cases.

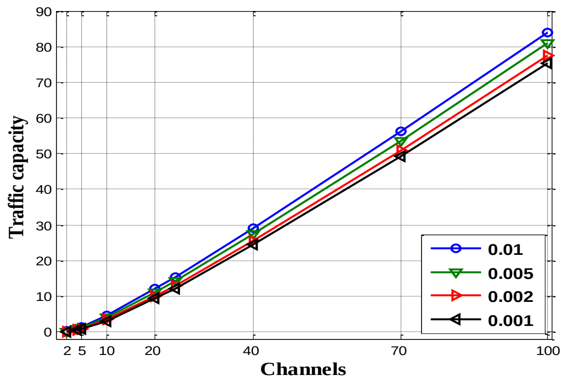

Fig. 2: Traffic capacity with respect to the number of channels at different *GoS* in a non-queued trunked system.

3.1 Case 1: Non-Queued System

Fig. 2 illustrates the effect of the number of channels on traffic capacity when Grade of Service (GoS) is taken as *GoS* = 0.001, 0.002, 0.005 and 0.01. At *GoS* = 0.001 *C* = 10, the traffic capacity of the system is 3.092. When *C* changes either from 10 to 20 or from 20 to 40, the traffic capacity changes from 3.092 to 9.411 or from 9.411 to 24.443 respectively. Similarly, when *C* changes from 40 to 70, the traffic capacity changes from 24.443 to 49.238 at this particular *GoS*. It means traffic capacity increases due to the possibility of distributing more channels to the system at a specific *GoS* value. Now, again, for C = 40, when *GoS* increases either from 0.001 to 0.002 or from 0.005 to 0.01, the respective traffic capacity increases from 24.443 to 25.5977 and from 27.3809 to 29.0059. Similar is the case for C = 100. It means the traffic capacity increases with increasing the blocking probability when particular numbers of channels are available in the system.

To see the behavior of *GoS* more precisely, we have plotted the total users and CPEs working in the non-queued environment for C = 2, 4, 5, 10, 20, 24, 40, 70, 100 in Figs. 3 and 4, respectively, over different values of *GoS*. When *GoS* = 0.001 and C = 20, the total number of users is 627, and the number of CPEs is 607, which can be observed from Figs. 3 and 4, respectively. It means the number of incumbents working in the system is 20. Now, when C is increased by 100%, i.e., C = 40, and assume that *GoS* remains unchanged, the increase in the total number of users and CPEs is 1003 and 983, respectively.

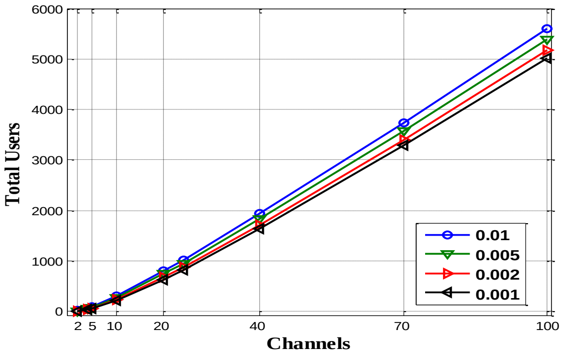

Fig. 3: Total users with respect to the number of channels at different *GoS* in a non-queued trunked system.

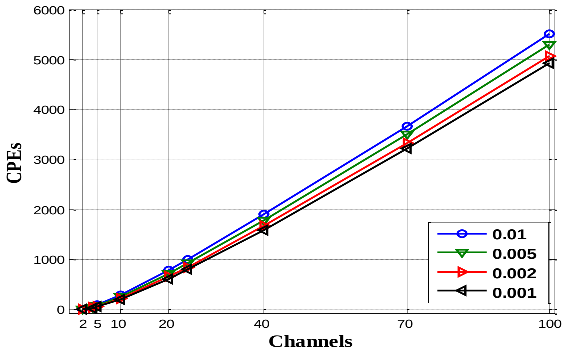

Fig. 4: Number of CPEs with respect to the number of channels at different *GoS* in a non-queued trunked system.

It implies that the number of incumbents in the system is 40, which indicates that the number of incumbents is increased by 100%. Similarly, when the number of channels increases to 100, the total number of users increases to 5015; the number of CPEs increases to 4915, and the resulting number of incumbents increases to 100. It is opponent that when the number of channels increases, the number of users including incumbents and CPEs increases significantly with the same value of *GoS*. Similar results can be seen from Figs. 3 and 4 when *GoS* increases between 0.001 and 0.01 at a particular number of channels.

Now we investigate the impact of distance (D) from CPE to BS on the performance in terms of internal delay (let's call it as delay, *Int_d*) and path loss. Since, the system is non-queued, so queueing delay is not included in the delay. As shown in Fig. 5, at $D = 3.4 \times 10^9$ m , the delay is almost less than 3.8×10^{-8} ms. When D increases to 3.7×10^9 m, the delay increases to 4.15×10^{-8} ms. It means when the distance between CPE and BS increases, the signal takes more time to reach the destination, i.e., the resulting delay increases. So, the farther CPEs will take more time to connect to the BS as compared to nearer ones. Now, from Fig. 6, at $D = 3.4 \times 10^9$ m, the path loss is nearly equal to 1.42×10^{12} db. When D reaches 3.7×10^9 m, path loss goes to 1.55×10^{12} db. Similarly, when D becomes 4.3×10^9 m, path loss becomes equal to 1.8×10^{12} db. It implies that when the distance between CPE and BS increases, path loss increases, and vice versa. The CPEs with larger distances will face more path loss in comparison with the CPEs closer to BS.

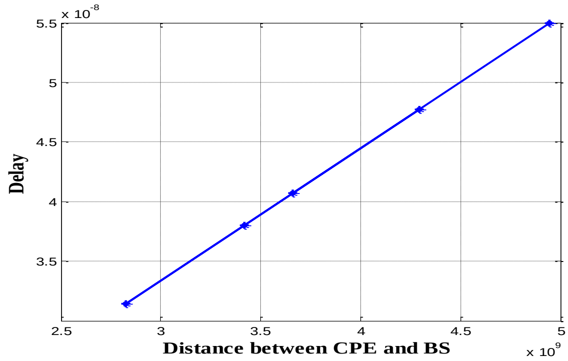

Fig. 5: Delay vs. distance between CPE and BS in the non-queued trunked system.

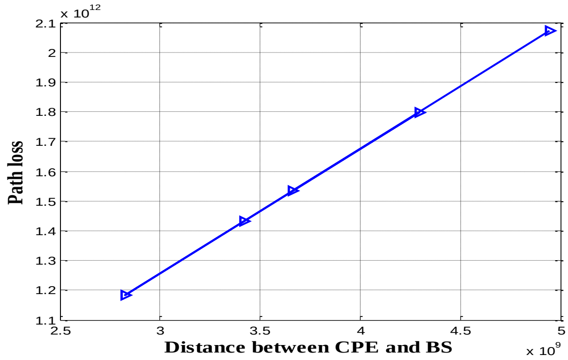

Fig. 6: Path loss vs. distance between CPE and BS in the non-queued trunked system.

3.2 *Case 2: Queued System*

Fig. 7 gives the traffic capacity of the trunked queued system for C = 2, 4, 5, 10, 20, 24, 40, 70, 100 with different *GoS*. When *GoS* = 0.001, C = 10, the traffic capacity is 2.9417. When the number of channels increases either from 10 to 20 or from 20 to 40, the traffic capacity increases from 2.9417 to 8.9131 or from 8.9131 to 23.1719, respectively.

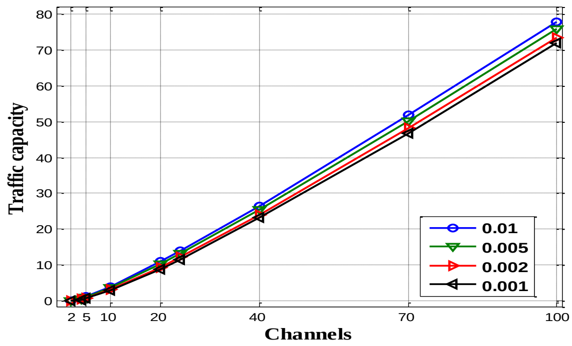

Fig. 7: Traffic capacity with respect to the number of channels at different *GoS* in a queued trunked system.

Again, when the number of channels further increases from 40 to 100, the traffic capacity increases significantly from 23.1719 to 71.4761 at the given *GoS*. On the other hand, let C = 40, when *GoS* increases to 0.001 – 0.01, the respective traffic capacity increases accordingly. It is obvious from Fig. 7, the traffic capacity increases either by increasing the number of channels or by increasing the Grade of Service.

Figs. 8 and 9 are plotted to see the impact of the number of channels on the total number of users and CPEs that the queued system can support at different *GoS*. At *GoS* = 0.001 and C = 20, the system can facilitate 594 total number of users, out of which 574 are CPEs and 20 are incumbents. To increase the total number of users up to 1545 with 1505 CPEs and 40 incumbents, the system should offer 40 channels at the same GoS as shown in Figs. 8 and 9. Similarly, to support 4783 total number of users along with 4683 CPEs at the same *GoS*, the system has to offer 100 channels. Similar is the case

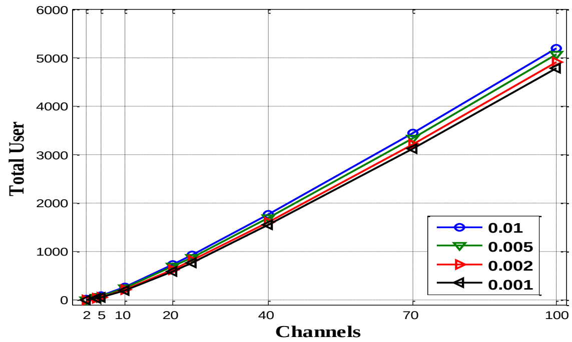

Fig. 8: Total users with respect to the number of channels at different *GoS* in a queued trunked system.

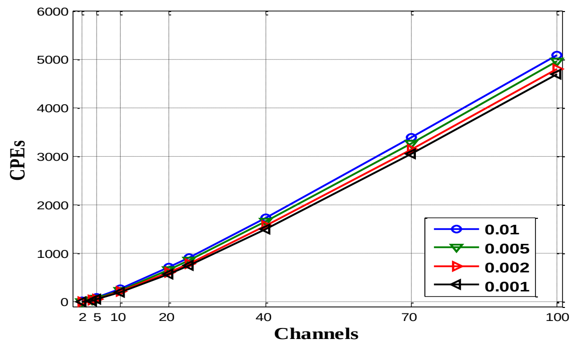

Fig. 9: Number of CPEs with respect to the number of channels at different *GoS* in a queued trunked system.

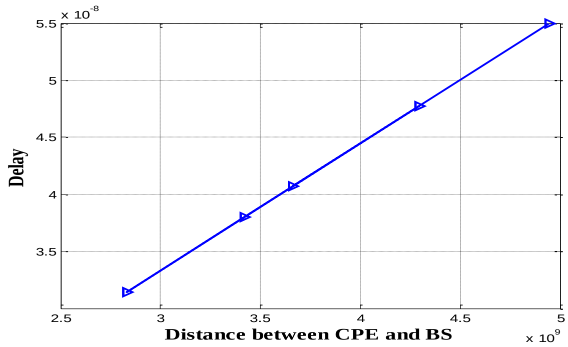

Fig. 10: Delay vs. distance between CPE and BS in a queued trunked system.

for other Grade of Services. It is important to note that, based upon *GoS* and the total number of users, the BS can schedule the required number of channels.

Figs. 10 and 11 depict the delay and path loss, respectively, of the queued system with respect to distance (D) of CPE to the BS. Since the system is queued, so queueing delay is also included in the delay. From Fig. 10, when D = 3.4×10^9 *m*, the delay is more or less 3.7×10^{-8} *ms*. Similarly, when D changes from 3.4×10^9 *m* to 3.7×10^9 *m*, the delay approaches to 4.1×10^{-8} *ms*. It is clear that when the distance between CPE and BS increases, the respective delay increases. Therefore, farther CPEs will have to wait longer in establishing a connection to BS as compared to nearer ones. Now, from Fig. 11, at $D = 3.4 \times 10^9$ *m*, the path loss is about 1.41×10^{12} *db*. When D moves from 3.4×10^9 *m* to 3.7×10^9 *m*, path loss increases from 1.41×10^{12} *db* to 1.52×10^{12} *db*. Similarly, when D becomes equal to 4.3×10^9 *m* from BS, path loss approaches 1.79×10^{12} *db*. It means that path loss increases with increasing distance of CPE from BS as is evident from Fig. 11. Hence, CPEs having a larger distance from BS will suffer from more path loss as compared to the CPEs closer to the BS.

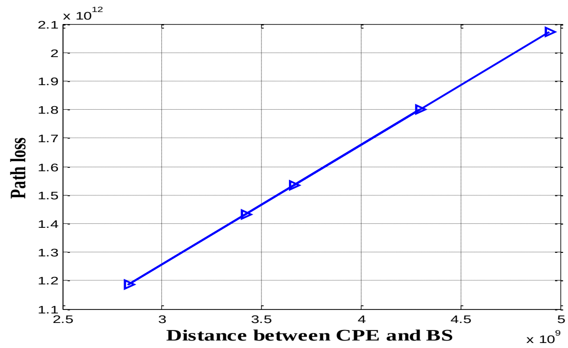

Fig. 11: Path loss vs. distance between CPE and BS in a queued trunked system.

Now, we see that in both cases traffic capacity, total users and the number of CPEs are dependent on the number of channels. These parameters increase with increasing number of channels at any Grade of Service. This increment is slightly more in a non-queued system as compared to a queued system. However, the users in a queued system experience less delay and path loss than in a non-queued system.

4 Conclusions

In this paper, an analytical model has been developed to analyze the performance of QoS parameters related to spectrum sharing in a wireless network. The traffic intensity, total number of users, number of CPEs, delay and path loss are investigated to evaluate the performance of the queued and non-queued trunked radio systems. We have shown that the traffic intensity, total number of users and number of CPEs are strongly dependent upon the Grade of Service (*GoS*) and the number of channels in the network. The delay and path loss depends upon the distance between CPE and BS. When distance increases, the resulting delay and path loss increases. Therefore, CPEs away from BS will suffer from greater path loss as compared to the CPEs nearer to the BS. This model can help BS in scheduling the number of channels based on *GoS* to facilitate maximum number of CPEs to become part of the network.

In future, we intend to evaluate the performance parameters of CR based Internet of Things (IoT), which is a powerful technique for improving spectrum utilization. It would be very beneficial in many real time environments like public safety, healthcare, disaster management and agricultural environment.

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