A Fair Listen-Before-Talk Algorithm for Coexistence of LTE-U and WLAN

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***Abstract*—Recently, there has been an increasing interest in operating long-term evolution (LTE) in unlicensed bands (i.e., LTE-U). However, since LTE and wireless local area networks (WLANs) are designed to operate in different bands, they have no coexistence mechanism, which leads to significant performance degradation. In particular, since LTE does not sense channel vacancy prior to transmissions, the LTE interference severely affects the WLAN operation. To address this problem, we propose a fair listen-before-talk (F-LBT) algorithm for coexistence of LTE-U and WLAN in unlicensed bands. F-LBT jointly considers the total system throughput and the fairness between LTE-U and WLAN and then allocates an appropriate idle period for WLAN. Evaluation results demonstrate that F-LBT can improve the total system throughput while providing the fairness between LTE-U and WLAN.**

***Index Terms*—Coexistence, discrete-time Markov chain (DTMC), fairness, listen before talk (LBT), LTE-unlicensed (LTE-U), throughput, unlicensed bands.**

I. Introduction

A recent report [1] has predicted that mobile data traffic will hit an annual run rate of 291.6 EB by 2019. More specifically, a compound annual growth rate in the data traffic from 2014 to 2019 is 57%. As a result, many researchers are paying attention to the interworking of different technologies such as long-term evolution (LTE) and wireless local area networks (WLANs) to maximize users' quality of experience [2], [3]. Specifically, there is an increasing interest in operating LTE in unlicensed bands (i.e., LTE-U) [4]–[8].

LTE-U operation allows seamless data offloading by using a carrier aggregation technique [8], [9]. However, since LTE and WLAN are designed to operate in different bands, they have no coexistence mechanisms, which leads to significant performance degradation. In particular, since LTE does not sense channel vacancy prior to transmissions, the interference due to LTE transmissions severely affects the WLAN performance [5]. To prevent severe performance degradation, a coexistence mechanism for LTE and WLAN needs to be designed, and a few studies are reported in the literature [6], [7]. Almeida *et al.* [6] introduced a simple coexistence scheme that uses a concept of blank subframe in the LTE frame structure where the LTE-U access point (AP)[1] transmits no data in the blank subframe, and thus, WLAN nodes can transmit data in the given blank subframe with no interference from LTE-U. However, it is not clearly mentioned how to allocate blank subframes depending on the number of WLAN nodes. On the other hand, Chaves *et al.* [7] proposed an LTE uplink power control scheme where LTE devices decrease the uplink transmission power, and then, WLAN nodes can transmit data if WLAN nodes confirm the idle channel (i.e., if the energy level is below a certain threshold). However, no method to optimize the performance such as the total system throughput and the fairness between LTE-U and WLAN is proposed.

By the European Telecommunications Standards Institute recommendation for unlicensed bands [10], the LTE-U AP should employ a listen-before-talk (LBT) mechanism where an equipment applies clear channel assessment (CCA) before using unlicensed bands. There are two LBT mechanisms: frame-based LBT and load-based LBT. The procedure of the frame-based LBT is as follows. An equipment checks the channel state during the CCA observation time. If the channel is idle, the equipment transmits data during the channel occupancy time (COT), and then, it should have an idle period, which is more than 5% of COT. Otherwise, the equipment shall not transmit on the channel during the next fixed frame period. On the other hand, the procedure of the load-based LBT can be described as follows. A piece of equipment checks the channel state during the CCA observation time. If the channel is idle, the equipment transmits data during COT. Otherwise, the equipment shall perform an extended CCA check during a randomly extended time. Since LTE operates with the fixed frame period, the frame-based LBT is easy to be applied in LTE. Therefore, we assume the use of the frame-based LBT throughout this paper.

In this paper, we propose a fair LBT (F-LBT) algorithm for coexistence of LTE-U and WLAN in unlicensed bands.[2] F-LBT determines an idle period in the frame-based LBT by jointly considering the fairness between LTE-U and WLAN, as well as the total system throughput. To this end, an analytical model for the system throughput based on a discrete-time Markov chain (DTMC) is developed. Evaluation results demonstrate that F-LBT can improve the system throughput while providing the fairness between LTE-U and WLAN. At the same time, F-LBT is based on the frame-based LBT, which is a tactical LBT approach, and thus, F-LBT can be easily implemented and deployed in real environments.

The remainder of this paper is organized as follows. The system model and the analytical model for the system throughput are presented in Sections II and III, respectively. F-LBT is described in Section IV. Evaluation results and concluding remarks are given in Sections V and VI, respectively.

II. System Model

We consider a network model where one LTE-U AP, N_L LTE-U nodes, and N_W WLAN nodes operate in the same unlicensed band. In addition, we assume that all nodes are fully connected, and therefore, there are no hidden nodes.

The frame structure of LTE-U AP is given in Fig. 1. Originally, a frame in LTE consists of ten subframes. The duration of one subframe is 1 ms, which is one transmission time interval, and thus, the duration of one frame in LTE is 10 ms. On the other hand, the LTE-U AP follows the requirement of the frame-based LBT [10], which indicates that the LTE-U AP should have an idle period more than 5% of COT

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[1]The LTE-U AP denotes evolved node B that operates in unlicensed bands.

[2]Since the downlink traffic is the main consideration of mobile data explosion problem, frequency-division duplexing (FDD) is assumed, and only downlink transmission (i.e., one frequency band) is considered for LTE-U system throughout this paper. On the other hand, since there is no FDD concept in the WLAN system, both uplink and downlink transmissions of WLAN are conducted in this frequency band.

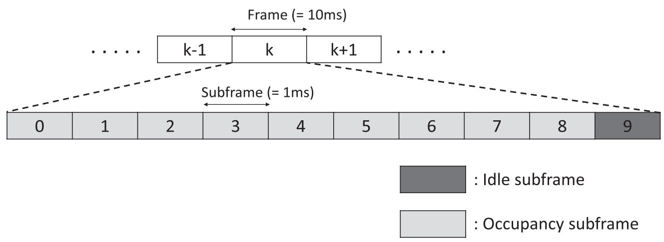


Fig. 1. Frame structure.

after it transmits data during COT. Therefore, a frame of the LTE-U AP has the dedicated idle subframes. Note that the number of idle subframes is decided by F-LBT, which is described in Section IV.

III. Analytical Model

To design F-LBT, we first develop an analytical model for the system throughput when LTE-U and WLAN coexist. Since we assume that all nodes are connected, the channel can be used only by one system (i.e., WLAN or LTE-U) at the same time. Therefore, the normalized total system throughput, i.e., S_{N_I}, when the number of the idle subframes is N_I can be expressed as $S_{N_I} = S_{N_I}^W + S_{N_I}^L$, where $S_{N_I}^W$ and $S_{N_I}^L$ are the normalized WLAN throughput and the normalized LTE-U throughput, respectively.[3]

To derive $S_{N_I}^W$, we introduce a DTMC model. As in [11], the behavior of the backoff process of one WLAN node can be modeled by two stochastic processes $s(t)$ and $b(t)$, which represent the backoff stage and the backoff counter at time t, respectively. The developed DTMC model is illustrated in Fig. 2, where the Idle state represents that there are no data in the WLAN node's buffer. In Fig. 2, p_f is the probability that backoff counter freezes due to busy channel, and m is the maximum backoff state. In addition, p_a represents the probability that there is at least one data arriving during the unit slot time σ, whereas p_L denotes the probability that the buffer is not empty. p_a can be obtained from $1 - \exp(-\lambda/\sigma)$, where λ is the packet arrival rate. In addition, p_L can be derived by λ/μ, where μ is the packet service rate [16]. Meanwhile, $W_k (0 \le k \le m)$ denotes the maximum backoff counter in the kth backoff stage.

By using the balance equations, we can obtain the closed form of the stationary probability of state (0, 0) as $b_{0,0} = 1/(W(1-(2p_c)^m)(1-p_c) + ((2p_c)^m W + 1)(1-2p_c)/2(1-2p_c)(1-p_c)(1-p_f)) + ((1-p_L)/p_a)$. On the other hand, the summation of stationary probabilities when the backoff counter is 0 (i.e., $\sum_{j=0}^{m} b_{j,0}$) is the transmission probability when the WLAN node and the LTE-U AP coexist, which is given by

$$\tau = \sum_{j=0}^{m} b_{j,0} = \frac{1}{1-p_c} b_{0,0} = \frac{1}{\frac{W(1-(2p_c)^m)(1-p_c)+((2p_c)^m W+1)(1-2p_c)}{2(1-2p_c)(1-p_f)} + \frac{(1-p_L)(1-p_c)}{p_a}}. \quad (1)$$

On the other hand, the backoff counter is decremented when $(N_W - 1)$ WLAN nodes and the LTE-U AP transmit no data with the probability $(1 - p_f)$. The corresponding probability $(1 - p_f)$ is given by $(1-\tau)^{N_W-1} p_d$, where $(1-\tau)^{N_W-1}$ is the probability that $(N_W - 1)$ WLAN nodes do not transmit data, and p_d is the probability that the LTE-U AP does not transmit data. p_d can be computed as the average number of idle subframes over the total number of subframes. Since the LTE-U AP cannot transmit data during all subframes when the

[3]The normalized throughput is defined as the fraction of time that the channel is used to successfully transmit payload bits [11].

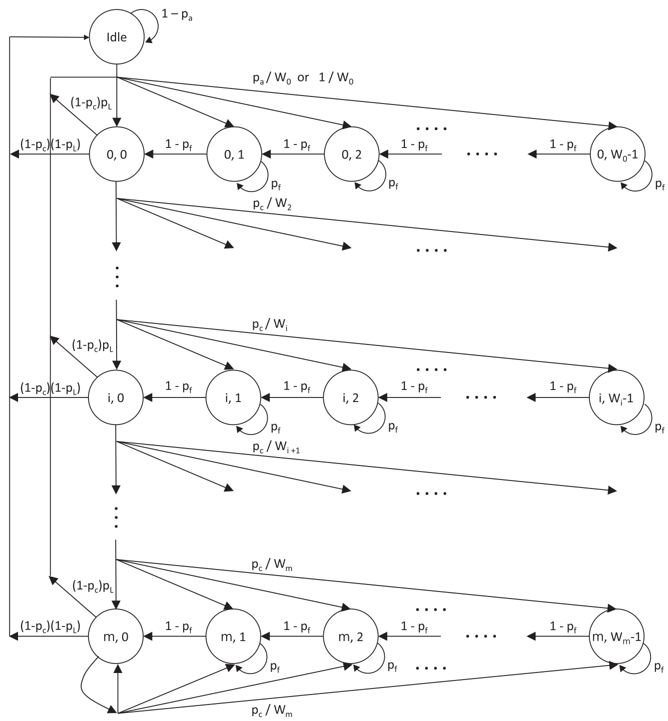


Fig. 2. Two-dimensional DTMC for WLAN node.

channel is busy and can transmit data, except during idle subframes, when the channel is idle, the average number of idle subframes can be computed as $(1-(1-\tau)^{N_W})N_T + (1-\tau)^{N_W} N_I$, where N_T denotes the total number of subframes. Therefore, $p_d = [(1-(1-\tau)^{N_W})N_T + (1-\tau)^{N_W} N_I]/N_T$.

Finally, $S_{N_I}^W$ can be represented by [11]

$$S_{N_I}^W = \frac{P_s P_{\mathrm{tr}} E_W[P]}{(1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}} P_s T_s + P_{\mathrm{tr}}(1-P_s)T_c} \quad (2)$$

where P_s is the probability that a successful transmission occurs, and P_{tr} is the probability that there is at least one transmitting WLAN node. Note that P_s and P_{tr} can be calculated by using τ and simple equations [11]. In addition, $E_W[P]$ is the average time for transmitting the payload in WLAN. T_s is the average time for successful transmission, whereas T_c is the average time when the channel is sensed busy by a collision event. Note that the propagation delay is contained in T_s and T_c.

When all WLAN nodes do not transmit with the probability $(1-\tau)^{N_W}$, the LTE-U AP can transmit data. In this situation, the fraction of the time that the LTE-U AP can transmit data is given by $(N_T - N_I)/N_T$. Therefore, $S_{N_I}^L$ can be represented by

$$S_{N_I}^L = \frac{E_L[P]}{H_L + E_L[P] + \delta} \frac{N_T - N_I}{N_T} (1-\tau)^{N_W} \quad (3)$$

where $E_L[P]$ is the average time for transmitting payload in LTE-U, and H_L is the transmission time for the packet header in LTE-U. In addition, δ is the propagation delay.

IV. Fair Listen-Before-Talk Algorithm

As shown in Fig. 3, F-LBT consists of two steps: (**Step 1**) estimation of the number of WLAN nodes and (**Step 2**) determination of the number of idle subframes.

In **Step 1**, the LTE-U AP listens to the channel to measure the collision probability (denoted by p_c^{AP}) among WLAN nodes at the LTE-U AP side and the channel idle probability p_i. The collision can

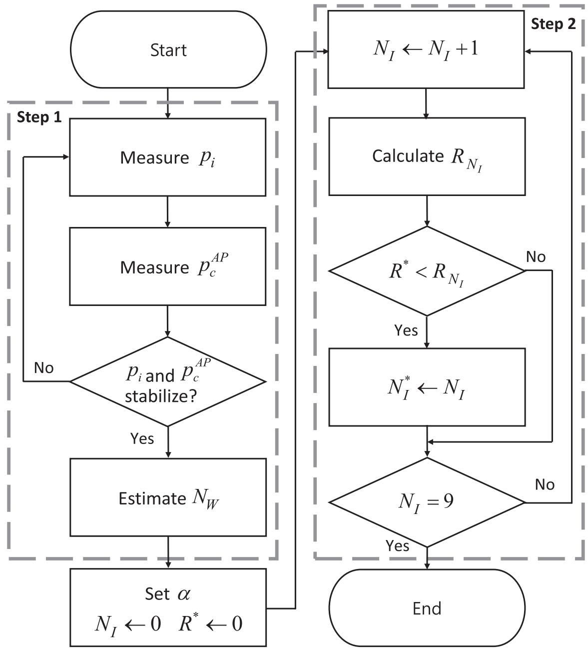


Fig. 3. F-LBT algorithm.

be detected by means of power sensing and signaling processing in the time domain [12] without synchronization to all WLAN nodes. When the total number of listened slot times and the number of collisions are denoted by N_s and N_c, respectively, p_c^{AP} can be approximated as $p_c^{\mathrm{AP}} = N_c/N_s$. Similarly, the channel idle probability p_i can be obtained by counting the number of situations when the channel is idle, i.e., $p_i = N_i/N_s$, where N_i is the number of idle time slots.

At the LTE-U AP side, no collision occurs when all WLAN nodes do not transmit or when only one WLAN node transmits. The probability that all WLAN nodes do not transmit is $(1-\tau_{\mathrm{NO}})^{N_W}$, where τ_{NO} is the transmission probability of a WLAN node when the LTE-U AP does not operate.[4] In addition, the probability that only one WLAN node transmits is $N_W\tau_{\mathrm{NO}}(1-\tau_{\mathrm{NO}})^{N_W-1}$. Therefore, the collision probability at the LTE-U AP side, i.e., p_c^{AP}, can be obtained from

$$p_c^{\mathrm{AP}} = 1 - N_W\tau_{\mathrm{NO}}(1-\tau_{\mathrm{NO}})^{N_W-1} - (1-\tau_{\mathrm{NO}})^{N_W}. \quad (4)$$

On one hand, since $p_i = (1-\tau_{\mathrm{NO}})^{N_W}$ and $N_W = \log_{(1-\tau_{\mathrm{NO}})} p_i$, (4) can be rewritten as

$$\log_{(1-\tau_{\mathrm{NO}})} p_i = \frac{(\tau_{\mathrm{NO}}-1)\left(p_c^{\mathrm{AP}} + p_i - 1\right)}{p_i\tau_{\mathrm{NO}}}. \quad (5)$$

Since only τ_{NO} is a variable in (5), we can calculate τ_{NO} by a numerical method such as binary search or Newton's methods [14]. After obtaining τ_{NO}, we can easily estimate N_W by using $N_W = \log_{(1-\tau_{\mathrm{NO}})} p_i$.[5]

To jointly consider the total system throughput and the fairness between LTE-U and WLAN, we define a reward function when the number of idle subframes is N_I, i.e., R_{N_I}, which can be expressed as

$$R_{N_I} = \alpha S_{N_I} + (1-\alpha)F_{N_I} \quad (6)$$

[4]The LTE-U AP does not try to send data during the estimation step and only listens to the channel. When the LTE-U AP listens to the channel for 774 ms in our simulation setting, sufficiently high accuracy in the estimation can be achieved, as shown in [13]. Note that the estimation can be done in contiguous or noncontiguous frames/time slots.

[5]Since p_i and p_c^{AP} are the estimation values, $\log_{(1-\tau_{\mathrm{NO}})} p_i$ cannot be integer value. Therefore, we simply use the rounding operation (i.e., $N_W = \mathrm{round}(\log_{(1-\tau_{\mathrm{NO}})} p_i)$).

TABLE I
ANALYTICAL RESULTS (A) VERSUS SIMULATION RESULTS (S)

N_W (N_I)	τ (A)	τ (S)
1 (3)	0.0189	0.0205
3 (5)	0.0291	0.0282
5 (6)	0.0306	0.0312

where F_{N_I} represents the fairness index [15] between LTE-U and WLAN when the number of idle subframes is N_I. α denotes a weighted factor to balance the throughput and the fairness.

If a round-robin scheduler is used in the LTE-U AP and all LTE-U nodes have independent and identically distributed ($i.i.d.$) channel qualities, the normalized LTE-U throughput per one node can be calculated by $S_{N_I}^L/N_L$ when the number of idle subframes is N_I. In addition, if all WLAN nodes have i.i.d. channel qualities and backoff procedure, the normalized WLAN throughput per one node can be calculated by $S_{N_I}^W/N_W$ when the number of idle subframes is N_I. Then, Jain's fairness index between LTE-U and WLAN, i.e., F_{N_I}, can be defined as

$$F_{N_I} = f\left(\frac{S_{N_I}^W}{N_W}, \frac{S_{N_I}^L}{N_L}\right) = \frac{\left(\frac{S_{N_I}^W}{N_W} + \frac{S_{N_I}^L}{N_L}\right)^2}{2\left[\left(\frac{S_{N_I}^W}{N_W}\right)^2 + \left(\frac{S_{N_I}^L}{N_L}\right)^2\right]}. \quad (7)$$

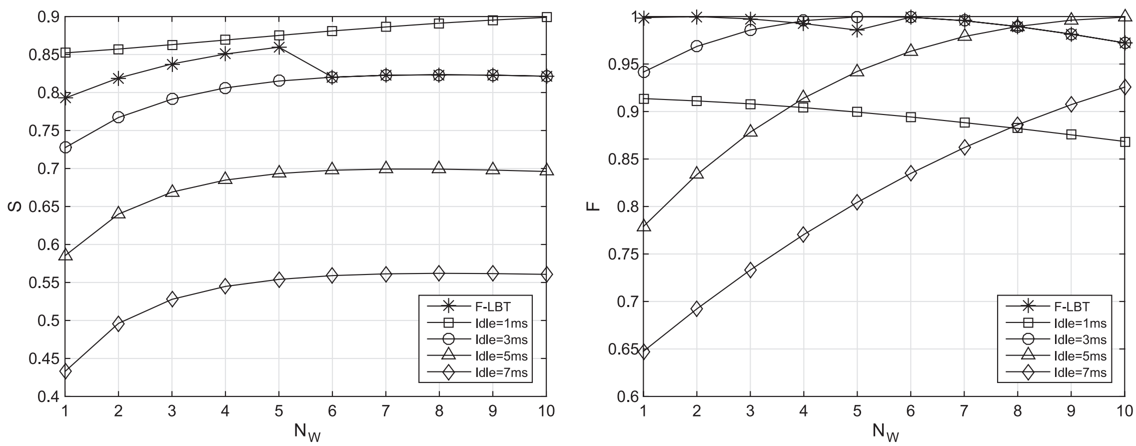
Finally, we can calculate R_{N_I} and find the optimal number of idle subframes, i.e., N_I^*, as follows. After α is set, the number of idle subframes N_I and the highest reward R^* are initialized (i.e., $N_I \leftarrow 0$ and $F^* \leftarrow 0$). After that, F-LBT searches N_I^* to maximize R_{N_I} by comparing R_{N_I} for all possible values of N_I (see **Step 2** in Fig. 3). Note that, since the maximum number of possible values of N_I is 9, the complexity of F-LBT is not high.

Since the performance of F-LBT is affected by the change of the number of LTE-U or WLAN nodes, the re-execution cycle needs to be determined. Although no strict rule for re-execution is specified in F-LBT, F-LBT can be re-executed as follows. Since the LTE-U AP can know the number of LTE-U nodes in its coverage, F-LBT algorithm can be re-executed whenever the number of LTE-U nodes is changed. Meanwhile, the LTE-U AP cannot know instantly the number of WLAN nodes; the mobility rate of WLAN nodes is used to determine the execution cycle of F-LBT. That is, when WLAN nodes have high mobility rate, the short execution cycle is established. On the other hand, when WLAN nodes have low mobility rate, the long execution cycle can be configured.

V. EVALUATION RESULTS

For performance evaluation, we compare F-LBT with the conventional frame-based LBT schemes with the fixed idle period [6]. Note that F-LBT and the conventional frame-based LBT schemes operate in LTE-U AP. The default values of N_L and N_W are 10 and 5, respectively. In addition, W_0 and m are set to 32 and 5, respectively [11]. The MAC and PHY header sizes are 272 and 128 bits, respectively. In addition, the acknowledgement packet and payload sizes are set to 240 and 8184 bits, respectively. On the other hand, the transmission rates of WLAN and LTE-U are assumed as 54 and 100 Mb/s, respectively. Meanwhile, SIFS and DIFS are set to 28 and 128 μs, respectively. δ is 1 μs. Meanwhile, the default value of α is set to 0.3. In addition, μ and λ are set to 1 and 0.9, respectively.

Table I shows the analytical and event-driven simulation results for τ, where N_I is selected by F-LBT, and N_L is set to 5. Note that we



(a) (b)

Fig. 4. Effect of N_W on S and F.

conduct the event-driven simulation based on the time scale of WLAN. α is set to 0, i.e., the fairness between LTE-U and WLAN is only considered. From Table I, it can be found that the analytical results are consistent with the simulation results. In addition, it can be seen that τ increases with the increase of N_W. This is because F-LBT allocates more idle subframes for WLAN when N_W is large to guarantee the fairness between LTE-U and WLAN. Interestingly, when N_W and N_L have the same values (i.e., $N_W = N_L = 5$), more idle subframes (i.e., $N_I = 6$) need to be allocated for WLAN to guarantee the fairness between LTE-U and WLAN. This is because WLAN uses a random access protocol, which can reduce the throughput compared with the scheduled transmission in LTE-U.

A. *Effect of* N_W

Fig. 4(a) and (b) show the effect of N_W on S and F, respectively. As shown in Fig. 4(a), since F-LBT selects N_I by considering S, S is maintained at a high level. In addition, it can be seen that S of Idle $= 1$ ms has the highest value among the comparison schemes.[6] This is because the scheduled transmission in LTE-U can minimize the channel waste in WLAN and can improve the total system throughput. On the other hand, when N_W is 6–10, three idle subframes guarantee the largest reward R, and thus, F-LBT also allocates three idle subframes. Consequently, the throughputs of F-LBT and Idle $= 3$ ms become comparable.

The effect of N_W on F is shown in Fig. 4(b). It can be found that F of F-LBT is maintained as almost 1 regardless of N_W. In Idle $= 1$ ms, since WLAN nodes cannot obtain sufficient transmission chances due to the lack of idle subframes, lower F is obtained. It can be also seen that F continuously increases as N_W increases when Idle $= 5$ ms and Idle $= 7$ ms. This can be explained as follows. In these schemes, excessive subframes are allocated to WLAN, whereas insufficient subframes are allocated to LTE-U when N_W is small. As a result, F of these schemes has a low value when N_W is small. However, since more subframes are needed in WLAN as N_W increases, F of these schemes can be improved.

[6]Although Idle $= 1$ ms is better than F-LBT in terms of S, it leads to the undesirable fairness between LTE-U and WLAN when N_W is large, as shown in Fig. 4(b).

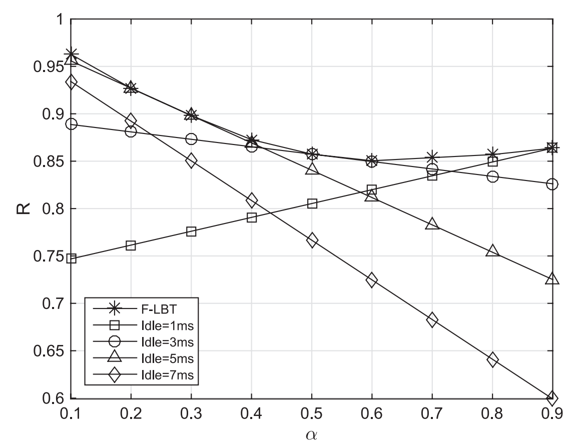


Fig. 5. Effect of α on R.

B. *Effect of* α

Fig. 5 shows the effect of α on R, where both N_W and N_L are set to 5. Since F-LBT selects N_I to maximize R, R of F-LBT has the highest value among all schemes, regardless of α. In Idle $= 1$ ms, R increases with the increase of α. This can be explained as follows. Large α means that S is more important than F and allocating a small number of subframes to WLAN (i.e., Idle $= 1$ ms) has the advantage of improving S and R. On the contrary, it can be observed that R of Idle $= 3$ ms, Idle $= 5$ ms, and Idle $= 7$ ms decreases as α increases. This is because excessive subframes are allocated to WLAN and cannot be effectively utilized due to the distributed operation of WLAN. In this situation, as the impact of S on R increases (i.e., α increases), smaller R is obtained.

VI. Conclusion

In this paper, we have proposed an F-LBT algorithm to allocate the appropriate number of idle subframes by considering the fairness between LTE-U and WLAN and the total system throughput. To this end, F-LBT estimates the number of WLAN nodes and then determines the number of idle subframes. Evaluation results demonstrate that F-LBT provides higher fairness between LTE-U and WLAN while maintaining high total system throughput. In our future work, we will extend the proposed algorithm to reflect different channel qualities of each nodes and investigate time-division-duplexing-based LTE-U system where both uplink and downlink transmissions are conducted in the same band.

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New D2D Peer Discovery Scheme Based on Spatial Correlation of Wireless Channel

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***Abstract*—Due to the increasing popularity of device-to-device (D2D) services, it is becoming increasingly important to find efficient means of identifying nearby users, i.e., by peer discovery. Herein, we propose a low-power peer discovery scheme, in which we exploit the tradeoff between the power consumption and the accuracy/scope of peer discovery. In our proposed scheme, the transmission of a proximity beacon is scheduled based on channel values, such that users in close proximity are likely to transmit beacons at similar time instants due to the spatially correlated wireless channel. As a result, users can find nearby peers accurately with a lower power consumption by shortening the reception period for the beacons. The performance of the proposed scheme, in terms of accuracy and power consumption, is derived. By means of simulation results, we show that nearby users can be found with lower power consumption than in conventional schemes, while achieving a high accuracy of peer discovery.**

***Index Terms*—Device-to-device (D2D) beacon, D2D service, peer discovery, power consumption, spatial correlation.**

I. Introduction

With the increasingly extensive use of wireless services, the demand for data traffic continues to increase exponentially over time. Base stations (BSs) of mobile communications systems (MCSs) in the current topology will very soon experience difficulties in processing the resulting huge volume of data traffic. Furthermore, location-based services have recently gotten more popular, requiring localized communications in which nearby users exchange data. The network topology of current MCSs is not appropriate for providing these kinds of services.

Recently, MCSs have begun to adopt device-to-device (D2D) services in which direct communications between users are enabled to address the problems described earlier [1]–[3]. For example, the Long-Term Evolution (LTE) standard makes use of the D2D service, which is also known as a proximity service (ProSe) in its latest release, i.e., Rel. 12 [1], [4], [5]. By adopting the D2D service, excessive load imposed on BSs can be reduced, and new location-based services can be provided, all of which holds attraction for service providers and operators of MCSs [5]. While the D2D service is similar to conventional ad hoc networks, it is more practical and efficient because the whole process of communication can be managed by BSs [1].

D2D services can be separated into two parts: D2D communications and peer discovery. While D2D communication refers to the transfer of data from one D2D user to another, peer discovery describes the search for nearby users for the D2D service. In particular, peer discovery has

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