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Performance analysis of LTE-U coexistence network with WiFi using queueing model

Hu Zhiqun (✉), Lu Zhaoming, Lin Shangjuan, Wen Xiangming, Xu Hen

School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

Abstract

The unforeseen mobile data explosion as well as the scarce of spectrum resource pose a major challenge to the performance of today's cellular networks which are in urgent need of novel solutions to handle such voluminous mobile data. Long term evolution-unlicensed (LTE-U), which extends the LTE standard operating on the unlicensed band, has been proposed to improve system throughput. In LTE-U system, arriving users will contend the unlicensed spectrum resource with wireless fidelity (WiFi) users to transmit data information. Nevertheless, there is no clear consensus as to the benefits of transmission using unlicensed bands for LTE users. To this end, in this paper an analytical model is presented based on a queue system to understand the performance achieved by unlicensed based LTE system taking quality of services (QoS) and LTE-U users' behaviors into account. To obtain the stead-state solutions of the queue system, a matrix geometric method is used to solve it. Then, the average delay and utilization of unlicensed band for the LTE-U users is derived by using the queuing model. The performance of LTE-U coexistence is evaluated with WiFi using the proposed model and provide some initial insights as to the advantage of LTE-U in practice.

Keywords LTE-U, WiFi, queueing model, matrix geometric method

1 Introduction

With an exponential growth of the number of mobile devices and hungry-data demand applications emerging in an endless stream, the current wireless network is facing an explosive increase of the mobile data traffic. It's forecasted in Ref. [1] that the volume of traffic carried by wireless network is expected to be 1 000 times higher than that of 2010 by 2020. To meet the data demand, many new technologies have been proposed to improve the network capacity in the fifth generation communication, such as massive multiple-input multiple-output (MIMO), non-orthogonal multiple access, full-duplex communications. However, the scarcity of spectral band is still the major bottleneck issue. As a result, the increasing need for a largely extended bandwidth has recently driven to exploit the unlicensed band used by WiFi system. Since 2015, the 3rd generation partnership project (3GPP) has launched standardization to deploy LTE-advanced (LTE-A) networks on the 5 GHz unlicensed bands in Rel-13 [2–3].

To implement the LTE in unlicensed band, the issue of fairly and friendly coexistence with WiFi system should be addressed. Two mainly channel access schemes for the LTE-U systems, based on the duty cycle method (carrier sensing adaptive transmission, CSAT) and the listen-before-talk (LBT) mechanism, have been proposed to deal with it. The scheme based on duty cycle method, periodically turns the LTE signal on and off by using the blank subframes, and provides opportunities for the WiFi transmissions [4]. The LTE monitors the co-channel WiFi activity for a relatively long period of time and adaptively adjusts the duration of the WiFi transmissions. In this case, the LTE dominates the utilization of unlicensed band. In contrast, for the method based on the LBT mechanism [5–7], LTE monitors the channel occupancy before it accesses to the channel, which use carrier sensing and backoff rules in a similar manner to WiFi [8]. In Ref. [9], the authors

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Corresponding author: Hu Zhiqun, E-mail: huzhiqun@bupt.edu.cn
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concluded that the LBT mechanism is not inherently fairer than CSAT. It shows that for sufficiently long LTE transmission times, the LTE throughput with both CSAT and LBT is almost identical.

Recently, existing works on the performance of the coexistence of LTE-U and WiFi system have focused primarily on the throughput and capacity. In Refs. [10–11], the stochastic geometry theory was used to analyze the throughput and fairness of both LTE and WiFi system on the condition that LTE contends the unlicensed band using LBT mechanism. Ref. [6] showed that the carrier detection threshold can greatly affect the fairness of LTE and WiFi system in the LTE-U system based on LBT mechanism. In Ref. [12], an adaptive carrier selection scheme in LTE-U was developed to improve the network throughput. The neighboring small cells select different carriers to avoid collision each other so that larger number of active small cells can be retained after LBT channel sensing. Ref. [13] investigated the fundamental question whether the existing scheduling based radio access is still optimum when an LTE-licensed assisted access (LTE-LAA) network coexists with WiFi networks. The authors derived the condition that LTE-U users should dynamic switch between scheduling-based and random access schemes. However, these works only analyze the coexistence performance between LTE-U and WiFi system based on LBT mechanism. Ref. [14] analyzed the optimal duration time that LTE transmits packet in the unlicensed band based on CSAT mechanism. But it does not take the LTE users' QoS into account.

In this paper, we analyze the performance of LTE-U and WiFi coexistence system considering the LTE-U users' delay deadline. The packets in the queue of LTE-U, who wait to transmit via unlicensed band, have to be delivered by the licensed band until the delay deadline expired. On the other hand, the user behaviors are also considered, which arriving LTE-U users could balk (do not use unlicensed band) and renege (switch the licensed band to serve after waiting the unlicensed band). In other words, the user may get impatient and leave the queue without getting service and the user may doubt whether chooses the unlicensed band to service. In this scenario, we take the arrivals and fulfillments of data services of LTE-U users as an $M/M/1/N$ queue model, where M characterizes the arrival process of data service requests waiting to be served by unlicensed band and queue length N controlling the average service delay. In this paper, we propose a two-dimensional discrete Markov chain to characterize $M/M/1/N$ queue model. To solve it, we use a matrix geometric method to derive the closed-form expression for the delay and utilization of unlicensed band.

The rest of this paper is organized as follows. The system model is presented in Sect. 2. We derive the expression of some performance metrics of LTE-U users in Sect. 3. Sect. 4 presents the evaluation of its performance by some exemplary simulation results. Finally, this paper is concluded in Sect. 5.

2 System model

In this section we introduce a discrete time $M/M/1/N$ queue model with reneging for modeling LTE-U users' data services. Based on this model, we can evaluate the delay and utilization of LTE-U system in unlicensed band.

Assume the LTE-U employ CSAT to access the unlicensed band, which is a time division multiplex coexistence mechanism based on medium sensing [15]. The access process of LTE-U is depicted in Fig. 1. The CSAT mechanism uses duty-cycling instead of a Listen before talk mechanism. It adaptively adjusts the transmission period in the duty cycle period according to the load of the WiFi. An important observation in Fig.1 is that during the LTE-U 'on' period, the LTE-U user transmits data via the unlicensed band. Otherwise, during the LTE-U 'off' period, it mutes. WiFi will detect that the channel is free and can schedule its transmission. Therefore, LTE-U can guarantee the fairly coexistence with WiFi.

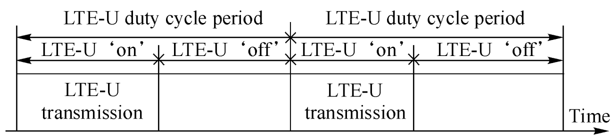


Fig. 1 Duty-cycle mechanism used by LTE-U

Consider an LTE-U user which obtains and gives up unlicensed band due to the fairness coexistence with WiFi. We assume that LTE-U users can always choose licensed band to transmit information. To fully utilize the unlicensed band, the traffic of LTE-U's users will wait in the queue until contending for unlicensed band. However, each traffic has a maximum delay that it can wait. If the deadline expires before the traffic can be transmitted through the unlicensed band, then it is transmitted via the licensed band. The duration of obtaining unlicensed band is assumed to be an exponentially distributed random variable with rate η. Similarly, the duration of giving up unlicensed band is assumed to be independent and exponentially distributed with rate γ. The LTE-U packets arrive according to a Poisson process with parameter λ and their service times is exponentially distributed with mean $1/\mu$. The packet's deadline is random variable that is exponentially distributed with rate ε. We consider the first come first served as the queue discipline. The queue capacity N represents the maximum number of service requests in the system, and thus the queue buffer length is (N–1). The impatient customer-type of queue is considered, which means that if one service request enters the queue, it will wait a certain time t for unlicensed band, otherwise it directly choose the licensed band to deliver data. Assume the user impatient time t, which is a random variable followed negative exponential distribution with parameter r. However, if a service arrives with a full queue, the service request will be directly serviced by the licensed band.

A 2-dimensional discrete Markov chain is used to characterize $M/M/1/N$ queue model, as shown in Fig. 2. The pair of (i, w) and (i, c) are used to describe the Markov states with unlicensed band transmission and without unlicensed band for LTE-U users, respectively. i represents the number of data requests in the system. During unlicensed band transmission, the system empties at rate u since traffics are transmitted one by one; and during muting state (without unlicensed band) the system empties at rate $i(\varepsilon+r)$ since any of the i queued packets can renege due to expired deadline and impatient. The following theory uses matrix geometry method to derive the mean system time for this queue.

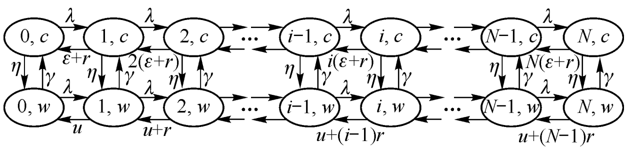


Fig. 2 2-D Markov chain process

3 Performance analysis of the LTE-U system

3.1 Queue analysis

Let i ($0\leqslant i\leqslant N$) denote the number of packets in the LTE-U system. There are (i–1) packets in the system have to wait for serving via the unlicensed band. Since the waiting time t is a random variable following an exponential distribution with mean 1/r and users are independent of each other, the average renege rate is (i–1)r when there is i packets in the queue. Therefore, it is

$$r_{i,w}=r_{i,c}=\begin{cases}0; & i=0\\(i-1)r; & 1\leqslant i\leqslant N\\0; & i>N\end{cases} \tag{1}$$

where $r_{i,w}$ and $r_{i,c}$ are the average number of packets, which have to wait in the queue when the user is in obtaining the unlicensed bands and otherwise, respectively.

Let $P_{i,w}$ and $P_{i,c}$, $i\in[0,N]$ be the stationary distribution of the chain, which denotes the probability of finding i packets when LTE-U system obtains the unlicensed band and does not win it, respectively. Then, in the unlicensed band state, the steady-state balance equations in Fig. 2 can be obtained by

$$P_{0,w}(\lambda+\gamma)=uP_{1,w}+\eta P_{0,c};\quad i=0 \tag{2}$$

$$P_{i,w}(\lambda+\gamma+u+(i-1)r)=(u+ir)P_{i+1,w}+\lambda P_{i-1,w}+\eta P_{i,c};\quad 1\leqslant i\leqslant N-1 \tag{3}$$

$$P_{N,w}(\gamma+u+(N-1)r)=\lambda P_{N-1,w}+\eta P_{N,c};\quad i=N \tag{4}$$

In the case of licensed band without obtaining the unlicensed band, the steady-state balance equations can be given by

$$P_{0,c}(\lambda+\eta)=\gamma P_{0,w}+(\varepsilon+r)P_{1,c};\quad i=0 \tag{5}$$

$$P_{i,c}(\lambda+\eta+i(\varepsilon+r))=(i+1)(\varepsilon+r)P_{i+1,c}+\lambda P_{i-1,c}+\gamma P_{i,w};\quad 1\leqslant i\leqslant N-1 \tag{6}$$

$$P_{N,c}(N(\varepsilon+r)+\eta)=\gamma P_{N,w}+\lambda P_{N-1,c};\quad i=N \tag{7}$$

The steady-state probability that finds the LTE-U system in some region with unlicensed band is $P_w=\eta/(\eta+\gamma)$. Similarly, the probability that finds the LTE-U system with only licensed band is $P_c=\gamma/(\eta+\gamma)$.

3.2 Matrix geometric solution

By using the matrix geometric method [16], we develop the steady-state probability $\boldsymbol{P}_i$, $0\leqslant i\leqslant N$, where $\boldsymbol{P}_i=[P_{i,c}\ \ P_{i,w}]$. Based on the 2-D Markov chain process in Fig. 2, the corresponding transition matrix $\boldsymbol{Q}$ of the Markov chain can be given by

$$\boldsymbol{Q}=\begin{bmatrix}\boldsymbol{B}_0 & \boldsymbol{C}_0 & \boldsymbol{0} & & \\ \boldsymbol{A}_1 & \boldsymbol{B}_1 & \boldsymbol{C}_1 & & \\ & \ddots & \ddots & \ddots & \\ & & \boldsymbol{A}_{N-1} & \boldsymbol{B}_{N-1} & \boldsymbol{C}_{N-1}\\ & & & \boldsymbol{A}_N & \boldsymbol{B}_N\end{bmatrix} \tag{8}$$

where

$$\boldsymbol{B}_0=\begin{bmatrix}-(\eta+\lambda) & \eta \\ \gamma & -(\gamma+\lambda)\end{bmatrix}$$

$$\boldsymbol{B}_i=\begin{bmatrix}-[i(\varepsilon+r)+\eta+\lambda] & \eta \\ \gamma & -[u+(i-1)r+\gamma+\lambda]\end{bmatrix};\quad 1\leqslant i\leqslant N-1$$

$$\boldsymbol{B}_N=\begin{bmatrix}-[N(\varepsilon+r)+\eta] & \eta \\ \gamma & -[u+(N-1)r+\gamma]\end{bmatrix}$$

$$\boldsymbol{A}_i=\begin{bmatrix}i(\varepsilon+r) & 0 \\ 0 & \mu+(i-1)r\end{bmatrix};\quad 1\leqslant i\leqslant N$$

$$\boldsymbol{C}_i=\begin{bmatrix}\lambda & 0 \\ 0 & \lambda\end{bmatrix};\quad 0\leqslant i\leqslant N-1$$

Let $\boldsymbol{P}$ be the corresponding steady-state probability vector of $\boldsymbol{Q}$, where $\boldsymbol{P}=[\boldsymbol{P}_0,\boldsymbol{P}_1,\boldsymbol{P}_2,...,\boldsymbol{P}_N]$. According to the theory of matrix geometric method, by solving the steady-state equations $\boldsymbol{PQ}=\boldsymbol{0}$, it follows that

$$\boldsymbol{P}_0\boldsymbol{B}_0+\boldsymbol{P}_1\boldsymbol{A}_1=\boldsymbol{0} \tag{9}$$

$$\boldsymbol{P}_{i-1}\boldsymbol{C}_{i-1}+\boldsymbol{P}_i\boldsymbol{B}_i+\boldsymbol{P}_{i+1}\boldsymbol{A}_{i+1}=\boldsymbol{0};\quad 1\leqslant i\leqslant N-1 \tag{10}$$

$$\boldsymbol{P}_{N-1}\boldsymbol{C}_{N-1}+\boldsymbol{P}_N\boldsymbol{B}_N=\boldsymbol{0} \tag{11}$$

From Eqs. (9) and (10), we can get

$$[\boldsymbol{P}_0\quad \boldsymbol{P}_1]\begin{bmatrix}\boldsymbol{B}_0 & \boldsymbol{C}_0 \\ \boldsymbol{A}_1 & \boldsymbol{B}_1+\boldsymbol{R}_2\boldsymbol{A}_2\end{bmatrix}=\boldsymbol{0} \tag{12}$$

In analogy with the point situation [17], there exists a constant matrix $\boldsymbol{R}_i$, which can be expressed by $\boldsymbol{P}_i=\boldsymbol{P}_{i-1}\boldsymbol{R}_i$, for i=2,3,…,N. Combining with Eqs. (10) and (11), we can get

$$\boldsymbol{R}_i=\begin{cases}-\boldsymbol{C}_{i-1}(\boldsymbol{B}_i+\boldsymbol{R}_{i+1}\boldsymbol{A}_{i+1})^{-1};\quad 2\leqslant i\leqslant N \\ -\boldsymbol{C}_{N-1}\boldsymbol{B}_N^{-1};\ i=N\end{cases} \tag{13}$$

and

$$\boldsymbol{P}_i=\boldsymbol{P}_i\boldsymbol{R}_i^*;\quad 2\leqslant i\leqslant N \tag{14}$$

where $\boldsymbol{R}_i^*=\prod_{j=2}^{i}\boldsymbol{R}_j$.

Finally, by means of the relations Eq. (13), stead-value of $\boldsymbol{P}_0$ can be determined by the normalization condition as follows:

$$\sum_{i=0}^{N}\boldsymbol{P}_i\boldsymbol{e}=1 \tag{15}$$

where $\boldsymbol{e}$ is a column vector with each component equal to one.

Then, based on Eqs. (12) and (15), the normalization yields

$$[\boldsymbol{P}_0\quad \boldsymbol{P}_1]\begin{bmatrix}\boldsymbol{e} \\ \boldsymbol{e}+\sum_{i=2}^{N}\boldsymbol{R}_i^*\boldsymbol{e}\end{bmatrix}=1 \tag{16}$$

3.3 Service delay and utilization of LTE-U system

Using the steady probability $\boldsymbol{P}$, the mean number of packets $E[N]$ in the system can be represented as a function of N, which can be given by

$$E[N]=(P_{1,c}+P_{1,w})+2(P_{2,c}+P_{2,w})+...+i(P_{i,c}+P_{i,w})+...+N(P_{N,c}+P_{N,w}) \tag{17}$$

Finally, using the little's law [18] $E[N]=\lambda E[T]$, the average packet delay can be obtained by

$$E[T]=\frac{1}{\lambda}[(P_{1,c}+P_{1,w})+2(P_{2,c}+P_{2,w})+...+i(P_{i,c}+P_{i,w})+...+N(P_{N,c}+P_{N,w})] \tag{18}$$

The probability that an arbitrary traffic arriving to the system will renege, i.e. either its deadline will expire before it can be transmitted via unlicensed band or the users are impatient, is

$$P_{\text{renege}}=\sum_{i=1}^{N}i(\varepsilon+r)P_{i,c}+\sum_{i=2}^{N}(i-1)rP_{i,w} \tag{19}$$

Let P_{balk} be the average balk probability that users do not enter the queue system in the case that the queue is up to the maximal queue capacity when a new traffic arrives. Then, we have

$$P_{\text{balk}}=P_{N,w}+P_{N,c} \tag{20}$$

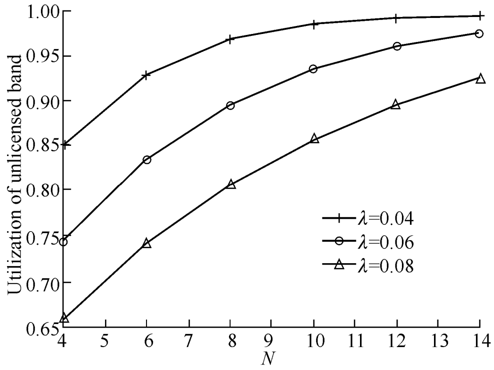
Finally, the unlicensed band utilization rate of the system is

$$E_{\text{u}}=1-P_{\text{balk}}-P_{\text{renege}} \tag{21}$$

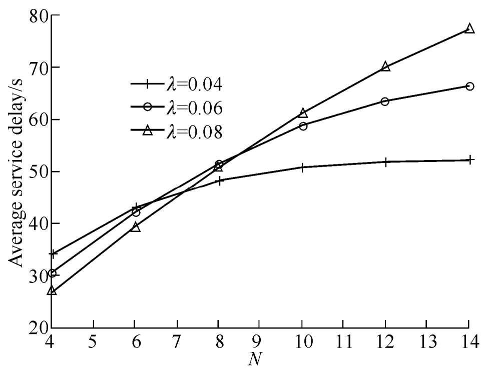
4 Numerical results

In this section, we will evaluate the LTE-U system performance based on the proposed model by numerical simulation. The parameters, where the duration of LTE-U obtains the unlicensed bands and does not hold the unlicensed bands, are required from independent exponential distributions with rates γ and η, respectively. Without special state, $\gamma=1/30$ s and $\eta=1/60$ s [19], respectively. The deadline follows exponential distribution with parameter ε and the duration of impatient of LTE-U users obeys exponential distribution with rate r. Finally, unless otherwise state, traffic arrival is a Poisson process with rate λ. For simplicity, the packet size is assumed to be 10 Mbit and the data rate of LTE-U users in the unlicensed band is assumed to be 2 Mbit/s.

Fig. 3(a) shows the variation of utilization of the unlicensed band with different value of system capacity N. We can see that the utility increases as the increase of the system capacity N, which means that the large portion of mobile data can be serviced via the unlicensed band. The reason is that with larger *N*, more requests can be temporarily buffered and then served when the LTE-U obtained the unlicensed band. On the other hand, if *N* is smaller, more service requests are blocked due to a full queue. However, there is a tradeoff between the utility and average service delay. The average service delay is presented in Fig. 3(b). It can be seen that a larger *N* leads to larger average service delay, which may decrease the user satisfactory. It is interesting to note that a large value of arrival rate of packet λ increases the average service delay and decreases the utilization of the unlicensed band due to a larger traffic load. It can be seen that when the system capacity *N* is too smaller, a large arrival rate of packet λ results in a smaller average service delay.



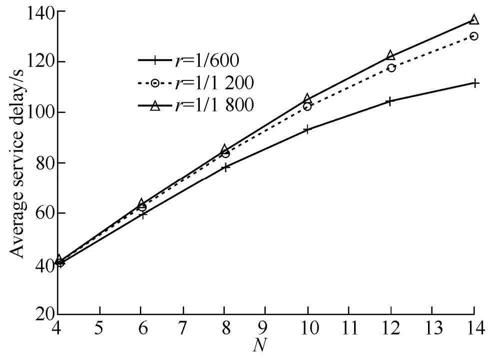
(a) Utilization of unlicensed band



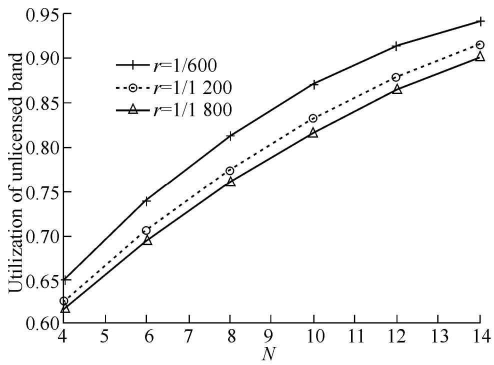
(b) Average service delay

Fig. 3 Utilization of the unlicensed band and average service delay versus *N* for different value of arrival rate, where *r* = 1/1 200 and deadline is set to 300 s

Fig. 4 presents the effect of reneging rate on the performance of the LTE-U system. Fig. 4(a) shows average service delay for different value of reneging rate. We can observe that the average service delay decreases as the increase of the reneging rate, i.e., more users leave the queue due to impatient. Consequently, the queue length becomes short and results in the short service delay. However, large reneging rate *r* means the large loss of requests, which shows in Fig. 4(b). We can see that the utilization of the unlicensed band decreases as the increase of the reneging rate. It is worth to mention that the utilization of the unlicensed band seem to insensitive to the changes in *r* when *r* is small.



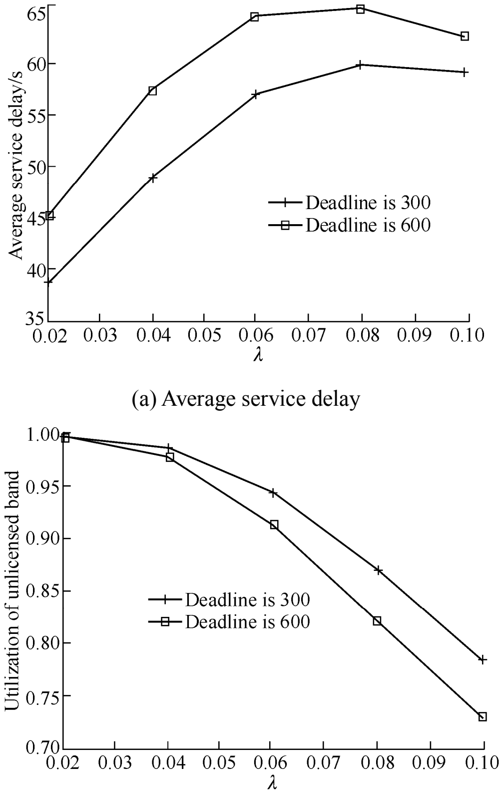
(a) Average service delay



(b) Utilization of unlicensed band

Fig. 4 Utilization of the unlicensed band and average service delay versus *N* for different value of reneging rate *r*, where $\lambda = 0.06$ and deadline is set to 300 s

In Fig. 5, we present the average service delay and utilization of unlicensed band for the variation of the arrival rate with different deadline, where $N = 10$ and $r = 1/800$, respectively. In Fig. 5(a), it is observed that the average service delay first increases as the increase of the arrival rate of the requests, and then decreases as the further increase of the arrival rate of the requests. The reason is that the average queue length obtains when the arrival rate is large. From Fig. 5(b), we observe that the utilization of the unlicensed band reduces with the increase of deadline, because large deadline brings high balk probability even through it can decrease the loss of requests.



(a) Average service delay

(b) Utilization of unlicensed band

Fig. 5 The average service delay and utilization of unlicensed band against λ, where $r = 1/800$ and $N = 10$

Fig. 6 shows that the average LTE-U throughput with the variation of the system capacity. It can be seen that throughput increases with N, since the utilization of the unlicensed band E_u increases. When the queue is overloaded (e.g., $\lambda = 0.25$ in Fig. 6) the upper bound of the average LTE-U throughput via the unlicensed band in such a scenario is about 0.98 Mbit/s.

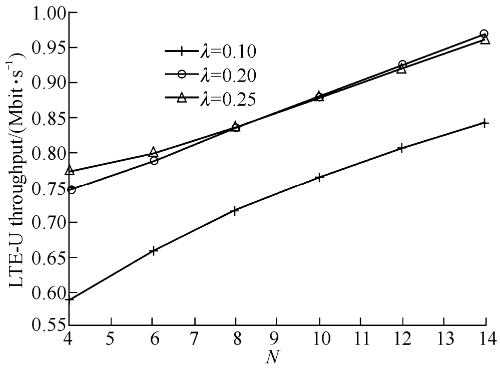


Fig. 6 The LTE-U throughput against system capacity N for different λ, where $\varepsilon = 1/300$ and $r = 1/1\,200$

To guarantee the fairness of the WiFi network in the coexistence with LTE-U, LTE-U should adaptively adjust the LTE off period for the WiFi can access the channel. If the number of Wifi APs is large, we prefer the long LTE off period. Otherwise, the short LTE off period is selected to improve the utilization of the unlicensed band. Therefore, the density of WiFi determines the unlicensed band availability ratio (UAR) that the LTE-U can obtain the unlicensed band, denoted as ρ, which can be defined as

$$\rho = \frac{E_{T_{\mathrm{ON}}}}{E_{T_{\mathrm{ON}}} + E_{T_{\mathrm{OFF}}}} = \frac{\eta}{\eta + \gamma} \tag{22}$$

Finally, we plot the utilization of the unlicensed band (solid line) and LTE-U throughput (dotted line) for availability ratio of the unlicensed band. From Fig. 7, it displays an intuitive feeling of the variation trend of the utilization of unlicensed band and throughput in LTE-U network when the value of UAR varies. The performance of the utilization of the unlicensed band improves significantly when the arrival rate is low. However, the low arrival rate does not achieve high throughput. When the UAR is low, the LTE-U throughput does not depend on the arrival rate of packet due to the low availability of the unlicensed band. And a low arrival rate of packet may contribute to improve the LTE-U throughput. However, in the case of the high UAR, the high arrival rate of packet greatly improves the LTE-U throughput.

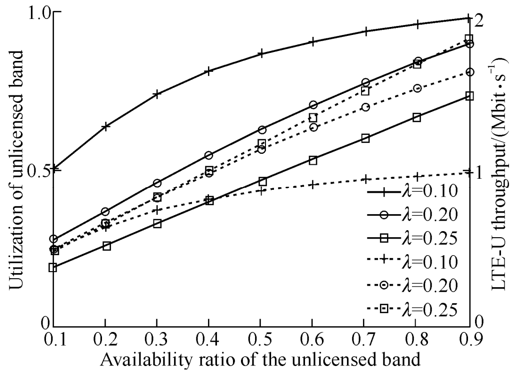


Fig. 7 The utilization of the unlicensed band and LTE-U throughput against availability ratio of the unlicensed band for different value of λ, where N = 10, r = 1/1 200, and $\varepsilon = 1/300$

5 Conclusions

In this paper, we analyze the LTE-U performance in unlicensed band using queue model. LTE-U users adopting the CSAT mechanism share the unlicensed bands with WiFi users. To alleviate the pressure of licensed spectrum, we assume that LTE-U users wait for the unlicensed band before the deadline expires. Meanwhile, the user behaviors, such as balking and impatient, are also considered. We present a 2-D Markov model to evaluate the performance of the LTE-U in terms of its delay and utility of unlicensed band in the coexistence network with LTE and WiFi. We evaluate the performance of LTE-U coexistence network with WiFi using our proposed model and provide some initial insights as to the advantage of LTE-U in practice.

Acknowledgements

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