Analyzing 5G NR-U and WiGig Coexistence with Multiple-Beam Directional LBT

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***Abstract*— The mmWave radio frequency (RF) spectrum allocations provide a large bandwidth and an excellent dynamic spectrum sharing (DSS) opportunity for emerging 5G New-Radio unlicensed (NR-U) and Wireless Gigabit (WiGig) services. To support constructive DSS, we outline a new modeling and analytical method to jointly evaluate the effects of a multiple-beam directional listen-before-talk (MB-DLBT) protocol, intercell interferences (ICIs), and spectrum sensing errors on the NR-U and WiGig DSS system performance. Available works did not provide a systematic and analytical approach to evaluate these effects, but only relied on computer simulations. Our numerical evaluation provides an insightful observation on the performance advantage of the MB-DLBT over the single-beam DLBT and omni-directional LBT schemes. This result provides a powerful tool to support performance analysis and optimization of mmWave DSS schemes.**

Index Terms: Coexistence, directional LBT, imperfect spectrum sensing, intercell interference, mmWave, NR-U, WiGig.

I. Introduction

Future dynamic spectrum sharing (DSS) communication in the mmWave radio frequency (RF) bands (such as the 60 GHz RF band) involves different radio access technologies, including 5G New Radio unlicensed (NR-U) [1] and Wireless Gigabit (WiGig) services, such as IEEE 802.11ad/ay systems [2]–[4]. The broad mmWave bandwidth provides great opportunity for high-speed communication and DSS, but it also brings various system design challenges [5], [6].

To address the large channel propagation loss, various beamforming schemes and directional listen-before-talk (DLBT) medium access control (MAC) protocols have been proposed. The work in [5] presents mmWave channel and cellular network modeling methods, and develops a stochastic geometry approach to compute the network performance. The authors of [6] describe standards and technology development of unlicensed spectrum sharing with focus on the 60 GHz RF band, and review some LBT schemes, such as omni-directional LBT (OLBT) and DLBT. To reduce the impact of hidden-node and exposed-node problems related with DLBT, [7] proposes an NR-U LBT switching procedure, and [8] develops a listen-before-receive scheme in addition to transmitter sensing DLBT. The authors of [9] provide a simulation based evaluation of NR-U and WiGig coexistence performance. In [5]–[9], the effects of various DLBT protocols and intercell interferences (ICIs) have not been theoretically analyzed, but are evaluated only based on Monte Carlo simulations. Furthermore, these works focus on performance evaluation of a single beam DLBT (SB-DLBT) case. Recently in [11], we evaluated the LAA and wireless local area network (WLAN) multicell coexistence performance with an in-depth analysis of ICI, sensing errors and the LBT protocol, and verified the analysis by simulation result. However, the methods in [11] have not considered DLBT in the mmWave band.

In this paper, we propose a multiple-beam DLBT (MB-DLBT) protocol to improve the communication throughput performance. We also develop a new modeling and analytical method which maps system parameters to the achieved key performance indicators (KPIs) such as user and cell throughput. It enables faster performance evaluation of larger scale NR-U and WiGig DSS systems than the simulation does. To address the large complexity of system evaluation, we apply a moment generating function (MGF) approach [14], [15] to model the impact of MAC and physical layer parameters. This is more efficient than the traditional probability density function (PDF) method.

Numerical results demonstrate a significant performance improvement of the MB-DLBT scheme than the OLBT and SB-DLBT counterparts. This technique can be used as a benchmark to validate different simulation tools, and generate significant theoretical and practical value.

II. System Model

Consider an NR-U system with C_{NR} small cells and a WiGig system with C_W cells (i.e., contention zones), and $C_{\text{NR}} + C_W = C_{\text{tot}}$. Each NR-U or WiGig cell is controlled by a gNode B (gNB) or access point (AP). We denote the gNB or AP in cell c as Node c and the associated user n in cell c as Node (c, n), where there are N_c users in cell c. All cells share a single wide-band channel. Only downlink transmission is considered in this paper.

A. Directional Beam Patterns

We assume that Node c has the same beamforming pattern G_c for both its transmission and receiver parts. A popular single main-beam pattern on the mmWave beamforming is given by [5], where the main beamwidth and beam gain are $\theta_{\text{MB},c}$ and $G_{\text{MB},c}$, and the side (or null) beamwidth and gain are $2\pi - \theta_{\text{MB},c}$ and $G_{\text{NB},c}$, respectively. Consider a node (which can be an associated user or a gNB/AP) in a random location away from Node c. Based on a uniform random 2-D distribution assumption of all the nodes, the probabilities that this node lies in the main beam and side beam directions of Node c are given by $P_{\text{MB},c} = \frac{\theta_{\text{MB},c}}{2\pi}$ for $G_c = G_{\text{MB},c}$, and $P_{\text{NB},c} = 1 - P_{\text{MB},c}$ for $G_c = G_{\text{NB},c}$, respectively. We can express the PDF of G_c as

$$f_{G_c}(x) = \sum_{k=1}^{2} P_{B,c,k}\delta(x - G_{B,c,k}). \quad (1)$$

where $P_{B,c,1} = P_{\text{MB},c}$, $G_{B,c,1} = G_{\text{MB},c}$, $P_{B,c,2} = P_{\text{NB},c}$, $G_{B,c,2} = G_{\text{NB},c}$, and $\delta(\cdot)$ is the Dirac delta function.

As an extension of Eq. (1), when Node c has $N_{B,c}$ main beams (with $N_{B,c} \geq 1$), we express the PDF of G_c observed by another random node as:

$$f_{G_c}(x) = \sum_{k=1}^{N_{B,c}+1} P_{B,c,k}\delta(x - G_{B,c,k}), \quad (2)$$

where $G_{B,c,k}$ and $P_{B,c,k}$ (for $k = 1, \dots, N_{B,c}$) are the beam gain and the associated probability of the k-th beam being aligned with a given node in a random location (e.g., a source of interference), and $G_{B,c,N_{B,c}+1}$ and $P_{B,c,N_{B,c}+1}$ are the beam gain and probability that the side beam is aligned with the random node. Here, $P_{B,c,k} = \frac{\theta_{\text{MB},c,k}}{2\pi}$, where $\theta_{\text{MB},c,k}$ is the beamwidth of the k-th main beam. We can verify that Eqs. (1) and (2) are valid PDFs. Furthermore, in Eqs. (1) and (2), the use of $\delta(\cdot)$ function is based on the assumption of a uniform-magnitude beamforming gain along the $\theta_{\text{MB},c,k}$ angle.

To model the ICI from Node c_2 to Node c, we define the combined beamforming gain as G_{c,c_2}. Obviously, $G_{c,c_2} = G_c G_{c_2}$ holds. Also, we assume that the channel is symmetric, i.e., $G_{c,c_2} = G_{c_2,c}$. By extending Eq. (2), we obtain the PDF of G_{c,c_2} as

$$f_{G_{c,c_2}}(x) = \sum_{k_1=1}^{N_{B,c}+1} \sum_{k_2=1}^{N_{B,c_2}+1} P_{B,c,k_1} P_{B,c_2,k_2} \times\delta(x - G_{B,c,k_1} G_{B,c_2,k_2}). \quad (3)$$

Similarly, we express the combined beamforming gain from Node c_2 to Node (c,n) as $G_{(c,n),c_2}$, with $G_{(c,n),c_2} = G_{(c,n)} G_{c_2}$. We denote the power gain of channel from Node c_2 to user (c,n) as $h_{(c,n),c_2}$, and the power gain of channel from Node c_2 to Node c as h_{c,c_2}, respectively.

B. Multi-beam Directional LBT Scheme

We assume that at Node c, contention window size (CWS) is $W_{c,m}$ at backoff stage m (for $m = 0, 1, \dots, M_c$), where M_c is the maximum backoff stage. Further, beam steering and tracking has been implemented after a beam-training phase. As an extension of DLBT with a single main beam [6], we propose a **MB-DLBT** protocol, as shown below.

Node c (for all c) implements the following procedure:

1) Node c points its $N_{B,c}$ main beams to $N_{B,c}$ associated users, and senses the channels' status with energy detection (ED) in these directions.
2) If any of the channels is sensed busy, Node c freezes its backoff counter; otherwise, Node c reduces counter by one. Node c returns to Step 1) when the counter is larger than zero; otherwise Node c advances to Step 3).
3) Node c sends payload packets using $N_{B,c}$ main beams to $N_{B,c}$ associated users. If $N_{B,c} < N_c$, a random selection is used to support fair channel access.
4) If all transmissions are successful, Node c reduces CWS to $W_{c,0}$; otherwise, it doubles the CWS, unless stage M_c is reached. Node c returns to Step 1).

When $N_{B,c} = 0$ (or 1), the MB-DLBT scheme is reduced to the OLBT (or SB-DLBT) scheme. The directional beamforming is always used for data transmission for all the schemes considered in this paper.

III. Performance Analysis

We introduce a new modeling and analysis technique for performance evaluation of a multi-cell NR-U and WiGig coexistence system. With downlink transmission from Node c, the average throughput of user (c,n) is derived as

$$S_{(c,n)} = \alpha_{(c,n)} P_{\text{suc},c} T_{P,c} \cdot B_{(c,n)} E[\log_2(1 + \beta_{(c,n)}\gamma_{(c,n)})]/T_{\text{ave},c}, \quad (4)$$

where $\alpha_{(c,n)}$ is active time portion for Node (c,n) with $\sum_{n=1}^{N_c} \alpha_{(c,n)} = N_{B,c}$, $P_{\text{suc},c}$ and $T_{P,c}$ are the successful transmission probability and transmission duration of Node c, $B_{(c,n)}$ and $\gamma_{(c,n)}$ are the bandwidth and receive signal-to-interference-and-noise ratio (SINR) of Node (c,n), $\beta_{(c,n)}$ is the SINR gap function [13] related with target bit error rate (BER), and $T_{\text{ave},c}$ is the average time to support one successful transmission from Node c. Next, we show how to evaluate $\gamma_{(c,n)}$ following the MB-DLBT protocol. Other quantities in Eq. (4) can be derived by partly following the method given in [11], omitted here for brevity.

A. DLBT Detection Probability

We model the ICI received at a node (e.g., Node c) from each interference source, and then evaluate the channel idle probability and successful transmission probability (STP). We define $\tilde{I}_{c,c_2} = I_{c,c_2} + N_{0,c}$, where I_{c,c_2} is power of ICI from Node c_2 to c, and $N_{0,c}$ is the power of local noise. The channel idle probability and STP experienced by Node c is a function of P_{d,c,c_2}, the probability that Node c detects the transmission of Node c_2, for all $c_2 \neq c$. The P_{d,c,c_2} is given by

$$P_{d,c,c_2} = \Pr(\tilde{I}_{c,c_2} \geq \text{Th}_{c,\text{ed}}) = \int_{\text{Th}_{c,\text{ed}}}^{\infty} f_{\tilde{I}_{c,c_2}}(x)dx, \quad (5)$$

where $\text{Th}_{c,\text{ed}}$ is the ED decision threshold at Node c, and $f_{\tilde{I}_{c,c_2}}(x)$ is the PDF of $\tilde{I}_{c,c_2}$. To evaluate Eq. (5), we derive the PDF of I_{c,c_2} as

$$f_{I_{c,c_2}}(x) = \sum_{k_1=1}^{N_{B,c}+1} \sum_{k_2=1}^{N_{B,c_2}+1} P_{B,c,k_1} P_{B,c_2,k_2} \times\delta(x - P_{T,c_2} h_{c,c_2} G_{B,c,k_1} G_{B,c_2,k_2}), \quad (6)$$

where P_{T,c_2} is the transmit power of Node c_2. Obviously, it is challenging to evaluate Eq. (5) based on the PDF integration. Below, we develop an efficient MGF approach to address this technical problem.

Define the MGF of a random variable X as $\Phi_X(s) = E[\exp(sX)] = \int_{-\infty}^{\infty} f_X(x)e^{sx}dx$, where $f_X(x)$ is the PDF of X. Suppose that we use a duration of T_{SS} with sampling rate B_W for channel sensing in a backoff slot, and average the sampled signal and noise over $[T_{SS}B_W]$ samples to make a channel status decision, where $[x]$ rounds x to its nearest integer. The $N_{0,c}$ is the average power of the $[T_{SS}B_W]$ independent and identically distributed (i.i.d.) complex noise samples, where each sample has zero mean and variance $\bar{N}_{0,c}$. We obtain the MGF of $N_{0,c}$ as

$$\Phi_{N_{0,c}}(s) = (1 - s\bar{N}_{0,c}/[T_{SS}B_W])^{[T_{SS}B_W]}. \quad (7)$$

On the other hand, due to limited Doppler shift for small-cell communication, we model the inter-gNB/AP channel magnitude $\sqrt{h_{c,c_2}}$ via a Rician or Nakagami-m fading distribution. For Nakagami-m fading channel, since h_{c,c_2} follows a Gamma distribution, we obtain that $\Phi_{h_{c,c_2}}(s) = (1 - s\overline{h}_{c,c_2}/m_{c,c_2})^{-m_{c,c_2}}$, where $\overline{h}_{c,c_2} = E[h_{c,c_2}]$ and m_{c,c_2} are the average channel power and the Nakagami-m parameter of this channel, respectively.

Let the MGF of the $\tilde{I}_{c,c_2}$ be $\Phi_{\tilde{I}_{c,2c}}(s)$ conditioned on that Node c_2 starts its transmission. We obtain that

$$\begin{aligned}\Phi_{\tilde{I}_{c,c_2}}(s) &= \Phi_{N_{0,c}}(s) \sum_{k_1=1}^{N_{B,c}+1} \sum_{k_2=1}^{N_{B,c_2}+1} P_{B,c,k_1} P_{B,c_2,k_2} \\ &\times (1 - sP_{T,c_2}\overline{h}_{c,c_2} G_{B,c,k_1} G_{B,c_2,k_2}/m_{c,c_2})^{-m_{c,c_2}}. \quad (8)\end{aligned}$$

The probability that Node c detects Node c_2's transmission is given by $P_{d,c,c_2} = 1 - \mathrm{cdf}_{\tilde{I}_{c,c_2}}(\mathrm{Th}_{c,\mathrm{ed}})$, where $\mathrm{cdf}_{\tilde{I}_{c,c_2}}(x)$ is the cumulative distribution function (CDF) of $\tilde{I}_{c,c_2}$, and it can be obtained by using the inverse Laplace transform (ILT) of the MGF $\Phi_{\tilde{I}_{c,c_2}}(s)$. An efficient and robust formula for evaluating CDF of a variable from its MGF was developed in [14]. By using this formula we obtain

$$\begin{aligned}\mathrm{cdf}_{\tilde{I}_{c,c_2}}(x) &= 2^{-Q} e^{\frac{A}{2}} \sum_{q=0}^{Q} \binom{Q}{q} \sum_{n=0}^{N+q} (-1)^n \beta_n \\ &\times \Re\left(\frac{\Phi_{\tilde{I}_{c,c_2}}\left(\frac{A+jn2\pi}{2x}\right)}{A+jn2\pi} \right) + E_{A,N,Q}, \quad (9)\end{aligned}$$

where $\mathrm{Re}(z)$ is the real part of the $z \in \mathcal{C}$, $\beta_n = \begin{cases} 1, & n=0 \\ 2, & n=1,\ldots,N+Q \end{cases}$, A, N, and Q are parameters used to control the convergence, and $E_{A,N,Q}$ is an error term which diminishes as N and Q increase. Our method of detection probability evaluation given above properly models the impacts of multiple beams in MB-DLBT, fading channels, local noise, and sensing thresholds, and is robust and efficient to evaluate in the form of Eq. (9).

B. Downlink User SINR

For the MB-DLBT scheme we express the SINR $\gamma_{(c,n)}$ as

$$\gamma_{(c,n)} = \frac{P_{T,c} h_{(c,n),c} G_{(c,n),c}}{\tilde{I}_{\mathrm{tot},(c,n)}}, \quad (10)$$

where $G_{(c,n),c}$ is the combined beamforming gain from Node c to user (c,n) when their beams are aligned, and $\tilde{I}_{\mathrm{tot},(c,n)}$ is the sum of the noise power $N_{0,(c,n)}$ and total ICI $I_{\mathrm{tot},(c,n)}$ from neighboring active transmitters when the Node c to (c,n) transmission is successful. Note that $\tilde{I}_{\mathrm{tot},(c,n)} = N_{0,(c,n)} + \sum_{c_2=1, c_2\neq c}^{C_{\mathrm{tot}}} I_{(c,n),c_2}$, where $I_{(c,n),c_2}$ is the ICI from Node c_2 to user (c,n).

We obtain the MGF of $N_{0,(c,n)}$ as

$$\Phi_{N_{0,c}}(s) = (1 - s\bar{N}_{0,(c,n)}/[T_{sym,(c,n)}B_W])^{[T_{sym,(c,n)}B_W]}, \quad (11)$$

where $\bar{N}_{0,(c,n)}$ and $T_{sym,(c,n)}$ are the average noise power per sample and signal symbol duration at Node (c,n), respectively.

The MGF of $\tilde{I}_{\mathrm{tot},(c,n)}$, denoted as $\Phi_{\tilde{I}_{\mathrm{tot},(c,n)}}(s)$, can be obtained as

$$\Phi_{\tilde{I}_{\mathrm{tot},(c,n)}}(s) = \Phi_{N_{0,c}}(s) \prod_{\substack{c_2=1 \\ c_2\neq c}}^{C_{\mathrm{tot}}} \Phi_{I_{(c,n),c_2}}(s). \quad (12)$$

We derive the PDF of $I_{(c,n),c_2}$ under the condition that Node c's transmission is successful as follows

$$\begin{aligned}f_{I_{(c,n),c_2}}(x) &= (1 - \hat{P}_{\mathrm{tr},c_2})\delta(x) \\ &+ \hat{P}_{\mathrm{tr},c_2} \sum_{k_1=1}^{N_{B,(c,n)}+1} \sum_{k_2=1}^{N_{B,c_2}+1} P_{B,(c,n),k_1} P_{B,c_2,k_2} \\ &\times \delta(x - P_{T,c_2} h_{(c,n),c_2} G_{B,(c,n),k_1} G_{B,c_2,k_2}), \quad (13)\end{aligned}$$

where $\hat{P}_{\mathrm{tr},c_2}$ is the probability that Node c_2 generates ICI to Node c's transmission but does not cause the transmission failure. We obtain that

$$\hat{P}_{\mathrm{tr},c_2} = [P_{\mathrm{tr},c_2} + (1 - P_{\mathrm{tr},c_2})(1 - P_{d,c_2,c})](1 - P_{f,c,c_2}),$$

where P_{f,c,c_2} is the probability that Node c_2's transmission causes node c's transmission to fail. As a tight approximation, we set $P_{f,c,c_2} \simeq P_{d,c,c_2}$.

The MGF $\Phi_{I_{(c,n),c_2}}(s)$ can be obtained (assuming Nakagami-m fading) as

$$\begin{aligned}\Phi_{I_{(c,n),c_2}}(s) &= (1 - \hat{P}_{\mathrm{tr},c_2}) \\ &+ \hat{P}_{\mathrm{tr},c_2} \sum_{k_1=1}^{N_{B,(c,n)}+1} \sum_{k_2=1}^{N_{B,c_2}+1} P_{B,(c,n),k_1} P_{B,c_2,k_2} \\ &\times (1 - sP_{T,c_2}\overline{h}_{(c,n),c_2} G_{B,(c,n),k_1} G_{B,c_2,k_2}/m_{(c,n),c_2})^{-m_{(c,n),c_2}},\end{aligned}$$

where $m_{(c,n),c_2}$ is the Nakagami-m parameter of channel $h_{(c,n),c_2}$. The $\Phi_{I_{(c,n),c_2}}(s)$ for a Rician channel can be obtained using a similar procedure, omitted here for brevity.

By using Eqs. (12) in (9), we can numerically evaluate the CDFs and PDFs of total ICI $\tilde{I}_{\mathrm{tot},(c,n)}$ and SINR $\gamma_{(c,n)}$, and the throughput via formula (4). The detail of this procedure is omitted here for brevity. Furthermore, a Gaussian assumption of $\tilde{I}_{\mathrm{tot},(c,n)}$ may be used to simplify the computation.

Our method of downlink user SINR and throughput evaluation properly models the impacts of ICI detection probabilities among gNBs and APs, fading channels, and DLBT multiple beams on the throughput performance. It provides more technical depth than several state-of-the-art results [5]–[9] (and references therein) in terms of mmWave DLBT process modeling and performance analysis.

IV. Numerical Results

In this section, we provide numerical results to show the performance gain of the MB-DLBT over the SB-DLBT and OLBT schemes. We assume that the clear channel assessment time is $T_{\text{CCA}} = 5$ μs, the deferred CCA time is $T_{\text{DCCA}} = 8$ μs, $T_{SS} = 4$ μs, and $[T_{\text{sym},(c,n)} B_W] = 2$ for both NR-U and WiGig systems. Furthermore, payload durations are $T_{P,\text{NR}} = 5$ ms and $T_{P,W} = 2$ ms. A few equations to compute slot duration related MAC parameters are provided in [10]. Total area has size $X_0 \times Y_0$, with $X_0 = 20$ m and $Y_0 = 40$ m, and each cell has a radius of $r_0 = 10$ m for user association. All users have saturated backlogged traffic in the gNBs (or APs). Further, we assume carrier frequency $f_c = 60$ GHz, $B_{(c,n)} = 1$ GHz, target BER is $\text{BER}_{(c,n)} = 10^{-3}$, and $\alpha_{(c,n)} = N_{B,c}/N_c$ for all c and n. The background white Gaussian noise has power spectrum density of -174 dBm/Hz with a noise figure of 7 dB. The downlink transmit power is $P_{T,c} = 23$ dBm. We assume near line-of-sight channels, and set the path loss exponent to be $\alpha_d = 2.5$, and Nakagami-m parameter to be 10 for all the channels.

For a fair comparison between SB-DLBT and MB-DLBT schemes, we assume that the transmit power of the SB-DLBT is equal to the sum transmit power of all the beams of the MB-DLBT. The directionality gains of the gNB/AP and UE/STA with DLBT are set to 10 dB and 7 dB, respectively [6]. For the OLBT scheme, we set the gNB ED decision threshold as $\text{Th}_{\text{BS,ed}} = -69$ dBm and set the AP ED threshold to be $\text{Th}_{\text{AP,ed}} = -74$ dBm. For the DLBT scheme, we set larger decision thresholds that $\text{Th}_{\text{BS,ed}} = -64$ dBm and $\text{Th}_{\text{AP,ed}} = -69$ dBm. All numerical results are averaged over 100 independent location profiles of all the nodes.

Assume that there are N_{NR} (or N_W) users in each NR-U (or WiGig) cell, with CWS $W_{\text{NR},0}$ (or $W_{W,0}$), and maximum backoff stage M_{NR} (or M_W), respectively. We assume a total of 8 cells with $C_{\text{NR}} = C_W = 4$, $N_{\text{NR}} = N_W = 5$, $W_{\text{NR},0} = W_{W,0} = 16$, $M_{\text{NR}} = 1$, and $M_W = 3$.

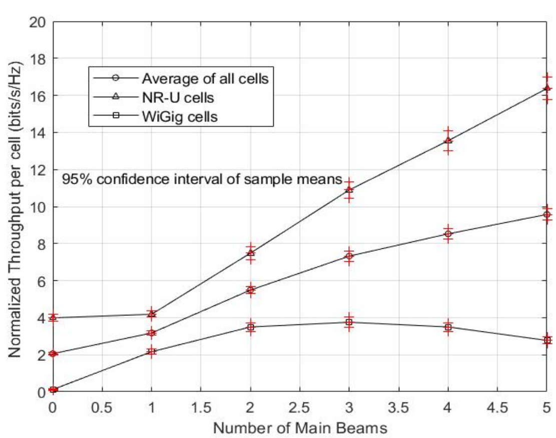

Fig. 1: Normalized cell throughput of the NR-U and WiGig systems vs. number of main beams of gNBs (or AP), with 95% confidence interval (vertical bars) of the sample means.

We define the normalized cell throughput as the downlink throughput in the cell normalized by the transmission bandwidth. Fig. 1 shows that the normalized throughput of NR-U and Wigig systems increases differently with the number of beams $N_{B,c}$. The NR-U system has a higher throughput than the WiGig system. This is because we assume a larger payload duration, a smaller backoff stage, and a larger (i.e., less sensitive) threshold for the NR-U transmissions than the WiGig counterparts.

V. Conclusion

In this paper, we have provided an efficient and powerful modeling and analytical technique for performance evaluation of an NR-U and WiGig DSS system taking into account multi-beam directional LBT, multi-cell interference, fading channels, and spectrum sensing errors. Numerical results demonstrate significant performance enhancement of MB-DLBT over the O-LBT and SB-LBT schemes. We assumed a transmitter-based channel sensing for the MB-DLBT. In future work, we will study the performance of other MB-DLBT schemes, such as joint transmit and receiver sensing, and provide performance optimization results. Furthermore, the measurement validation via hardware testbed will be implemented when applicable.

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