Dynamic switch between load based and frame based channel access mechanisms in unlicensed spectrum

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***Abstract*—In unlicensed spectrum, a 5G device is required to access to a channel by using load based equipment (LBE) where it does channel sensing whenever it has data to transmit or frame based equipment (FBE) where it only does channel sensing per fixed period. The devices using LBE and FBE can coexist in the 5G network. Therefore, this paper provides a Markov chain model to analyze the system where the LBE devices and the FBE devices coexist. Subsequently, based on channel access time and transmission probability from the Markov chain model, we propose that the devices are able to switch dynamically from FBE to LBE to serve data with high priority such as Ultra-reliable low-latency communication or data with high arrival rate and from LBE to FBE to serve data with low priority such as Enhanced mobile broadband or data with low arrival rate. The numerical results show the benefits of the dynamic switch between LBE and FBE in reducing channel access time for high priority data and energy consumption for low priority data.**

***Index Terms*—5G, URLLC, unlicensed spectrum, load based equipment, frame based equipment**

I. Introduction

A. 5G overview

The emerging applications such as industrial automation, autonomous vehicles, remote driving, augmented/virtual reality, smart grid, to name but a few with different requirements have made the 3rd Generation Partnership Project (3GPP) define three main service categories in 5G New Radio: Enhanced mobile broadband (eMBB), Massive machine-type communication and Ultra-reliable low-latency communication (URLLC). In these three services, URLLC design is the most challenging one because of two conflicting fators in the requirements: latency and reliability.

In 3GPP Release 15, the URLLC requirements are defined in [1] to target the use cases such as augmented/virtual reality and smart grid: "A general URLLC reliability requirement for one transmission of a packet is 10^{-5} for 32 bytes with a user plane latency of 1 ms". In 3GPP Release 16, higher URLLC requirements with reliability up to 10^{-6} and short latency in the order of 0.5 to 1 ms are specified to support new use cases such as factory automation, transport industry including the remote driving use case and electrical power distribution [2].

B. URLLC physical layer design in 3GPP Release 15 and Release 16

URLLC has higher requirements than Long Term Evolution (LTE) so the URLLC features in 5G have been specified in 3GPP Release 15 and Release 16 - the latest version - to make the system attain the URLLC requirements.

The values of subcarrier spacing in 5G are 15 kHz, 30 kHz, 60 kHz, 120 kHz and 240 kHz instead of a single value of 15 kHz in LTE to reduce the duration of the Orthogonal frequency-division multiplexing symbols [3].

A transmission time interval in 5G can be a sub-slot of 2, 4 or 7 symbols instead of a slot in LTE [3]. Therefore, a transmission can start at the beginning of a sub-slot rather than waiting the beginning of a slot to reduce the alignment time.

The user equipment (3GPP terminology: UE) is allowed to transmit uplink (UL) data in the configured grant resources configured by the base station (3GPP terminology: gNB) without sending scheduling request and receiving UL grant as the dynamic grant transmission on the dynamic resources to reduce latency [4]. To increase an UL transmission's reliability, the UE is able to transmit several repetitions in the consecutive slots or sub-slots without feedback from the gNB [4].

C. URLLC in unlicensed spectrum

The URLLC features in Release 15 and 16 are specified in licensed spectrum. Due to the new use cases in the industrial scenario, the operation of URLLC in unlicensed spectrum has become one of the main objectives in the ongoing Release 17.

In unlicensed spectrum, a transmitter is required to do Listen Before Talk (LBT) in order to acquire a channel prior to a transmission. There are two channel access mechanisms in LTE and 5G: load based equipment (LBE) and frame based equipment (FBE) [5]. In LBE, a transmitter attempts to access to a channel whenever it has data to transmit. There are two stages to initiate the transmitter's channel occupation time (COT): Initial Clear Channel Assessment (iCCA) and Extended Clear Channel Assessment (eCCA) [6]. In iCCA, the transmitter senses the channel in a defer duration T_d to be

$$T_d = t_f + m_p \times t_{sl}. \tag{1}$$

where t_f is 16 μs, t_{sl} is 9 μs that is duration of a sensing slot. m_p is the number of consecutive sensing slots depending on channel access priority class p defined in Table I and Table II.

Upon the success of iCCA, the transmitter performs an eCCA. The transmitter senses the channel in N additional sensing slots. N is chosen randomly between 0 and CW_p where CW_p is the contention window size in Table I and

Table II. If the channel is idle in a sensing slot, the counter starting from N decreases by 1. If the channel is busy in a sensing slot, the transmitter senses the channel in an additional defer duration and the counter stops until all sensing slots of the additional defer duration are idle. When the counter reaches 0, the transmitter occupies channel for $T_{MCOT,p}$ in Table I and Table II.

TABLE I
CHANNEL ACCESS PRIORITY CLASS FOR DL

Channel access priority class (p)	m_p	$T_{mcot,p}$	**Allowed CW_p sizes**
1	1	2ms	{3, 7}
2	1	3ms	{7, 15}
3	3	8 or 10ms	{15, 31, 63}
4	7	8 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

TABLE II
CHANNEL ACCESS PRIORITY CLASS FOR UL

Channel access priority class (p)	m_p	$T_{mcot,p}$	**Allowed CW_p sizes**
1	2	2ms	{3, 7}
2	2	4ms	{7, 15}
3	3	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}
4	7	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

In FBE, a transmitter attempts to access to a channel and starts a transmission at the fixed occasions. The period of these occasions is called fixed frame period (FFP) with a duration (T_{FFP}) of 1, 2, 2.5, 4, 5 or 10 ms consisting of a COT and an idle period with the durations of T_{COT} and T_{idle}, respectively as shown in Fig. 1. The duration of T_{idle} is at least 5% of T_{FFP} but not smaller than 100 μs. The transmitter does channel sensing within 9 μs in a single observation slot of 25 μs (T_{CCA}) within the idle period. If the channel is busy, the transmitter waits until the observation slot in the next FFP to attempt to access to the channel. If the channel is idle, the transmitter occupies the channel for T_{COT} and stops the transmission before the idle period.

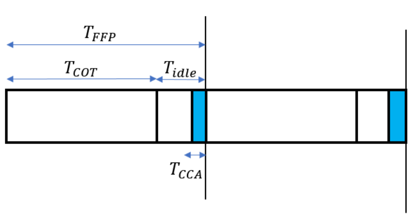

Fig. 1. Fixed frame period in FBE.

D. Related work

Several existing works have presented the models and analyzed the behavior of a transmitter using LBE in unlicensed spectrum where all transmitters in the system use LBE. [7] and [8] calculate the latency when a transmitter uses LBE to access to a channel. However, latency of LBE in these works does not take into account the additional process in eCCA when the counter is frozen. [9] shows the performance of LBE and the impact of LBE on URLLC but does not derive a closed-form expression of channel access latency in LBE. [10] and [11] present a Markov chain model for LBE to show the relation between the transmission probability and the probability of sensing a busy channel in a sensing slot. [11] also shows a closed-form expression of channel access time in LBE to demonstrate the impact of LBE on URLLC. [14] demonstrates the performance of the system where the devices using LBE coexist with the WIFI devices.

The behavior of a transmitter using FBE in unlicensed spectrum where all transmitters in the system use FBE is also analyzed in several existing works. [12] shows the throughput of the devices using FBE in the system. [13] and [14] evaluate the performance of the devices using FBE where the LTE devices using FBE coexist with the WIFI devices. [15] models FBE by a Markov chain to show the relation of the transmission probability and the probability of sensing a busy channel in an observation slot.

The existing works only consider a system with only LBE devices or FBE devices while the scenario where both LBE devices and FBE devices coexist is not analyzed. This paper focuses on the operation in unlicensed spectrum where the devices using LBE and FBE to access to a channel coexist in the 5G network. In Section II, the behavior of the devices using LBE and FBE that coexist in unlicensed spectrum is modeled by a Markov chain model. The model allows calculating channel access time and transmission probabilities of the devices based on the parameters in the system such as the probability of data arrival, the number of the LBE and FBE devices. Based on these calculations, Section III proposes a scheme to dynamically switch between LBE and FBE at the devices to serve data with different priorities, requirements and data rates. The numerical results in Section IV show the benefits of the proposed scheme. Section V concludes this paper with some remarks.

II. MARKOV CHAIN MODEL FOR THE COEXISTENCE OF THE DEVICES USING LBE AND FBE IN UNLICENSED SPECTRUM

A. System model

The devices in the 5G system of the paper share the same frequency resource in sub-6GHz bands, use omnidirectional sensing (omni-LBT) to sense and acquire a channel by following LBE or FBE then transmit data by using omnidirectional transmission. Every of the transmitters (the UE) can detect each other through channel sensing. The receiver (the gNB) uses omnidirectional reception to receive data. q is the probability that a transmitter (using LBE or FBE) has data to transmit. At each transmission by a transmitter using LBE, regardless of the number of retransmissions, the probability that a transmitter senses a busy channel in a sensing slot of

9 μs is p_{c_LBE}. In a t_f gap of 16 μs, energy measurement is done for a total of at least 5 μs with at least 4 μs of sensing falling within the sensing slot of 9 μs immediately before the transmission. Therefore, the busy probability in a 16 μs gap is approximated to be p_{c_LBE} as in a sensing slot of 9 μs. At each transmission by a transmitter using FBE, regardless of the number of retransmissions, the probability that a transmitter senses a busy channel within 9 μs in an observation slot is p_{c_FBE}.

B. LBE's model

When a transmitter uses LBE to access to a channel, the counter N is chosen randomly between 0 and W in eCCA where W is the contention window size. Based on the Markov chain model for LBE in [10] and [11], we can calculate transmission probability and channel access time of a transmitter in LBE. The probability that a transmitter using LBE acquires a channel to transmit data is

$$P_{t\_LBE} = \frac{2q(1-p_{c\_LBE})}{2(1-p_{c\_LBE})^2(1-q)+(W-2p_{c\_LBE}+1)q} \tag{2}$$

The average time that the transmitter spends in a busy defer duration is

$$\begin{aligned} T = &\, p_{c\_LBE}t_f + p_{c\_LBE}(1-p_{c\_LBE})(t_f+t_{sl})+ \\ &+ (1-p_{c\_LBE})^2 p_{c\_LBE}(t_f+2t_{sl}) + ... \\ &... + (1-p_{c\_LBE})^{m_p} p_{c\_LBE}(t_f+m_p t_{sl}). \end{aligned} \tag{3}$$

When a transmitter senses the channel in the defer duration, taking into account time spent in the busy defer duration, the average time spent by the transmitter until it senses an idle defer duration (the channel is idle in the t_f gap and and all t_{sl} slots) and gets out of the deferring state is

$$T_{D-out} = T_d + \frac{T}{(1-p_{c\_LBE})^{m_p+1}} - T. \tag{4}$$

The average time of the eCCA that the transmitter decrements the counter to 0 and acquires channel to transmit data is:

$$T_{all-backoff} = \frac{W}{2}((1-p_{c\_LBE})t_{sl} + p_{c\_LBE}(t_{sl}+T_{D-out})). \tag{5}$$

LBE consists of the iCCA and eCCA so the average time that the transmitter spends to initiate a COT for a transmission is

$$T_{access\_LBE} = T_{D-out} + T_{all-backoff}. \tag{6}$$

C. FBE's model

Based on the Markov chain model in [15], the probability that a transmitter accesses to a channel to transmit data in FBE is

$$P_{t\_FBE} = q(1-p_{c\_FBE}^K) \tag{7}$$

where K is the number of channel sensing that is allowed for a transport block at the transmitter in FBE.

The average time that a transmitter needs to access to a channel in FBE is

$$\begin{aligned} T_{access\_FBE} &= T_{CCA} + p_{c\_FBE}T_{FFP} + 2p_{c\_FBE}^2 T_{FFP} + ... \\ &= T_{CCA} + T_{FFP}\sum_{i=1}^{\infty} i p_{c\_FBE}^i \\ &= T_{CCA} + T_{FFP}\frac{p_{c\_FBE}}{(1-p_{c\_FBE})^2}. \end{aligned} \tag{8}$$

D. Coexistence of LBE and FBE's model

When the transmitters using LBE and the transmitters using FBE coexist in the system, a model based on the model for LBE in Section II-B and the model for FBE in Section II-C is used to calculate the transmission and collision probabilities of the transmitters. In the model, there are $N1$ transmitters using LBE and $N2$ transmitters using FBE. For any transmitter using LBE, it senses a busy channel in a sensing slot when at least one transmitter (using LBE or FBE) in the system transmits at that time. The probability of sensing a busy channel in a sensing slot and transmission probability of a LBE transmitter in the coexisting model are

$$\begin{cases} p_{c\_LBE} = 1-(1-P_{t\_LBE})^{N1-1}(1-P_{t\_FBE})^{N2} \\ P_{t\_LBE} = \frac{2q(1-p_{c\_LBE})}{2(1-p_{c\_LBE})^2(1-q)+(W-2p_{c\_LBE}+1)q} \end{cases}. \tag{9}$$

Similarly, for any transmitter using FBE, it senses a busy channel in an observation slot when at least one transmitter (using LBE or FBE) in the system transmits at that time. The probability of sensing a busy channel in an observation slot and transmission probability of a FBE transmitter in the coexisting model are

$$\begin{cases} p_{c\_FBE} = 1-(1-P_{t\_LBE})^{N1}(1-P_{t\_FBE})^{N2-1} \\ P_{t\_FBE} = q(1-p_{c\_FBE}^K) \end{cases}. \tag{10}$$

III. Dynamic switch between LBE and FBE at the UE in unlicensed spectrum

A. Switch from FBE to LBE

In FBE, a transmitter is only allowed to do channel sensing at the fixed occasions with a period of T_{FFP}. If the channel is busy in a Channel Clear Access (CCA) occasion, the transmitter must wait until the CCA occasion in the next FFP to sense the channel. This limits the opportunity of the transmitter to attempt to acquire the channel. In contrast, in LBE, a transmitter senses the channel continuously whenever it has data to transmit. Therefore, the average access time of the LBE transmitter with low channel access priority class is smaller than that of the FBE transmitter with the same probability of sensing a busy channel.

When a transmitter using FBE has a high priority packet such as an URLLC packet with a required latency of 1 ms, the performance of FBE with the current parameters $(q, W, N1, N2)$ in the system might not satisfy the URLLC requirement. In this case, the FBE transmitter can dynamically switch to LBE mode to have a better performance of channel access. In another case, the latency requirement is satisfied by using FBE with the current set of parameters then the data rate increases leading to a higher value of q. This makes the probability of sensing a busy channel increase and the transmitter needs longer time to acquire a channel so the latency requirement is not ensured anymore. To overcome this problem, the transmitter is also allowed to dynamically switch to LBE so as to reduce the average channel access time.

In the system, at the beginning, there are $N1$ LBE transmitters and $N2$ FBE transmitters. We have the probabilities of sensing a busy channel for the LBE and FBE transmitters

$$\begin{cases} p_{c\_LBE} = 1-(1-P_{t\_LBE})^{N1-1}(1-P_{t\_FBE})^{N2} \\ p_{c\_FBE} = 1-(1-P_{t\_LBE})^{N1}(1-P_{t\_FBE})^{N2-1} \end{cases}. \tag{11}$$

When a FBE transmitter switches to LBE due to a high priority packet or a higher data rate, we have the probabilities of sensing a busy channel for $N1+1$ LBE transmitters and $N2-1$ FBE transmitters

$$\begin{cases} p'_{c\_LBE} = 1-(1-P'_{t\_LBE})^{N1}(1-P'_{t\_FBE})^{N2-1} \\ p'_{c\_FBE} = 1-(1-P'_{t\_LBE})^{N1+1}(1-P'_{t\_FBE})^{N2-2} \end{cases}. \tag{12}$$

P_{t_LBE} and P'_{t_LBE} are calculated from (2). P_{t_FBE} and P'_{t_FBE} are calculated from (7).

For the FBE transmitter of interest switching to LBE, it has more chances to do channel sensing and access to the channel in an interval. Therefore, the transmitter needs less time to access to a channel and attains the latency requirement in LBE with low channel access priority class as calculated from (6) and (8).

The decision to switch from FBE to LBE at a transmitter (a UE) is made by the gNB or the transmitter. If the transmitter transmits data on the configured resources, it calculates channel access time based on the parameters including $q, W, N1, N2$. If channel access time is higher than the data requirement, it switches to LBE then informs this switch to the gNB through uplink control information (UCI) or radio resource control (RRC). Subsequently, the gNB updates the number of the LBE and FBE transmitters in the system and informs them to all the transmitters through downlink control information (DCI) or RRC so that the transmitters can use this information to calculate transmission probability, sensing busy channel's probability and channel access time for the upcoming packets. If the transmitter transmits data on the dynamic resources, it sends a scheduling request to the gNB. The gNB can calculate the variables related to the UL transmission requested and makes the decision to switch by itself. The gNB demands the transmitter to switch from FBE to LBE if necessary through DCI playing the role of UL grant.

B. Switch from LBE to FBE

When a transmitter using LBE has the low priority packets without a strict latency requirement, the transmitter can switch to FBE with a longer channel access time to reduce the number of channel sensing. This also mitigates the detecting burden at the gNB because the gNB only needs to detect data at the fixed moments at the beginning of the FFP. Even if the transmitter has the high priority packets such as URLLC packets then the URLLC data rate decreases leading to a smaller value of q, the transmitter also can switch to FBE to save energy while still achieving latency requirement. This switch is helpful for the power limited devices.

In the system, at the beginning, there are $N1$ LBE transmitters and $N2$ FBE transmitters. We have the probabilities of sensing a busy channel for the LBE and FBE transmitters

$$\begin{cases} p_{c\_LBE} = 1-(1-P_{t\_LBE})^{N1-1}(1-P_{t\_FBE})^{N2} \\ p_{c\_FBE} = 1-(1-P_{t\_LBE})^{N1}(1-P_{t\_FBE})^{N2-1} \end{cases}. \tag{13}$$

When a LBE transmitter switches to FBE to reduce energy consumption when priority of data or data rate is low, we have the probabilities of sensing a busy channel for $N1-1$ LBE transmitters and $N2+1$ FBE transmitters

$$\begin{cases} p'_{c\_LBE} = 1-(1-P'_{t\_LBE})^{N1-2}(1-P'_{t\_FBE})^{N2+1} \\ p'_{c\_FBE} = 1-(1-P'_{t\_LBE})^{N1-1}(1-P'_{t\_FBE})^{N2} \end{cases}. \tag{14}$$

P_{t_LBE} and P'_{t_LBE} are calculated from (2). P_{t_FBE} and P'_{t_FBE} are calculated from (7).

The transmitter of interest switching from LBE to FBE does channel sensing less frequently and needs less steps to acquire a channel. The gNB also only needs to detect the transmission at the beginning of the FFP. Therefore, energy consumption at the gNB and the transmitter is reduced.

Similarly to Section III-A, the decision to switch from LBE to FBE can be made by the gNB or the transmitter. The information related to the switch is exchanged between the gNB and the transmitter through UCI, DCI or RRC. The information about periodicity and the starting point of the FFP is preconfigured by the gNB through the activation DCI or RRC in the configured grant transmission or included in DCI playing the role of UL grant in the dynamic grant transmission.

IV. Numerical Results

The simulations in this section are done to show the performance of a UE switching between LBE and FBE and the benefits of this switch. The parameters of the simulations are shown in Table III.

TABLE III
SIMULATION PARAMETERS

Parameters	**Values**
Number of the LBE UEs	5
Number of the FBE UEs	5
Channel access priority class	2
Contention window size (W)	7
Fixed frame period	1 ms
The allowed number of channel sensing (K)	2

The first simulation is done to show the performance of a UE switching from FBE to LBE. At the beginning, there are

5 LBE UEs and 5 FBE UEs in the system. The UE of interest uses FBE to access to the channel and transmits URLLC data. The UE of interest might switch from FBE to LBE to make the URLLC transmission achieve the latency requirement when probability of arriving data (data rate) increases. After the UE of interest switches from FBE to LBE, there are 6 LBE UEs and 4 FBE UEs in the system.

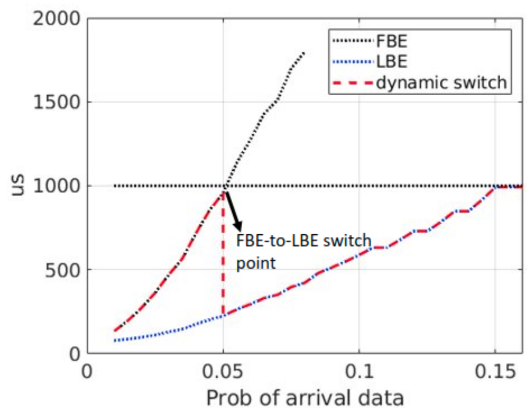

Fig. 2. Channel access time of a UE using FBE, LBE and dynamic-FBE-to-LBE-switch scheme.

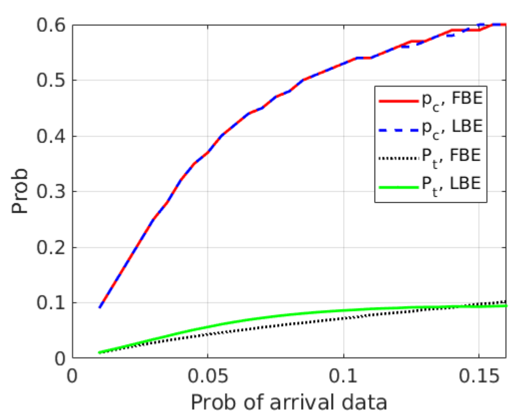

Fig. 3. Probability of sensing a busy channel and transmission probability of a UE using FBE and LBE.

Fig. 2 shows channel access time when the UE of interest uses FBE, channel access time when the UE of interest uses LBE and channel access time when the UE of interest uses a dynamic switch scheme to switch from FBE to LBE. URLLC has a latency requirement of 1 ms so when the UE transmits URLLC packets, channel access time must not be bigger than 1 ms. If channel access time in FBE is bigger than 1 ms, the UE must switch to LBE to attain the URLLC requirement. As shown in Fig. 2, if the probability that the UE has data to transmit q is smaller than 0.05, channel access time in FBE is smaller than 1 ms so the UE can use FBE to access to the channel and transmits URLLC data because FBE process is less complex and requires a smaller number of channel sensing that leads to lower energy consumption at the transmitter and receiver. On the other hand, if q is bigger than 0.05, channel access time in FBE is bigger than 1 ms so the UE must switch to LBE. Fig. 3 demonstrates that the UE has a higher probability of transmission after the switch, although the probabilities of sensing a busy channel before and after the switch are nearly equal. By using LBE when data rate increases and makes q higher than 0.05, the UE has channel access time smaller than 1 ms to satisfy the URLLC requirement as shown in Fig. 2. When the UE uses LBE, it has to do more channel sensing and the gNB also has to do more blind detection to detect a transmission. Therefore, a switch from FBE to LBE requires higher energy consumption at the UE and the gNB.

The second simulation is done to show the performance of a UE switching from LBE to FBE. At the beginning there are 5 LBE UEs and 5 FBE UEs in the system. The UE of interest uses LBE to access to the channel and transmits URLLC data. The UE might switch from LBE to FBE to reduce the sensing burden at the UE and the detecting burden at the gNB while still achieving the URLLC latency requirement. After the UE of interest switches from LBE to FBE, there are 4 LBE UEs and 6 FBE UEs in the system.

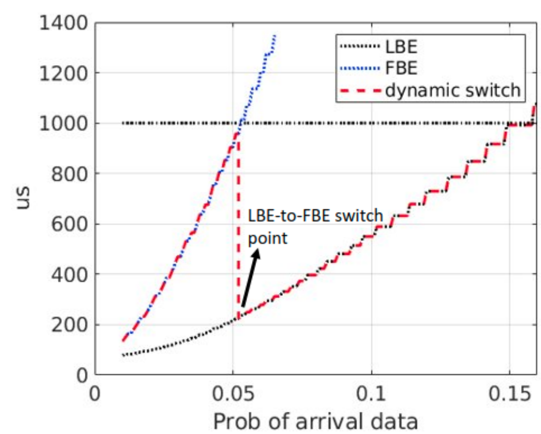

Fig. 4. Channel access time of a UE using FBE, LBE and dynamic-LBE-to-FBE-switch scheme.

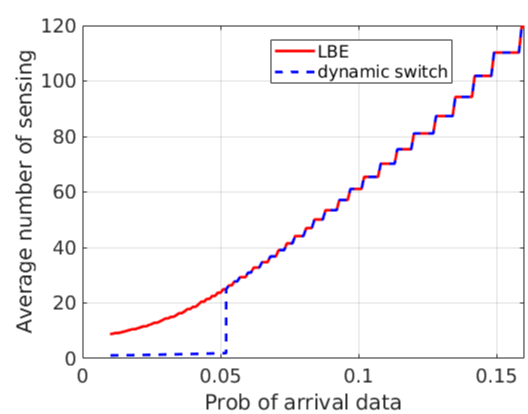

Fig. 5. Number of channel sensing of a UE using LBE and dynamic-LBE-to-FBE-switch scheme.

Fig. 4 shows channel access time when the UE of interest uses FBE, channel access time when the UE of interest uses LBE and channel access time when the UE of interest uses a dynamic switch scheme to switch from LBE to FBE. The UE is configured to use LBE so that it can access to the channel in the URLLC latency budget of 1 ms. As can be seen in Fig. 4, if the probability that the UE has data to transmit q is smaller than 0.052, the UE can use FBE and still achieves the URLLC requirement. Therefore, if data rate decreases and q is smaller than 0.052, the UE switches from LBE to FBE in order to access to the channel. By using FBE, the sensing burden at the UE is reduced that leads to lower energy consumption. As shown in Fig. 5, when q is smaller than 0.052 and the UE switches from LBE to FBE, it needs to do a smaller number of channel sensing to access to channel so energy consumption decreases while the URLLC requirement is still ensured.

V. Conclusion

This paper presented a Markov chain for the coexistence of the LBE and FBE devices in the system. To serve data with different priorities and arrival rates, we proposed that the devices are capable of dynamically switching between LBE and FBE based on the parameters calculated from the Markov chain. When a device has high priority data such as URLLC with a strict latency requirement or data with high arrival rate, it switches from FBE to LBE to reduce channel access time and increase transmission probability. On the other hand, when a device has low priority data such as eMBB or data with low arrival rate, it switches from LBE to FBE to mitigate the sensing burden at the transmitter and the detecting burden at the receiver. The benefits of the dynamic switch between LBE and FBE have been shown in the numerical results.

Acknowledgments

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