LTE-like Paging and Synchronization for Ambient Backscatter

Yunyun Feng, Wei Gong*
University of Science and Technology of China
yunyunf@mail.ustc.edu.cn, weigong@ustc.edu.cn

***Abstract*—The continuous and ubiquitous nature of LTE traffic makes it advantageous as a backscatter carrier. However, existing backscatter works ignore the importance of being LTE-like, resulting in incompatibility with the standard and inability to access LTE services. We observe that achieving LTE-like requires a service initiation mechanism, that is, paging and accurate downlink synchronization. To this end, we present LTElike, a novel backscatter design that can page tags to initiate LTE service requests. Specifically, we page our tag using the form of amplitude modulation, enabling the ultra-low-power tag to receive paging and wake up. Further, we design an accurate synchronization strategy combining detection and template matching based on correlation, which improves the accuracy to single symbol level. We prototype LTElike using FPGAs, SDR LTE eNBs and UEs. The evaluation results show that the paging identification rate is as high as 100%, and the mean synchronization error of LTElike is 17x better than the counterpart of LScatter.**

I. Introduction

Backscatter [1], [2], [3], [4], [5], [6] has attracted much attention for its promise to enable ultra-low-power communications for billions of sensors. Many state-of-the-art backscatter systems propose to carry sensor data using ambient RF signals, such as Bluetooth and WiFi. However, these ambient excitation signals share the same limitations: intermittent transmission in time, limited coverage in space, and narrow bands in frequency. LTE traffic can make up for these disadvantages because of its continuous transmission, ubiquitous coverage and diverse frequencies. Therefore, LTE signals are extremely advantageous as backscatter carriers.

The vast majority of current backscatter systems have limited functions and are primarily used to transmit sensor data, which makes sensors quite different from commercial devices. Obviously, it is of great significance for backscatter tags to be LTE-like. On the one hand, LTE-like tags can support LTE services. LTE effectively improves the user's mobile service experience due to features such as high bandwidth and low latency, and better meets the service needs of the mobile Internet era. Typical services in the LTE network include mobile video telephony, real-time mobile video surveillance, and high-definition video conference, etc. On the other hand, backscatter communication requires no customized devices. The transmission needs can be met using the existing infrastructure, thus greatly reducing the cost.

*Corresponding author: Wei Gong.

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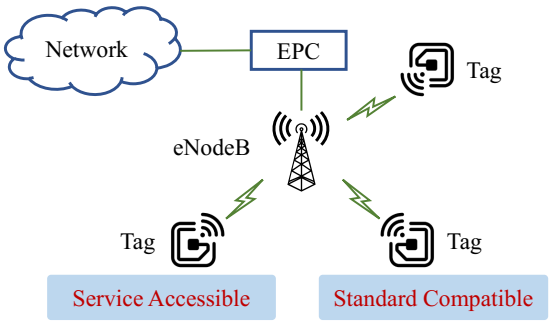


Fig. 1. Conceptual design of LTElike. Our tag can achieve paging message decoding and precise synchronization similar to LTE UE, making it standards-compliant and accessible to services.

Unfortunately, all prior systems fail to achieve LTE-like, which results in incompatibility with standard LTE or unable to access LTE services. Taking LScatter [7] as an example, although LScatter [7] proposes a high-throughput LTE backscatter system, it destroys the frame structure, resulting in incompatibility with LTE standard reception, not to mention access to LTE services. This means that LScatter [7] can only use customized receiver to receive backscattered signals and has no potential to support LTE services. The failure of all prior work to achieve LTE-likeness is due to the fact that they suffer from two crucial drawbacks.

1) *Lack of paging*. Paging is a mechanism to initiate service for UEs (User Equipment) in idle mode. Without paging, UEs in idle state cannot be woken up, making it impossible to initiate service requests. Likewise, to support LTE services, the backscatter tag has to design a paging reception mechanism similar to that of the UE. However, none of the existing backscatter systems have paging. Even for LScatter [7], the first LTE backscatter system, also does not achieve the paging mechanism, ignoring the important role of paging for accessing the network. Specifically, for SyncScatter [8] with wake-up design, its wake-up mechanism is used to indicate that the next packet is available for WiFi backscatter modulation, which is incompatible with the LTE standard and therefore cannot be applied to LTE paging.
2) *Inaccurate synchronization*. In wireless communication, the most critical premise is to establish timing synchronization between the transmitter and the receiver.

Likewise, timing synchronization between the transmitter and the tag is essential for backscatter communications. However, backscatter tags generally cannot afford the high-power standard synchronization algorithms, such as cross-correlation. As a result, most backscatter systems, such as SyncScatter [8], employ a detection method based on energy detection to determine the start of one packet. Unfortunately, this method suffers from response delay, which affects the synchronization accuracy. More importantly, such a method can only detect but not identify signals, so it does not work for continuous LTE signals.

To address the above issues, we present LTElike, the first LTE backscatter system that can page tags and accurately synchronize with LTE signals. As shown in Figure 1, compared to standard LTE reception, our tag can achieve paging reception and synchronization similar to LTE UE. Such a design is not only compatible with LTE, no customized devices required, but also has the ability to initiate service requests. However, realizing this system faces two main challenges:

1) *How to page tags in an ultra-low-power way?* Generally, the power consumption of a standard LTE UE is quite high in the whole process from receiving to decoding paging signals. It is extremely difficult to perform such a process on the tag, because the tag does not have power-hungry components to acquire and decode high-bandwidth signals. Further, this undoubtedly exacerbates the problem for tags with limited resources. Our solution is to forward the paging information in the form of AM (Amplitude Modulation), and the tag decodes AM signals to obtain the paging information.
2) *How to accurately synchronize LTE downlink signals?* The standard UE uses the cross-correlation algorithm to detect PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal) for downlink synchronization, while the ultra-low-power tag cannot afford the multiplication-based cross-correlation algorithm. The majority of state-of-the-art backscatter systems treat energy detection as synchronization of the start of the packet, which suffers from response delays and cannot be used for continuous LTE signals. To address this, we propose a synchronization strategy combining detection and correlation-based template matching to synchronize LTE signals.

To verify the performance of our system, the evaluation results are as follows. The paging identification rate is as high as 100%, and the packet error rate (PER) of paging messages is as low as 2‰. The mean synchronization error of LTElike is 17x better than that of LScatter. Moreover, the wake-up rate reaches 95%.

II. LTE Primer

LTE is a fourth-generation (4G) wireless standard that provides increased network capacity and speed for cellular devices such as cell phones. LTE is designed to reduce latency and increase bandwidth, which makes perfect sense for the Internet of Things. Moreover, LTE delivers a variety of data services, including mobile high-definition multimedia, real-time mobile video surveillance, and more.

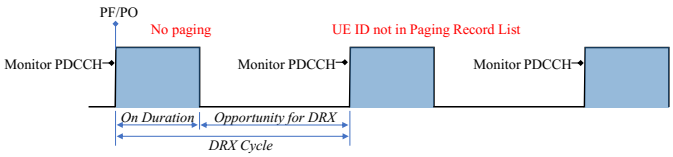


Fig. 2. Paging reception process.

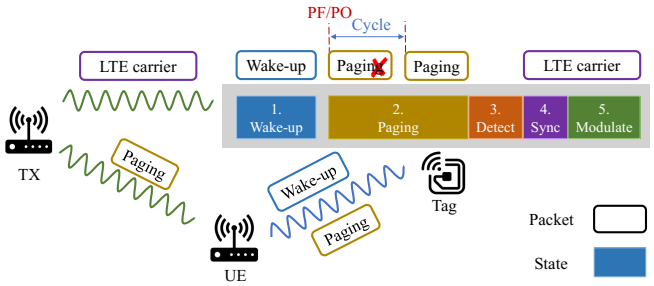
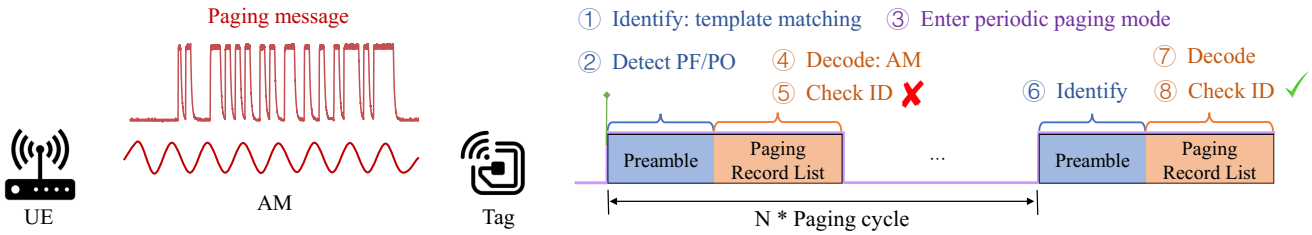


Fig. 3. Overview of system design.

The duration for one FDD ((Frequency Division Duplexing)) LTE frame is 10 ms, which consists of 10 consecutive subframes. Each subframe is divided into two slots of 0.5 ms duration, and one slot contains 7 symbols. The transmitted LTE frames are seamless. Consequently, LTE frames are transmitted continuously in the time domain. The LTE frame contains two synchronization signals, PSS and SSS, which are used to obtain cell identity and downlink timing synchronization. PSS is based on frequency domain Zadoff-Chu sequences and SSS is based on maximum length sequences (m-sequences). Two synchronization signals are mapped to 72 active subcarriers, centered around the DC subcarrier in slot 0 and slot 10.

To prevent the UE from continuously monitoring the network even when there is no traffic, LTE introduces a discontinuous reception (DRX) scheme to save energy. A typical DRX cycle includes On Duration, which is in the active state, and Opportunity for DRX, which is in the sleep state. According to the UE state, DRX is divided into idle mode DRX, also known as paging and connected mode DRX (CDRX). Since this paper is only related to paging, only paging is discussed here. The process of paging reception is shown in Figure 2. First, the UE determines the paging time, which is identified by the paging frame (PF) and paging occasion (PO). PF indicates the system frame number where the paging message should appear, and PO indicates subframes where there may be P-RNTI (Paging Radio Network Temporary Identifier) transmitted on PDCCH with paging. Second, in each paging cycle, the UE wakes up at the paging moment and monitors the PDCCH (Physical Downlink Control Channel) to check for the presence of paging messages. Finally, if the PDCCH indicates that a paging message is transmitted in the subframe, the UE reads each PagingRecord in the pagingRecordList to confirm whether its UE identity matches a certain ue-identity.



(a) Paging transmission. (b) Paging reception.

Fig. 4. Paging transmission and receiving process. (a) The transmitter leverages the UE to send the paging message in the AM mode, enabling ultra-low-power tag to decode the paging signal. (b) The tag first identifies the paging message to detect PF and Po, and then enters the periodic paging mode. Next, the tag decodes the paging record list until it finds its ID in the paging record list.

III. LTELike Design

A. Overview

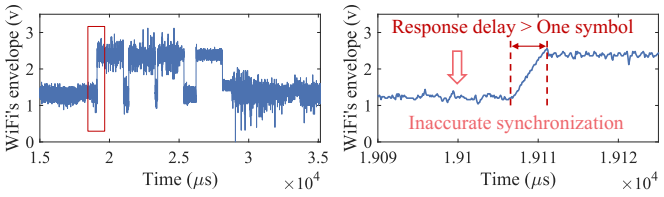
Figure 3 shows the overview of our system. Once the tag receives the wake-up packet, it indicates that the paging message is coming. To enable the ultra-low-power tag to decode the paging message, the LTE base station leverages the UE to forward the paging record list, and our tag identifies and decodes the paging signal. First, the tag determines PF and PO by identifying paging, then decodes the paging record list, and decides whether to leave or maintain the periodic paging mode according to the existence of the tag paging identity in the paging record list. After confirming that the paging information is indeed directed to the tag, the tag must detect and accurately synchronize with the carrier LTE traffic in order to modulate its data.

B. Paging

LTE paging can be used for RRC (Radio Resource Control) connection establishment and service request initiation. Although the standard paging mechanism is comprehensive, the entire receiving process, whether acquiring high-bandwidth signals or decoding, requires quite high power consumption. However, this is challenging for ultra-low-power tags. On the one hand, tags have no energy-intensive components to enable fine-grained reception of paging messages. On the other hand, the resources of tags are so limited that they cannot carry complex computations. So how to make the tag get paging messages?

To address this issue, we move standard paging processing from low-power backscatter devices to external edge computing centers. LTE UEs can just fill such a role, handling the complex paging reception and decoding. Therefore, we choose to utilize UE to solve this problem. However, it is not enough for the UE to decode the paging. It is the key that the tag receives the paging message. To this end, we add the function of forwarding the paging message to the UE so that the tag can obtain the paging message. To make the tag decode in an ultra-low-power way, the decoding calculations must be simple, which usually requires the modulated signal to have distinct envelope characteristics to distinguish the modulated data, such as amplitude and packet length. In this way, we can only rely on the envelope to demodulate signals to meet the requirements of ultra-low power consumption. Therefore, we can modulate the forwarded paging signal with AM or PLM (Packet Length Modulation) method. However, the length of one symbol using PLM mode is longer than using AM mode, which increases the decoding time of the tag, makes it impossible to complete decoding within a paging cycle, and increases the delay. Therefore, choosing AM modulation method to transmit paging signals is more in line with our needs. Figure 4a shows the transmission process of paging. The transmitter leverages the UE to send the paging message in the form of amplitude modulation, enabling the ultra-low-power tag to decode the signal.

Relative to paging transmission, we are more concerned about how ultra-low-power tags receive paging signals. The receiving process of paging is shown in Figure 4b. For standard paging in LTE, UE first needs downlink synchronization and acquisition of the system frame number (SFN) to locate the exact subframe (PO) and frame (PF). Similarly, tag also must determine the paging frame and paging occasion. Although the tag can realize downlink synchronization by detecting synchronization signals, and locate the position of the subframe, the key issue is how the tag obtains the SFN to locate paging frame. The standard practice is to obtain the SFN by decoding the MIB (Master Information Block), but the ultra-low-power tag cannot afford such a process. In order to locate the PF and PO, we do not use the standard method, instead, our solution is to take the start moment of the identified paging signal as the PF/PO. Such a solution needs to identify the paging signal. For this reason, the UE adds a predefined preamble to the paging packet header. The tag uses the idea of correlation-based template matching to identify the paging signal by matching the preamble, and the length of the preamble is fixed. Consequently, the paging moment can be determined by subtracting the length of the preamble from the end of the identification. After determining the paging moment, the tag starts to enter the periodic paging mode to save power. Second, the tag gets the paging message. Standard paging decoding is to decode PDSCH (Physical Downlink Shared Channel) data containing paging messages. The decoding process includes operations such as FFT, demodulation, and descrambling, which is not only complicated, but also difficult to achieve for tags with limited resources. In order to solve this problem,



(a) Envelope of WiFi signal (b) Response delay

Fig. 5. The effect of response delay. (b) is the enlargement of the part framed by (a), it can be seen that there is a response delay using the rising edge detection, and the duration of response delay is about 4.5 µs, which is longer than the duration of one WiFi symbol, resulting in inaccurate synchronization.

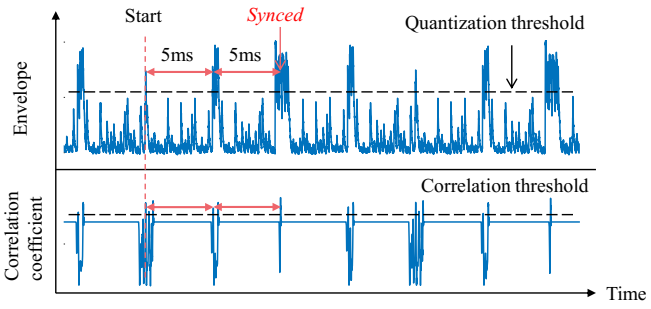


Fig. 6. LTElike's synchronization. Our synchronization method combines detection and correlation, which has the ability to distinguish signals, and utilizes the periodicity of LTE signals to detect synchronization signals three times in a row, improving synchronization accuracy.

our tag demodulates the paging signal modulated using AM mode, which not only ensures the accuracy of decoding but also meets the requirements of low power consumption. The tag decodes the paging message and obtains the paging record list. Then, the tag starts to check whether its identity matches an item in the paging record list. If a match is found, it indicates that the paging message is sent to itself. As a result, the tag will leave the periodic paging mode and perform the next operation, otherwise, it will stay in the paging mode.

C. Synchronization

The tag has to determine the starting position of modulation before modulating its own data, which requires the tag to synchronize with the carrier. Unfortunately, existing LTE backscatter systems suffer from inaccurate synchronization, and achieving accurate synchronization has several challenges. First, the downlink synchronization in the LTE standard relies on the detection of synchronization signals PSS and SSS to achieve timing synchronization, which involves cross-correlation algorithms. While standard synchronization achieves high accuracy, multiplication-based cross-correlation operations are unaffordable for resource-constrained tags. Therefore, standard downlink synchronization cannot be applied to backscatter communications. Second, most state-of-the-art backscatter systems rely on energy detection to determine the start of a packet, such as SyncScatter [8]. Signal detection is used to detect the arrival of a packet, which is different from synchronization. The main difference is that the detection only uses energy level, and does not utilize the feature of the preamble in the packet, so the signal cannot be identified. Therefore, the scope of application of signal detection is limited, and it cannot be used for signals with interference from other signals or continuous signals. More importantly, the detection is affected by the response delay, which is related to the discharge speed of the capacitor in the detection circuit. As shown in Figure 5, for WiFi signals, tags determine the start of a packet using rising edge detection, which has a response delay. We observe such a delay to be approximately 4.5 µs, over the duration of one WiFi symbol (4 µs), so the response delay affects the synchronization of WiFi signals.

To address the above challenges, we propose a synchronization scheme combining detection and correlation, which utilizes the idea of detecting PSS and SSS in standard downlink synchronization. Instead of directly using the cross-correlation operation based on multiplication, the template matching draws on the matching method of Multiscatter [9], and converts the multiplication into an addition through quantization, which reduces the resource consumption of the FPGA.

In order to reduce the loss of synchronization accuracy caused by the low sampling rate and further improve the synchronization accuracy, as shown in Figure 6, we leverage the periodicity of the LTE synchronization signal to continuously detect PSS and SSS. This is because LTE synchronization signals PSS and SSS appear every 5 milliseconds, and detecting synchronization signals only once will introduce misjudgment. Therefore, successive multiple detections extend the length of the template and naturally improve the synchronization accuracy. Compared to only detecting rising edges, such as LScatter [7], our synchronization method gets rid of the effect of response delay and has the ability to identify the signal, enabling to distinguish between the synchronization signal and other signals in continuous LTE signals. And our method utilizes the periodicity of the LTE signal to continuously detect the synchronization signal. Therefore, our method has stronger anti-interference and higher synchronization accuracy. In addition, such a synchronization method combining detection and correlation is not only suitable for continuous LTE signals, but also for burst WiFi, Bluetooth and other signals. Thus, this method has a wide range of applications. Furthermore, the selection of γ [1] in such a method has an impact on the synchronization effect. Generally, the longer the template, the higher the synchronization accuracy. The setting of template length is discussed in Section V.

D. Wake-up

The purpose of wakeup is to indicate that the paging signal is coming. Likewise, in order for the tag to decode wake-up packets in a low-power manner, we need to decode packets using metrics that can be easily measured by passive detectors,

[1] γ is defined as template length in this paper.

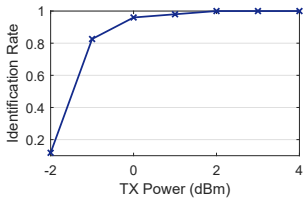


Fig. 7. Paging identification rate.

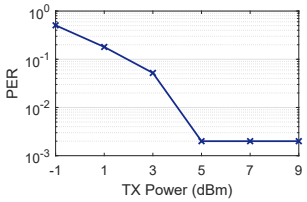


Fig. 8. Packet error rate of paging messages.

such as packet length and amplitude. However, the signal strength decays with distance, which reduces the signal-to-noise ratio, thus AM does not work well over long distances or in the presence of ambient traffic. Since the packet length does not degrade due to distance, the packet length modulation is more robust than the amplitude modulation in a low SNR environment. So using the PLM method to wake up the tag is a better choice.

In this method, we use packets with durations L0 and L1 to represent bit 0 and bit 1, respectively, and the transmitter sends packets with predefined durations to control the packet length. So what is the wake-up transceiver mechanism? First, the transmitter sends packets of L1 and L0 durations in succession to construct the wake-up pattern. Then, the tag uses the passive detector to obtain the envelope, and then measures the duration of the high level through the voltage comparator to evaluate the duration of the packet. If the packet length is L0, it is decoded as bit 0, otherwise, it is decoded as bit 1.

IV. Implementation

We build a prototype of LTElike tag using FPGA and USRPs. The implementation is as follows. Our tag prototype includes a passive detector, comparator and FPGA. The passive detector is a high bandwidth rectifier, and TLV3501 comparator is used to build a threshold tuning circuit. Paging reception and signal synchronization are implemented on a ZYNQ XC7Z010 FPGA. For the core logic of the tag, the total resource consumption is 12,746 Look-Up-Tables (LUTs), of which 36, 304 and 9,555 LUTs are consumed for wakeup, paging and synchronization. The tag prototype is used for functional verification, and we will further optimize the resources in future work.

We run open-source LTE stack library OpenAirInterface [10] and srsLTE [11] as eNodeB and UE using USRP B210. We use two Dell E6440 laptops to run EPC (Evolved Packet Core), eNodeB and UE with two USRPs B210, where EPC and eNodeB run on the same laptop and UE runs on another laptop.

Our experimental setup is as follows. For wakeup, we set the sampling rate of the transmitter and tag to 20 MHz and 1 MHz respectively, and the L0 and L1 in the PLM package are set to 150 µs and 350 µs, respectively. For paging, the transmission sampling rate is set to 20 MHz, and the duration of one symbol in the paging packet is 10 μs. The receive sample rate of our tag is set to 1 MHz.

V. Evaluation

In this section, we test our system's performance in paging, synchronization, and wake-up.

A. Paging Reception

1) *Paging identification rate*. As shown in Figure 7, we evaluate the paging identification rate at different transmit powers, and we observe that with the gradual increase of the transmit power, the paging identification rate first increases rapidly and then increases slowly. The maximum paging identification rate is 100%. When the transmit power was lower than -1 dBm, the identification rate was extremely low, close to 0. The reason is that due to the low received signal strength, the signal-to-noise ratio is low, resulting in data distortion.
2) *PER of paging messages*. We also evaluate the PER of paging messages under different transmit powers. As shown in Figure 8, we observe that with the gradual increase of transmit power, the PER of paging messages gradually decreases until the change is insignificant. When the transmit power is not higher than -1 dBm, the PER is up to 50%, which is much higher than the error rate of paging identification. Moreover, when the transmit power reaches 5 dBm, the PER is 0.2%, which is as low enough to meet our needs for paging signal reception.

B. Signal Synchronization

1) *Synchronization accuracy*. We evaluate the synchronization accuracy at different received signal strengths by measuring the synchronization error, which is the time difference between the synchronization signal detected by the tag and the synchronization signal in the LTE envelope. Figure 9 shows that no matter what the RSRP, the mean synchronization error of LTElike is much lower than that of LScatter and 17x better than that of LScatter. We observe that the mean minimum synchronization error of LTElike is 15 µs, and the synchronization effect is excellent when the RSRP is higher than -105 dBm. When the RSRP is -105 dBm, the synchronization errors of both LTElike and LScatter become larger, because the poor SNR makes the tag unable to extract the envelope.
2) *Impact of template length*. Additionally, we evaluate the effect of template length (γ) on synchronization. Figure 10 shows that the synchronization error is much larger for a template length of 100 μs (only one detection) than for a template length of 300 and 600 μs (3 and 6 consecutive detections). We observe that the 50th percentile of synchronization error for γ = 600 μs is 10 μs, which is 8x better than that for γ = 100 μs. For the 80th percentiles of synchronization errors, γ = 600 μs is 7x better than γ = 100 μs. Further, γ = 300 μs and γ = 600 μs have little difference in synchronization error, thus, we set γ = 300 μs in our experiments.

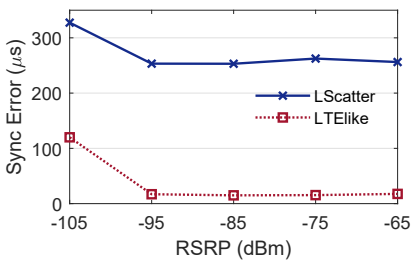


Fig. 9. Synchronization accuracy.

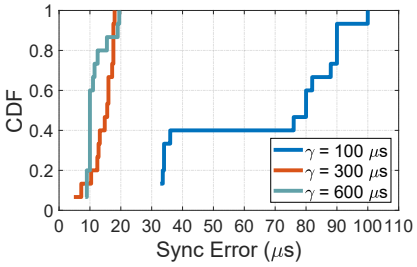


Fig. 10. Impact of tempalte length.

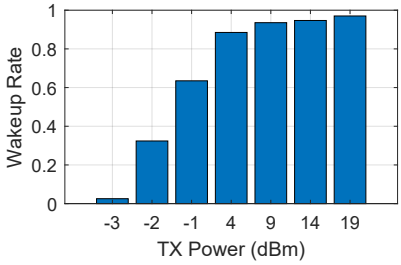


Fig. 11. Wakeup rate.

C. Wakeup Reception

Finally, we evaluate the wake-up rate at different transmit powers. As shown in Figure 11, with the continuous increase of the transmit power, the wake-up rate first increases rapidly, and then increases slowly. We observe that the wake-up rate increases almost linearly when the transmit power does not exceed 4 dBm, this is due to the transition from poor SNR to better SNR in the process. When the transmit power is higher than 4 dBm, the wake-up rate does not change significantly, because when the transmit power is 4 dBm, the signal-to-noise ratio can already meet the wake-up requirement.

VI. Related Work

In the past decade, backscatter has attracted much attention due to its advantages of low power and low cost. Ambient backscatter [1] first proposes to use the TV signal as the excitation source, which opens the door for backscatter systems using the ambient signal as the carrier. Synchronization plays a very important role in backscatter communication, and many backscatter systems have studied synchronization. Hitchhike [12] and LScatter [7] synchronize the carrier signal based on rising edge detection. This method is affected by the response delay, and the synchronization effect is poor. Especially in the presence of interference, the method will fail. Although SyncScatter [8] uses a high-bandwidth detector to reduce the response delay, because it does not eliminate but alleviate the impact of the response delay, the synchronization of SyncScatter [8] still does not fundamentally solve the problem. PLoRa [13] and Multiscatter [9] use correlation to eliminate the effect of response delay, improve synchronization accuracy compared to rising edge detection, and have the ability to identify signals. Synchronization based on this method is applicable even in the presence of interference.

VII. Discussion

With the deployment of 5G network, it can provide higher speed, lower latency and larger capacity than LTE network, and support VR and autonomous driving applications. Based on beam sweeping, the next generation node base station (gNB) periodically transmits SS bursts carrying multiple SSBs (Synchronization Signal and PBCH blocks). A possible solution is that tags use template matching to synchronize with 5G signals according to the fixed distribution of SSBs in SS bursts. For paging, the NR (New Radio) and LTE mechanisms are similar, therefore, we believe our paging approach can be extended to 5G backscatter. For multiple access, each paging message contains up to 16 LTE UE identities, which enables our system to have 16 paging capacity and can page multiple tags simultaneously.

VIII. Conclusion

In the paper, we present LTElike, a novel backscatter system that can page tags and achieve single-symbol synchronization accuracy. The main contributions are to page the tag in an ultra-low-power way and design a synchronization scheme that combines detection and correlation. We have built a prototype of the tag and conducted experiments to verify the performance of our system. LTElike is expected to provide opportunities for backscatter tags to access LTE services and wireless connectivity.

IX. Acknowledgement

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