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Performance Evaluation of TDMA Medium Access Control Protocol in Cognitive Wireless Networks*

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Abstract

Cognitive radio paradigm has been revealed as a new communication technology that shares channels in wireless networks. Channel assignment is a crucial issue in the field of cognitive wireless networks because of the spectrum scarcity. In this work, we have evaluated the performance of TDMA medium access control protocol. In our simulation scenarios, primary users and secondary users utilize TDMA as a medium access control protocol. We have designed a network environment in Riverbed simulation software that consists of primary users, secondary users, and base stations. In our system model, secondary users sense the spectrum and inform the base station about empty channels. Then, the base station decides accordingly which secondary user may utilize the empty channel. Energy detection technique is employed as a spectrum sensing technique because it is the best when information about signal of primary user is acquired. Besides, different number of users is selected in simulation scenarios in order to obtain accurate delay and throughput results. Comparing analytical model with simulation results, we have shown that performance analysis of our system model is consistent and accurate.

Keywords: Cognitive radio, delay analysis, TDMA, wireless networks.

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1 Introduction

In recent years, the usage of wireless communication technologies has been growing rapidly with the increase of wireless devices and services [1]. Due to the increasing number of users and fixed spectrum allocation strategies, spectrum scarcity problem has revealed [2]. Cognitive radio is a new wireless communication technology that aims to utilize the spectrum in a more dynamic and effective way [3]. In cognitive radio networks, secondary users exploit spectrum holes temporarily without causing any interference to the primary users. Secondary users use various signal detection techniques and algorithms in order to sense the unutilized portions of the spectrum [4]. Among spectrum sensing techniques, energy detection is widely preferred due to not requiring any prior knowledge about signal of the primary user [5].

Several medium access control protocols have been described in the literature to regulate access [6]. They mainly are grouped into two categories, namely distributed and centralized. In the distributed approach, each node decides on its own when is the best time for the transmission process [7]. If multiple users transmit, then these protocols must provide mechanisms to resolve the collision [8]. In the centralized approach, a base station is responsible for deciding who can access the channel [9]. The base station allocates a time slot for every user in turn.

In this work, performance analysis of TDMA (Time Division Multiple Access) based wireless cognitive radio network is examined. The proposed network structure is composed of two different groups of users including primary and secondary users. Both groups of users employ TDMA as a medium access control technique. All of the users share time slotted based common communication channel. Primary and secondary users communicate through primary base station and secondary base station correspondingly.

Because primary users are licensed users, they have a right to use the spectrum any time. Secondary users only access to the spectrum when action of primary users is not sensed in the spectrum. Simulation scenarios have been developed using Riverbed simulation software. In

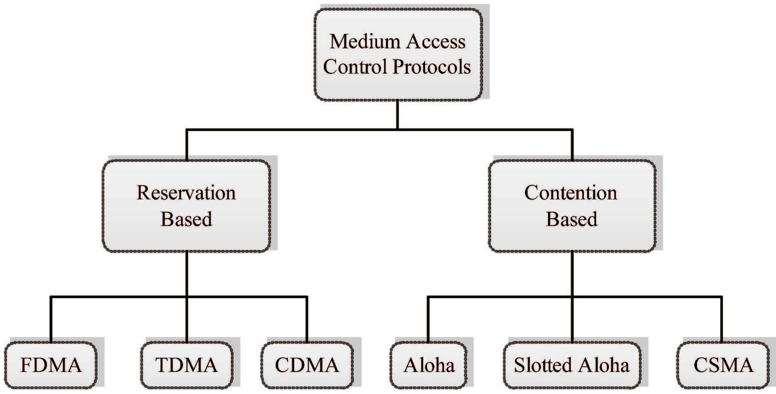

Figure 1. Classification of medium access control protocols

order to evaluate performance of our network model; end to end delay analysis, throughput analysis and capacity analysis are carried out. Besides, equations for throughput and delay characteristics of TDMA protocol are derived.

2 Medium access control protocols in cognitive radio networks

Multiple access techniques allow an access to the limited bandwidth of the spectrum for multiple users at the same time effectively [10]. Because available spectrum is limited for wireless communications, spectrum needs to be allocated efficiently [11]. Medium access control protocols are employed to utilize the limited bandwidth effectively by means of reservation based and contention based techniques [12].

In Figure 1, classification of medium access control protocols in wireless cognitive radio networks is shown. FDMA (Frequency Division Multiple Access), TDMA and CDMA (Code Division Multiple Access) are reservation based protocols while Aloha, Slotted Aloha and CSMA (Carrier Sense Multiple Access) are contention based protocols.

2.1 Related works

In recent years, a lot of researches about cognitive radio and effective spectrum access are made. Li et al. proposed a new Slotted Aloha based distributed access cognitive radio network [11]. In their study, secondary users select a random set of channels to sense, and then perform the transmission process after detecting an idle channel. They have also confirmed the obtained analytical results with some important simulation models. Choe proposed a Slotted Aloha based multichannel cognitive radio network [4]. In his work, delay analysis of the network model has been carried out. While calculating end to end delay, spectrum sensing time is not taken into account in his study.

Lien et al. presented a new CSMA based protocol in cognitive radio networks [12]. In their study, secondary users employ CSMA based medium access technique that is different from conventional network systems. For the proposed network model, delay analysis is also calculated. When compared to the conventional CSMA based network systems, throughput performance of the proposed system is significantly increased.

Yang examined design of medium access protocols for primary users and secondary users in cognitive radio networks [13]. In his work, primary users employ Slotted Aloha technique while secondary users utilize Slotted Aloha and CSMA techniques as a medium access control protocol in order to exploit idle time slots of primary users. In addition, the average delay performance and throughput performance of the network model are examined. All analytical results obtained are verified with the simulation results in his work.

Choe and Park presented a Slotted Aloha based new protocol for multichannel cognitive radio networks [5]. In addition, the idle channel selection based protocols are confirmed to have better performance than the random channel selection protocols in their study. Moreover, Slotted Aloha technique has shown to give better results than Aloha technique. However, spectrum sensing time is ignored in their delay and throughput equations.

Different than studies in the literature, spectrum sensing time and

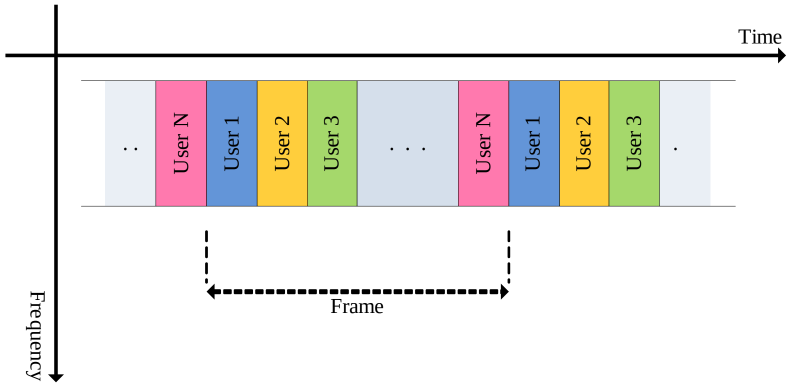

Figure 2. TDMA frame structure in wireless cognitive radio networks

probability of missed detection parameters are taken into consideration in our network models. Spectrum sensing time is described as a duration secondary users spend time for finding an idle spectrum. Probability of missed detection is expressed as detecting a supposed idle channel when it actually is busy. Opposite to the traditional networks, probability of missed detection decreases the throughput of the cognitive radio networks.

2.2 Reservation based medium access control protocols

One of the best advantages of reservation based medium access control protocols is that they prevent collision by allocating bandwidths to users [14]. Reservation based medium access techniques are mainly examined under three different sections, namely FDMA, TDMA and CDMA [15].

In Figure 2, TDMA frame structure in cognitive radio networks is shown. In TDMA systems, the radio spectrum is divided into time slots and each user sends or receives packets in their own time slots. If this system is applied to certain time duration, multiple users on the same spectrum and in different time slots may perform the transmission operation independently.

In TDMA structure, each resource in the spectrum is sampled in order to obtain data series in the environment [16]. Sampling frequency is the frequency of the user which is changing frequency band most rapidly and selected according to the sampling theorem [13]. It also has features similar to all the information sources used in the same sampling frequency [17].

In TDMA medium access control protocol, if resources with different characteristics of the spectrum are available, these resources are joined together to have better performance [13]. The data rate is directly related to the bandwidth of the spectrum [18]. If the bandwidth of the transmission medium is high, then it is possible to achieve very high data rates [3].

3 System model of the network

The Riverbed (OPNET) Modeler simulation software includes several tools such as designing, simulation, and data aggregation [19]. In Riverbed software, performance of a simulation model is evaluated by means of discrete event simulations [19].

Configuration of the network model is carried out in three stages: namely network stage, node stage, and process stage. In the network stage, topology of the network is built. The node stage defines the characteristics of the node. The process stage is characterized by state machines that are created with states and transitions between states. The source code of Riverbed Modeler is written on C programming language [19].

Our network model composes of secondary users and the secondary base station in the same communication environment with the primary users and the primary base station. TDMA is employed as medium access control protocol by primary and secondary users [20]. The procedure of a secondary user in the network model is as follows. In the beginning of each time slot, every secondary user senses the spectrum in order to learn status of the time slots. If the time slot sensed is used by a primary user, then the secondary user waits for the availability of following time slots. If the time slot sensed is empty, then the

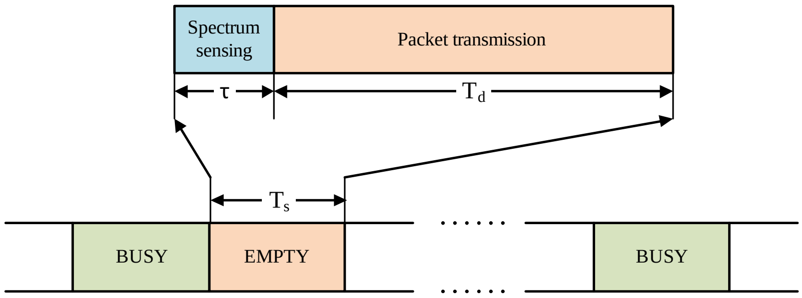

Figure 3. TDMA time slot structure used in the network model

secondary user transmits its packet [21].

Total number of channels that is supported simultaneously in a TDMA system is expressed with the following equation;

$$NC = \frac{m(B_t - 2B_g)}{B_c}, \tag{1}$$

where m is maximum number of users that can be supported by each frequency channel [3], [6], [18]. In (1), B_t denotes total spectrum allocation, B_g denotes guard band and B_c denotes channel bandwidth.

Throughput delay characteristics of TDMA protocol with different number of users is expressed as follows;

$$D = 1 + \frac{M}{2(1 - S)}, \tag{2}$$

where D, M and S represents delay, number of users and throughput correspondingly [1], [6], [10]. By means of (2), various throughput delay characteristics of TDMA may be obtained using different values. Expected end to end delay for TDMA scheme is calculated as dividing sum of delay in a time slot by number of slots in a frame [6].

In the network model, time slot structure shown in Figure 3 is used. Because the primary users employ TDMA technique as a medium access control protocol, the time axis is divided into fixed length of time slots. As shown in the figure, some of the time slots are used by primary users while some of them are empty. Time slots utilized by primary users are called busy. By means of cognitive radio, secondary users may exploit empty time slots of primary network opportunistically. Busy and empty time slots of users are directly related to offered load of primary users. The rise of offered load reduces empty time slots while increasing the number of busy time slots.

The time slots of primary users are composed of two parts, namely spectrum sensing and packet transmission. In spectrum sensing stage, secondary users sense the signal of primary users without attempting to transmit. If the absence of primary users is detected, secondary users may send their packets in packet transmission stage. If the idle time slot is not found, secondary users continue to sense the next time slots.

3.1 System model of the primary network

In the communication area of the network model, there are a variable number of primary users and a primary base station. Primary users communicate via the base station using TDMA scheme. In the proposed primary network model, number of time slots in a frame is assumed to be equal to the number of primary users. Therefore, a unique time slot is allocated to each primary user for transmitting their packets.

Figure 4 shows simulation scenario designed for primary network on Riverbed software where primary users and the primary base station are illustrated. Characteristics of all the primary users in the network scenario are identical. Code of each designed user and the base station are written in Riverbed simulation software using C programming language.

Moreover, each primary user is presumed to have unlimited buffer. Packet length of primary users is equal to the time slot in a frame. Besides, each primary user is an independent Poisson source where λ_p represents the average number of packets produced per time slot. The total load offered to the network, G_p, is obtained by using the following expression:

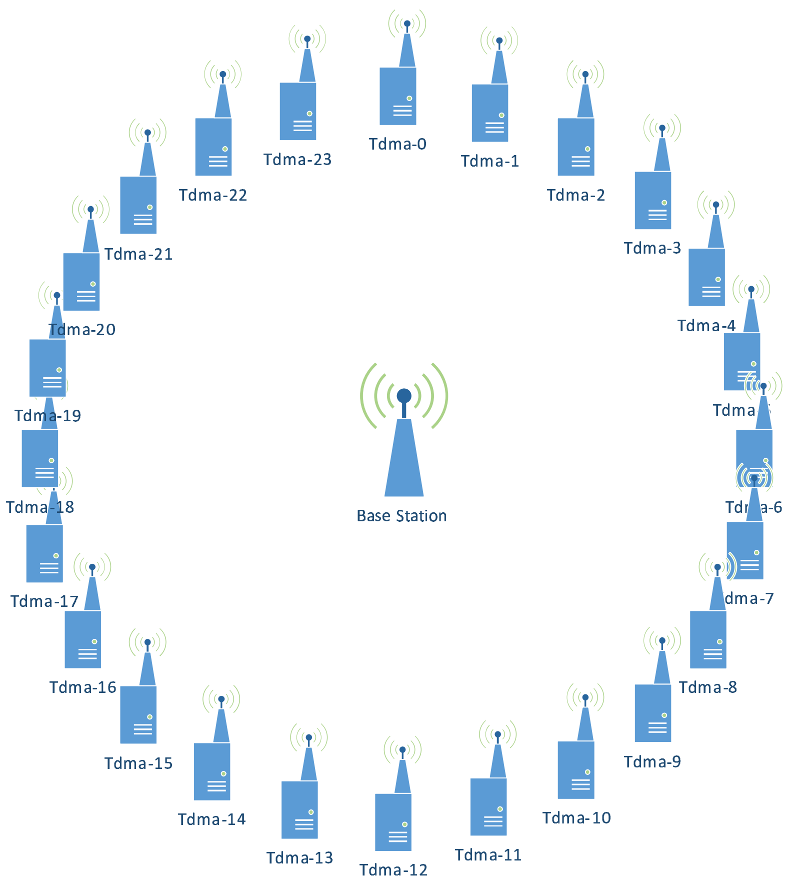

Figure 4. Primary network model in Riverbed simulation software

$$G_p = \lambda_p N_p, \tag{3}$$

where N_p is the number of primary users [2]. Since throughput of the network is one of the performance metric used in this work, throughput of the analytical model and simulation model is evaluated. Throughput is defined as the average number of packets successfully received by the base station in a given time. The number of packets sent through the network in a given time is called offered load of the network [2].

Since TDMA medium access scheme is not a contention-based protocol, TDMA packets do not collide with each other [8]. Therefore, when offered load of the network is less than 1, throughput equals to offered load in traditional networks. In the case where the load is equal to 1 or greater than 1, throughput is equal to 1.

However, the packets of the secondary users may collide with the packets of primary users because of the missed detection probability in cognitive radio networks [17]. Missed detection slightly decreases the throughput of the network. Taking missed detection into account, throughput of TDMA scheme for primary users in wireless cognitive radio networks is expressed as in (4).

$$S_p = \begin{cases} G_p(1-P_m), G_p < 1 \\ (1-P_m), G_p \geq 1 \end{cases} . \tag{4}$$

In (4), P_m indicates the probability of missed detection and it is obtained by subtracting detection probability from 1 [16]. S_p represents throughput of TDMA based primary network in wireless cognitive radio networks.

3.2 System model of the secondary network

In the communication area of the secondary network model, there are ten secondary users and a secondary base station. Secondary users communicate through the secondary base station using TDMA medium access control protocol.

In our secondary network model, it is assumed that each secondary user produces packets according to the Poisson process. Furthermore,

Table 1. Simulation parameters utilized for the secondary network

Parameter	**Value**
Time slot length of the primary users	100 ms
Number of secondary users	10
Receiving frequency	2.4 GHz
Transmitting frequency	1.85 GHz
Bandwidth	2 MHz
Modulation scheme	BPSK
Transmit power	0.1 W
Probability of detection	0.90
Probability of false alarm	0.10
Data rate	1 Mbps
Packet length of secondary users	10 Kb

the packet length of secondary users is shorter than that of primary users due to the effect of spectrum sensing time. Simulation parameters of the secondary users used in Riverbed software are given in Table 1.

Taking missed detection and false alarm into consideration, throughput of TDMA scheme for secondary users in wireless cognitive radio networks is computed as in (5);

$$S_s = \begin{cases} G_s(1 - P_m - P_{fa}), G_s < 1 \\ (1 - P_m - P_{fa}), G_s \geq 1 \end{cases}, \qquad (5)$$

where P_{fa}, S_s and G_s denote probability of false alarm, throughput of secondary network and offered load of secondary users respectively. Different from throughput equation of primary network, throughput of secondary network is affected from probability of false alarm. In addition to probability of missed detection, probability of false alarm reduces throughput.

End to end delay characteristics of secondary users are expressed as follows taking spectrum sensing time into consideration;

$$D = 1 + \frac{M}{2(1-S)} + T_s, \tag{6}$$

where D, M and S denote delay, number of users and throughput respectively [1], [16], [20]. In (6), T_s denotes spectrum sensing time which reduces packet length of secondary users [21].

4 Analytical and simulation results

For our network simulation scenarios, we have evaluated throughput, capacity and end to end delay characteristics of TDMA scheme. All analytical results obtained from equations precisely match to the simulation results obtained from Riverbed simulation software [19].

4.1 Throughput characteristics of the network

In traditional TDMA scheme, throughput is proportional to the offered load. In cognitive radio networks, different parameters like missed detection may decrease throughput.

In Figure 5, comparison of TDMA scheme under different network conditions is made. In cognitive radio networks, throughput is lower due to the missed detection. Missed detection is defined as sensing the spectrum idle when it actually is utilized by primary users. When offered load is more than one, throughput remains about 0.9 in cognitive radio networks.

In Figure 6, network throughput values for primary network and secondary network are illustrated. Secondary network has lower throughput than primary network because of the false alarm parameter. False alarm is described as sensing the spectrum busy, when it actually is not used by primary users.

In Figure 7, channel capacity of TDMA medium access scheme is examined. In the analytical model of channel capacity, each frame is assumed to be divided into ten time slots. Accordingly, number of users supported by TDMA is acquired. Each frequency channel supports ten

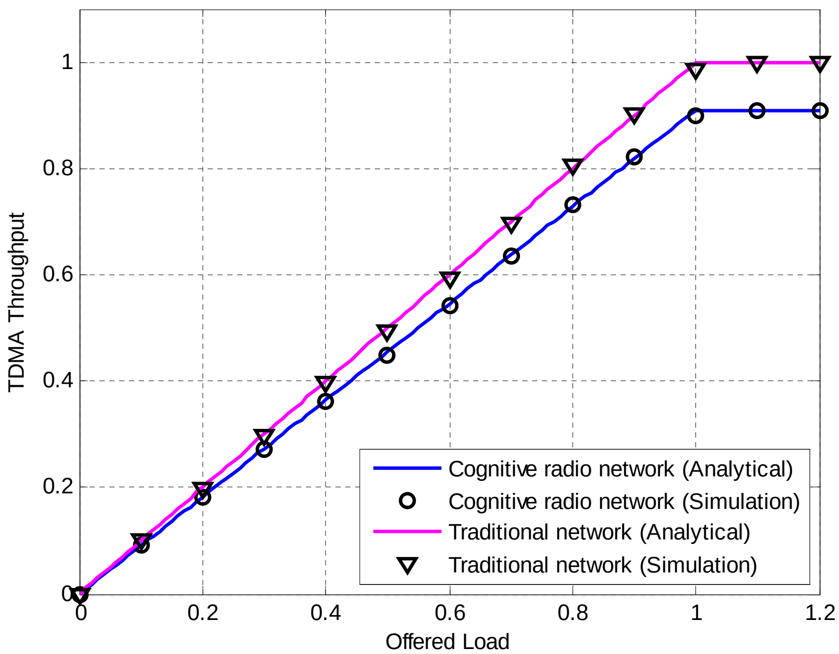

Figure 5. TDMA throughput analysis in traditional and cognitive radio networks

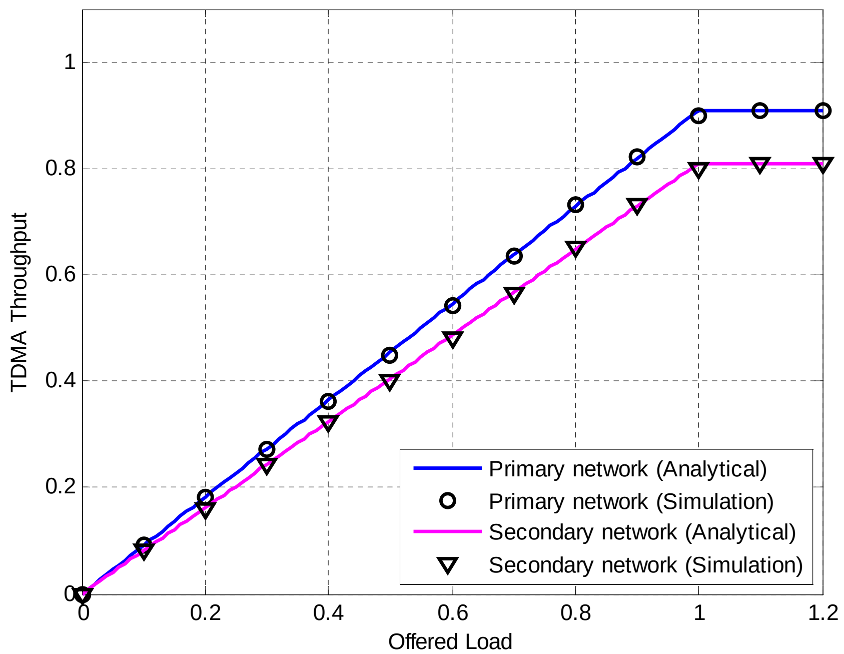

Figure 6. TDMA throughput comparison for primary and secondary network

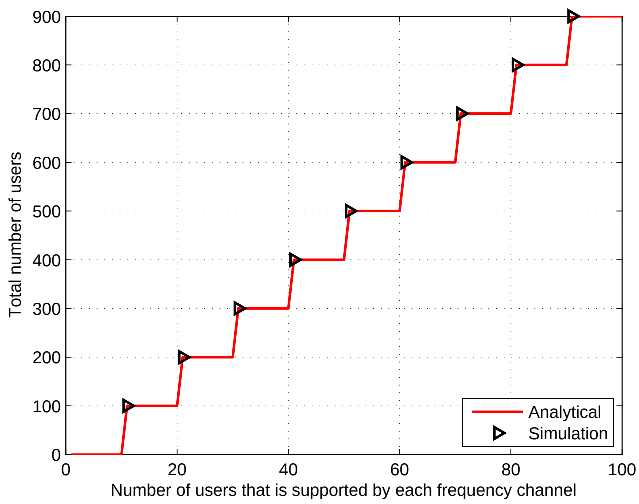

Figure 7. Number of users supported by TDMA assuming each frame is divided into ten time slots

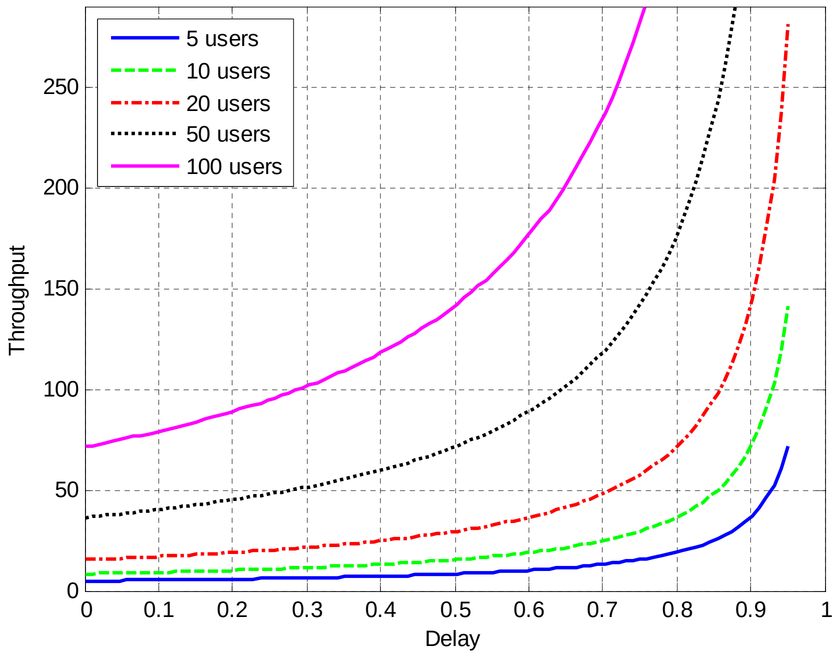

Figure 8. Throughput – delay characteristics of TDMA medium access control protocol

users in our model. However, because of the slot allocation, intermediate values do not affect the simulation results. For example, if forty five users are supported by each frequency channel, total number of users is still four hundred as is for forty users.

In Figure 8, throughput – delay characteristics of TDMA scheme is illustrated. As number of users is raised, exponential increase of delay and throughput are carried out. When maximum throughput is reached, delay becomes about one. Besides, maximum throughput changes according to the number of users.

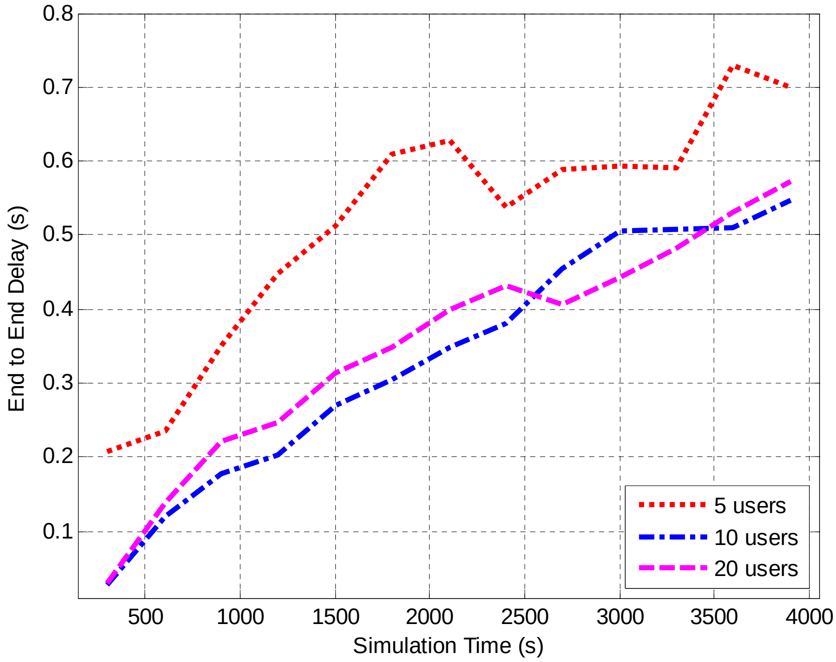

Figure 9. Delay analysis for primary network for less than 20 users

4.2 Delay results

Analytical end to end delay results of the network model are obtained using (2). And, simulation results obtained from Riverbed software are consistent with the analytical results.

In Figure 9, results of delay analysis for primary network are shown. For five users, end to end delay increases from 0.2 to 0.7. For ten and twenty users, end to end delay is almost the same. End to end delay for five users is higher because of the slot allocation. When ten time slots are assigned to five users, waiting time between slots gets higher so as to end to end delay.

In Figure 10, delay analysis of primary network with twenty five,

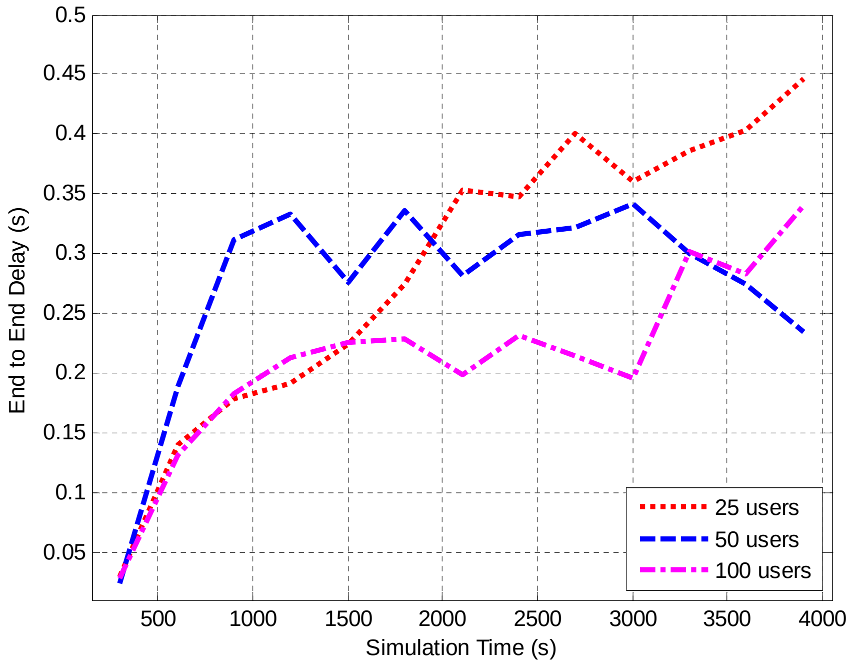

Figure 10. Delay analysis for primary network for more than 25 users

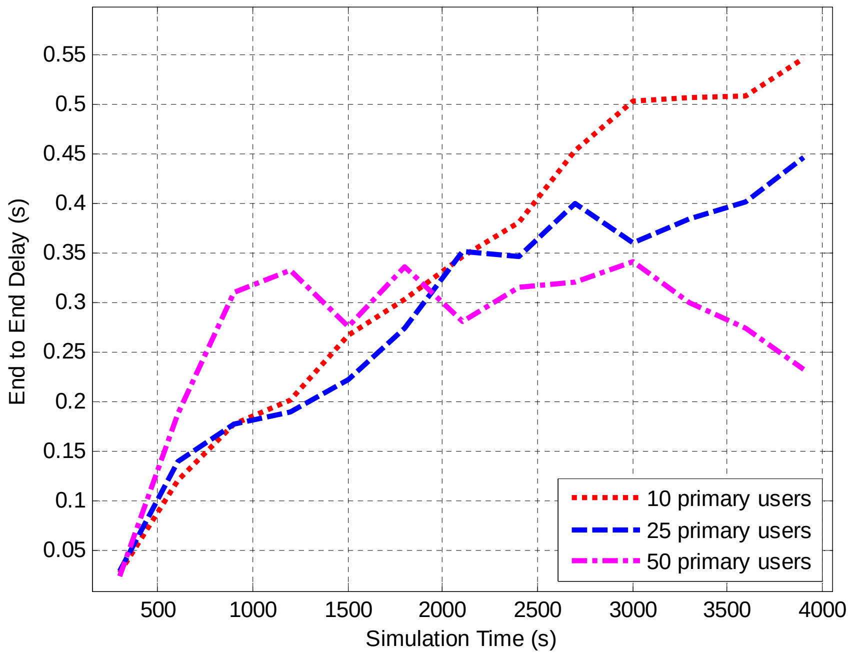

Figure 11. Delay analysis for primary network when number of secondary users is ten

fifty and hundred users are illustrated. The scenario which consists of twenty five users gives good results. For fifty and hundred users, some inconsistent results are obtained. Because the time slot of the users becomes smaller as number of users is increased.

In Figure 9 and Figure10, end to end delay results are obtained for primary networks without effect of secondary users. However, delay results are acquired when there are ten secondary users in the network scenario in Figure 11.

In Figure 11, end to end delay results of primary network that consists of ten secondary users are given. Because of the secondary users in the spectrum, end to end delay of the network increases. Owing to the missed detection which causes collision with secondary users, packet transmission time in the network model arises.

5 Conclusions

In this study, we have evaluated the performance of reservation based TDMA medium access control technique. In the simulation scenarios, primary users and secondary users employ TDMA as a medium access control technique. We have designed a communication medium in Riverbed simulation software that consists of primary users, secondary users, and base stations. In the network model, secondary users sense the spectrum bands and inform the base station about idle channels. Then, the base station decides accordingly which secondary user may utilize the idle channel. Energy detection technique is used as a spectrum sensing technique because it is the best one when information about signal of primary user is known in advance. Moreover, different number of users is selected in simulation scenarios in order to achieve correct delay and throughput results. Comparing analytical model results with the simulation results, we have proved that performance analysis of our system model is consistent and accurate. In future works, the performance analysis of the secondary networks using various medium access control protocols may be studied.

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