# Queue-Sensing-Based CSAT: A Downlink Transmission Scheme for LTE-M in Unlicensed Spectrum

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Abstract: A shortage of licensed spectrum is a major hindrance to the capacity of Long Term Evolution for Metro (LTE-M) to carry urban rail transit services at present. Inspired by LTE-Unlicensed (LTE-U) offloading some of data traffic transmitted in licensed spectrum by accessing the unlicensed 5GHz frequency band, we propose a queue-sensing-based Carrier Sensing Adaptive Transmission (CSAT) scheme for LTE-M in unlicensed spectrum based on LTE-U. The scheme calculates the minimum amount of data that should be transmitted during current transmission duration by queue length at the beginning of each LTE-U cycle, according to which, LTE-U adjusts its duty cycle to meet the requirement of LTE-M service. This paper focuses on the downlink transmission scheme for LTE-M in unlicensed spectrum, and verifies its performance by simulation, which tells that Queue-sensing-based CSAT will not only provide a reliable transmission for LTE-M services, but also maximize the fairness of channel occupancy in unlicensed spectrum.

## 1 INTRODUCTION

LTE-M is a new generation of train-ground communication system for urban rail transit integrated service based on LTE. According to the allocation of the wireless frequency band for urban rail transit in Beijing, LTE-M is allowed to use 1785-1795MHz band with the bandwidth of 10MHz in the aboveground area, while 1785-1805MHz band is allowed to use in the underground area (Beijing Radio Administration, 2017). Additionally, LTE-M specification requires a structure of dual-network redundancy to ensure reliable transmission of Communication Based Train Control (CBTC) service, where the A network carries multiple types of service, including CBTC, Passenger Information System (PIS) and Closed-circuit Television (CCTV), and the B network only carries CBTC service serving as a backup network (China Urban Rail Transit Association, 2016). Through the test of Hangzhou subway line 4, it can be seen that LTE-M integrated service system requires a bandwidth at least 10MHz (Shao and Xie, 2017), and the available spectrum resource in the aboveground area of Beijing cannot meet the requirements of LTE-M for dual-network redundancy and integrated service bearer. To solve this problem, a solution that offloading some of LTE-M service transmitted in licensed spectrum onto the unlicensed 5GHz frequency band has been proposed.

Many literatures focus on the coexistence of LTE and Wireless Local Area Network (WLAN) in unlicensed spectrum. For example, LTE based on Listen Before Talk (LBT) avoids channel collision through a WLAN-like competitive channel access mechanism (Hu et al, 2016). The duty cycle solution enables LTE and WLAN to access the channel in turn by time division multiplexing technology (Choi and Park, 2015). CSAT improves the duty cycle solution to enable LTE to dynamically adjust the duty cycle of LTE according to the current channel load (Qualcomm, 2014). At present, the two main technology for LTE in unlicensed spectrum are LTE-U based on the duty cycle mechanism and Licensed Assisted Access (LAA) based on LBT mechanism. Compared with the competitive channel access mechanism of LAA, the duty cycle mechanism of LTE-U is more convenient to control

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the transmission performance of LTE-M service by adjusting the duty cycle. Therefore, we choose LTE-U as the bearer technology for LTE-M service in unlicensed spectrum.

The rest of this paper will analyse the shortcomings of origin CSAT when carrying LTE-M service and propose a solution to improve the performance of CSAT for LTE-M in unlicensed spectrum. The paper is organized as follows. In Section 2, we analyse the shortcomings of LTE-U with CSAT mechanism to carry LTE-M service. Then introduce the design of queue-sensing-based CSAT in Section 3. And verify the performance of improved CSAT by simulation in Section 4. Finally, we conclude this work in Section 5.

## 2 SHORTCOMINGS OF CSAT

To guarantee the fairness of spectrum utilization in unlicensed spectrum, LTE-U is supposed to adopt CSAT mechanism. The rule for CSAT to adjust the duty cycle is denoted as

$$\begin{cases} T_{ON}(\mathrm{n+1}) = \min(\mathrm{T}_{ON}(\mathrm{n}) + \Delta_{UP}, \mathrm{T}_{ON,\max}) & \overline{MU(\mathrm{n})} < MU_{Thr1} \\ T_{ON}(\mathrm{n+1}) = T_{ON}(\mathrm{n}) & MU_{Thr1} \le \overline{MU(\mathrm{n})} \le MU_{Thr2} \\ T_{ON}(\mathrm{n+1}) = \max(T_{ON}(\mathrm{n}) - \Delta_{DOWN}, \mathrm{T}_{ON,\min}) & \overline{MU(\mathrm{n})} > MU_{Thr2} \end{cases} \quad (1)$$

where $T_{ON}(\mathrm{n})$ is the transmission duration of LTE-U in the $n^{th}$ cycle, duration of which is denoted as $T_{CSAT}$ . $\Delta_{UP}$ and $\Delta_{DOWN}$ are the steps to increase and decrease $T_{ON}(\mathrm{n})$ . $\overline{MU(\mathrm{n})}$ is the estimation of Medium Utilization (MU) which represents the channel occupancy of WLAN. $MU_{Thr1}$ and $MU_{Thr2}$ are the thresholds of MU to determine the change of $T_{ON}(n+1)$. $T_{ON,\max}$ is a limit imposed on the maximum time that $T_{ON}(\mathrm{n})$ can take. $T_{ON,\min}$ is defined as follows based on the number of WLAN Access Points (AP) that are operating in the environment:

$$T_{ON,\min} = \min\left\{ TONMininmilli\mathrm{sec}, \frac{(\mathrm{N}+1)\cdot \mathrm{T}_{CSAT}}{N+1+NumWiFiNodes} \right\} \quad (2)$$

where $TONMininmilli\mathrm{sec}$ is a configurable parameter aimed at guaranteeing a minimum duty cycle to avoid undetected APs' transmission. N is the number of LTE-U cells in the scenario. $NumWiFiNodes$ is the number of detected APs.

Since the number of WLAN APs in the real urban rail transit scenario is much larger than the number of LTE-U cells, the calculation result of $T_{ON,\min}$ is close to 0, which does not limit the minimum duty cycle of LTE-U. Therefore, when MU exceeds the threshold $MU_{Thr2}$, the duty cycle of LTE-U will continue to decline until reach $T_{ON,\min}$ , which will cause the security of LTE-M service under threat. We will prove this by simulation in Section 4. To avoid this happening, we improve traditional CSAT with Frame Level Scheduler (FLS) algorithm to ensure the reliable transmission of LTE-M service.

## 3 DESIGN OF QUEUE-SENSING-BASED CSAT

### 3.1 FLS Algorithm

FLS is a resource allocation algorithm for LTE downlink which defines frame by frame the amount of data that each service should transmit to satisfy its delay constraint (Piro et al, 2011). The algorithm is as follows.

$$u(k) = q(k) + \sum_{n=2}^{M} \left[ q(k-n+1) - q(k-n+2) - u(k-n+1) \right] c(n) \quad (3)$$

where $u(k)$ is the quota of data that should transmit in the $k^{th}$ frame to meet its Quality of Service (QoS) constraints. $q(k)$ is the queue length at time $t_k$ which represents the starting time of the $k^{th}$ frame. $c(n)$ is a system parameter to control the distribution of data to transmit in each frame. It has been proved that, for a service, if the amount of transmitted data in the $k^{th}$ frame can always meet the constraint of $u(k)$, a queuing delay smaller than M+1 frame length can be provided.

### 3.2 System Model

FLS is a resource allocation strategy for discrete events. It does not care about the change of queue length between two samples, but only evaluate the minimum amount of data to be transmitted in the next sampling interval based on the queue length obtained at sampling time. Therefore, change the sampling interval does not affect the function of the algorithm. Changing the sampling interval from a frame to an LTE-U duty cycle length can easily realize the combination of FLS and CSAT.

Figure 1 is the design of LTE-U transmission process in downlink with queue-sensing-based CSAT mechanism. In the figure, the solid line represents the transmission process of data, and the dotted line represents the work process of queue-sensing-based CSAT, during which there is no data transmitted.

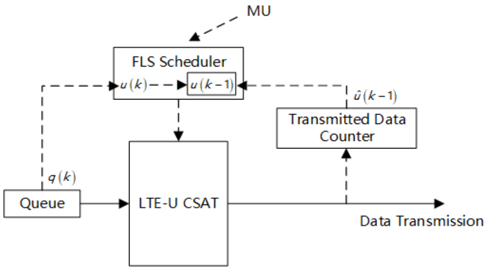


Figure 1: Design of queue-sensing-based CSAT.

FLS scheduler first obtains the current queue length $q(k)$ at each sampling time, according to which it calculates and saves $u(k)$. In the meanwhile, LTE-U transmitted data counter counts the amount of data transmitted in last LTE-U cycle, and save it as $\hat{u}(k-1)$. Then FLS scheduler comparing $\hat{u}(k-1)$ with $u(k-1)$, and adjust the duty cycle for the current LTE-U cycle according to the comparison result. The rule for queue-sensing-based CSAT to adjust the duty cycle is denoted as

$$\begin{cases} T_{ON}(\mathrm{n+1}) = \min(\mathrm{T}_{ON}(\mathrm{n}) + \Delta_{UP}, \mathrm{T}_{ON,\max}) & \left(\overline{MU(\mathrm{n})} < MU_{Thr1}\right) \vee \left(\hat{u}(k-1) < u(k-1)\right) \\ T_{ON}(\mathrm{n+1}) = T_{ON}(\mathrm{n}) & MU_{Thr1} \le \overline{MU(\mathrm{n})} \le MU_{Thr2} \\ T_{ON}(\mathrm{n+1}) = \max(T_{ON}(\mathrm{n}) - \Delta_{DOWN}, \mathrm{T}_{ON,\min}) & \left(\overline{MU(\mathrm{n})} > MU_{Thr2}\right) \wedge \left(\hat{u}(k-1) > u(k-1)\right) \end{cases} \quad (5)$$

The rule introduces FLS based on CSAT. Compared with the original algorithm, besides the case where MU is smaller than the threshold $MU_{Thr1}$, if $\hat{u}(k-1)$ is smaller than $u(k-1)$, LTE-U will also increase the transmission duration for the current cycle to ensure that the transmission performance of LTE-U meets the requirement of beared service. Additionally, only if MU greater than the threshold $MU_{Thr2}$ and $\hat{u}(k-1)$ is greater than $u(k-1)$, will LTE-U accept the reduction of duty cycle. Because LTE-M service has a high requirement for security, ensuring the reliable transmission of the service is a priority. Therefore, only if the transmission performance meets the requirement of LTE-M service, will LTE-U accept to decrease its transmission duration. Otherwise, the requirement of adjusting the duty cycle will be refused.

Queue-sensing-based CSAT provides a way to calculate the minimum amount of data that needs to be transmitted during the current LTE-U cycle based on the queue length. and make up for the lack of attention to LTE-U performance in original CSAT. With this solution, LTE-U could be a reliable bearer for LTE-M service in unlicensed spectrum.

# 4 SIMULATION RESULTS

## 4.1 Simulation Scenario

Figure 2 is the coexistence scenario for LTE-U and WLAN used in the simulation, which follows the indoor scenario in 3GPP TR36.889 (3GPP, 2015). A File Transfer Protocol (FTP) service is used for transmission tests. The packet arrival rate of the service obeys the Poisson distribution, and the packet size is fixed to 0.5MB.

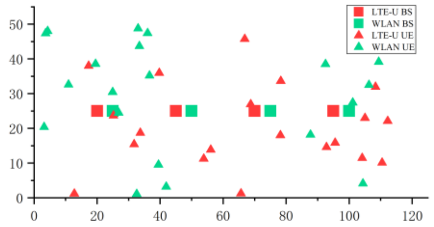


Figure 2: Coexistence scenario.

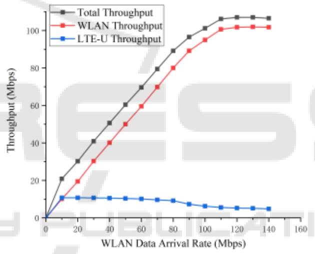


Figure 3: Result of transmission test.

Figure 3 is the simulation result of transmission test in downlink of the LTE-U CSAT and WLAN coexistence scenario mentioned above. In the test, the beared service of LTE-U is set to be a stable data stream with a data arrival rate of 10Mbps to simulate LTE-M service. And by gradually increasing the data arrival rate of WLAN, the overall throughput of the channel can gradually approach to the saturation capacity. The thresholds $MU_{Thr1}$ and $MU_{Thr2}$ are set to be 0.2 and 0.4.

Figure 3 shows the curve of overall throughput of the channel which tends to be flat when the data arrival rate of WLAN reaches 120Mbps, where the channel is closed to saturation. Therefore, in the following simulation, the data arrival rates of WLAN are selected to be 10Mbps, 60Mbps and 120Mbps to represent low, medium and high channel load condition respectively.

## 4.2 Simulation for CSAT

As shown in Figure 3, the throughput of LTE-U with CSAT mechanism decreases as the channel load increases. This is because of the shortcomings of CSAT mentioned in Section 2, when the channel load is aggravated, the data transmission duration of LTE-U will decrease and result in a reduction on throughput as shown in Figure 4.

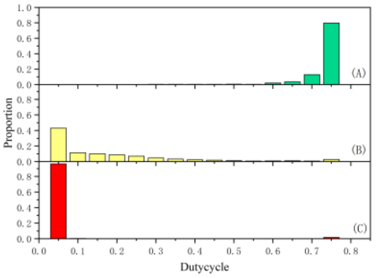


Figure 4: Duty cycle distribution under different load.

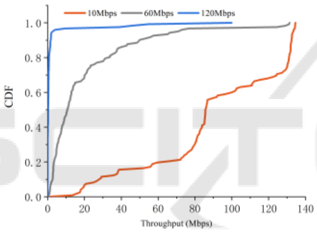


Figure 5: LTE-U throughput under different load.

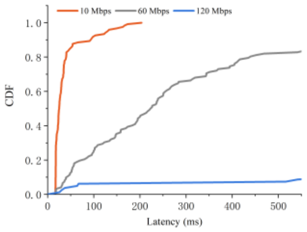


Figure 6: LTE-U latency under different load.

Figure 4 is the distribution of LTE-U duty cycle under different channel load, in which A, B, C subgraphs represent the distribution under low, medium and high channel load conditions respectively. In the figure, when the channel load is low, the distribution of duty cycle concentrates around the value of 0.75, which is the maximum value of duty cycle in the simulation. As the channel load increases, the distribution begins to concentrate around the minimum value. Finally, when the channel load becomes to the high level, almost all the duty cycle distributes at the minimum value.

Figure 5 and Figure 6 are the Cumulative Distribution Probability (CDF) of the throughput and latency of LTE-U CSAT under different channel load. In the figure 5, as the channel load increases, the throughput of LTE-U drops sharply. Under the high channel load condition, the throughput is almost zero. In the Figure 6, the distribution of delay is consistent with which of throughput. Under the high channel load conditions, the transmission delay of LTE-U increases dramatically. Therefore, the shortcomings of traditional CSAT mentioned in Section 2 has been proved.

Due to the LTE-M specification, the service delay should be less than 500ms, so LTE-U with traditional CSAT cannot provide a reliable transmission for LTE-M service.

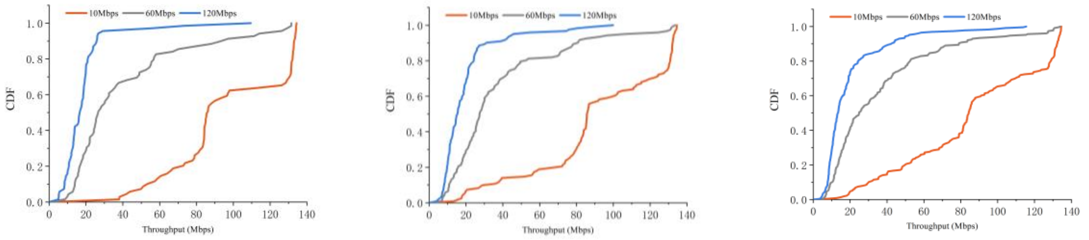
## 4.3 Simulation for Queue-Sensing-Based CSAT

### 4.3.1 Performance Verification

The cycle duration $T_{CSAT}$ is set to 80ms. According to the requirement of LTE-M service for the delay of service not exceeding 500ms, the FLS parameter M is set to 5, which means that the delay of LTE-M service will not exceed $(5+1)\times 80$ms=480ms.

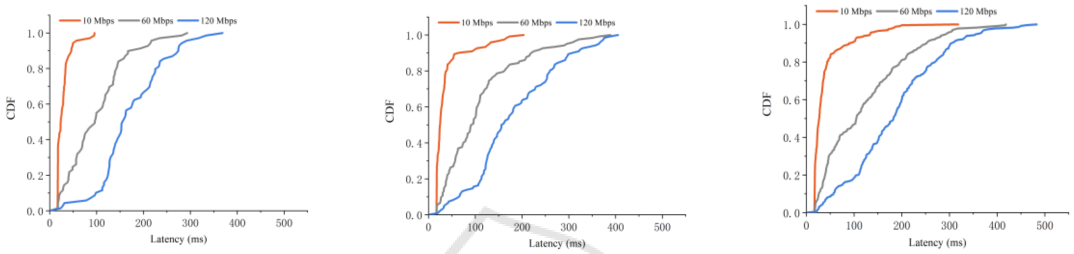
Figure 7 and Figure 8 are the CDF of the throughput and latency of LTE-U with queue-sensing-based CSAT under different channel load. And the subgraphs A, B, C in both figures represent the data arrival rates of LTE-U are set to 5Mbps, 10Mbps and 20Mbps respectively. Comparing Figure 7 subgraph B with Figure 5 where the data arrival rates of LTE-U are the same, under the low channel load condition, two transmission schemes have similar performance. This is because when channel load is low, the transmission performance of LTE-U can meet the requirement of LTE-M, and MU is smaller than the threshold $MU_{Thr1}$, so the improved CSAT works as the original CSAT to increase the transmission duration of LTE-U and get the same performance. As the channel load increases, the improved CSAT begins to show a better performance than the original one, and under the high channel load condition, the improved CSAT can still keep a proper throughput for LTE-U to ensure the reliable transmission of LTE-M service.

In the Figure 8 subgraph B, the distribution of delay is consistent with which of throughput. Significantly, the service delay under the high



(A) (B) (C)

Figure 7: Queue-sensing-based LTE-U throughput under different load.



(A) (B) (C)

Figure 8: Queue-sensing-based LTE-U latency under different load.

channel load condition is still less than 500ms. The performance of improved CSAT has been verified.

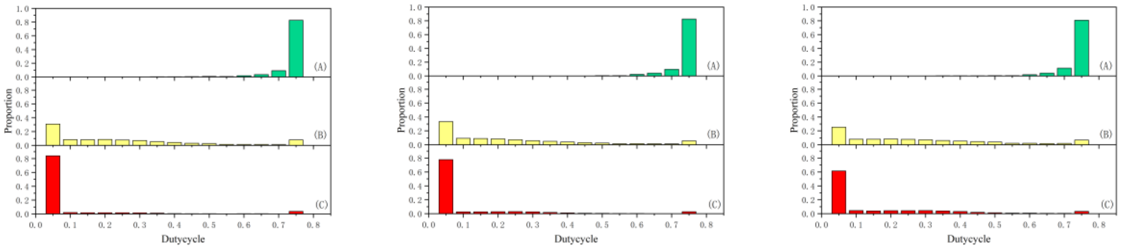
### 4.3.2 Adaptive Verification

Comparing A, B, C subgraphs in Figure 7, we can see that under the low channel load condition, as the data arrival rate of LTE-U increases, the distribution of throughput gradually moves towards a smaller value. This is because when the channel load is low, the duty cycle of LTE-U stays at the maximum value for most of the time, so when the data arrival rate increases, LTE-U cannot obtain more transmission duration for extra data transmission, which causes the queue length of LTE-U increasing, and the performance of service delay and throughput getting worse. On the contrary, when the channel load is high, as the data arrival rate increases, the performance of LTE-U throughput does not change a lot or even better. This is because, under the high channel load condition, the transmission duration of LTE-U is compressed in a low level, and only require the minimum resource to keep the normal operation of LTE-M service. When the data arrival rate increases, LTE-U can require more transmission duration through the FLS scheduler to obtain even higher instantaneous throughput, but the overall distribution of throughput will not change greatly.

In figure 8, the distribution of delay is consistent with throughput. When the data arrival rate of LTE-U increases, individual packets have an increase in delay, but all packets have a delay less than 500ms. In conclusion, the queue-sensing-based CSAT can make adaptive adjustments based on the change of service requirement to ensure the reliable transmission of beared service.

### 4.3.3 Fairness Verification

Figure 9 is the distribution of LTE-U duty cycle under different channel load, and in subgraphs A, B, C the data arrival rates of LTE-U are set to 5Mbps, 10Mbps and 20Mbps respectively. Comparing Figure 9 subgraph B with Figure 4 where the data arrival rates of LTE-U are the same, under the low channel load condition, they have the similar distribution of duty cycle as analysed above. As the channel load increases, the distribution of duty cycle at the minimum value in Figure 9 is less than which in Figure 4. This is because improved CSAT increases the duty cycle in some of LTE-U cycle to obtain better transmission performance according to the requirement of LTE-M service, but the overall distribution still concentrates around the value of 0.05. Comparing subgraphs A, B and C, we can see the similar distribution under the low channel load condition. And under the medium or high channel



(A) (B) (C)

Figure 9: Queue-sensing-based LTE-U l duty cycle distribution under different load.

load condition, as the data arrival rate of LTE-U increases, the distribution at the minimum duty cycle gradually decreases, and the reduced portion are distributed to other larger values. This is because the greater the data arrival rate is, the more transmission duration LTE-U needs, so the distribution changes as above. The result above indicates that queue-sensing-based CSAT adjust transmission duration of LTE-U according to the requirement of beared service. When the amount of data to transmit is large, improved CSAT will allocate more duration for LTE-U, and if the amount becomes smaller, it will return the transmission duration to WLAN. This mechanism maximizes the fairness of channel occupancy in unlicensed spectrum under the premise of ensuring the transmission performance of LTE-M service.

## 5 CONCLUSIONS

In this paper, we propose a queue-sensing-based CSAT downlink transmission scheme based on LTE-U. The scheme provides a minimum amount of data to transmit in the current transmission duration as a measure of the requirement of LTE-U transmission performance, according to which, LTE-U dynamically adjusts its duty cycle to provide a reliable transmission for LTE-M service in unlicensed spectrum. According to the results of simulation, this scheme also has a good performance in the fairness of channel occupancy.

Furthermore, future investigations will focus on the improvements on the duty cycle adjustment strategies, and introduce more factors which affect the transmission performance of LTE-U to get a more stable transmission scheme which adapted to various channel conditions.

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