Achieving Universal Low-Power Wide-Area Networks on Existing Wireless Devices

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Abstract*—Low-Power Wide-Area Network (LPWAN) is an emerging platform for Internet-of-Thing (IoT) devices to access the base station far away. However, two of the most popular IoT techniques, Bluetooth and ZigBee, can not be connected to LPWAN directly due to their very short communication distance (e.g., 30 meters). Our work, named as Symphony, implements an universal LPWAN on existing heterogeneous wireless devices by overcoming two challenges. First, Symphony achieves a long-range communication from both Bluetooth Low Energy (BLE) and ZigBee to LoRaWAN, enabling these ubiquitously deployed low-power devices to access a base station from faraway. It is achieved by exploiting *Narrow-Band Communication*, where the BLE/ZigBee devices generate ultra narrow-band signals (i.e., single-tone sinusoidal signals) through payload manipulation, while the LoRaWAN base station detects these signals via its demodulator, which has a high receiver sensitivity for long range communication. Second, Symphony enables concurrent transmissions from heterogeneous radios (i.e., BLE, ZigBee and LoRa) at a LoRaWAN base station. This is achieved by *Cross-Technology Parallel Decoding*, which is able to disentangle and decode the interfering transmissions. Our evaluations on USRP and commodity devices reveal that Symphony achieves a concurrent wireless communication from BLE, ZigBee and LoRa commercial chips to a LoRaWAN base station over 500 meters, 16× range extension over native BLE/ZigBee.

I. Introduction

Low-Power Wide-Area Network (LPWAN) enables low-power devices (e.g., milliwatts) to transmit at low data rates (e.g., kilobits per second) over long distances (e.g., kilometers). Long range connectivity is valuable for low-power (low-cost) IoT sensors, for they can report data to the cloud via a single-hop wireless link in a very easy way. Thus, LPWAN emerges as a promising platform for numerous IoT applications [1], [2], [3]. Several LPWAN protocols have emerged in the past few years, including those for the unlicensed band (LoRaWAN [4], SigFox [5]), and for the licensed band (LTE-M [6], NB-IoT [7]).

However, compared to the fast developing LPWAN, today's widely-used Wireless Personal Area Network (WPAN) technologies, including Bluetooth, ZigBee, etc., only provide a very short communication distance, e.g., tens of meters [8]. Therefore, if long distance connectivity is required for these low-power WPAN devices, multi-hop transmissions or multi-radio gateways are needed, which will either increase energy consumption and delay, or introduce hardware complexity and deployment cost.

It will be an appealing option to enable a wide-area connection ability to WPAN (e.g., Bluetooth, ZigBee) devices. For example, an old man with heart disease can send a urgent message calling for emergency treat via his BLE smartwatch [2] when he is traveling a long way outside from home (Figure 1). Also, a ZigBee sensor node deployed in a forest (e.g., [9]) for fire alarm can upload its critical sensed data directly to a remote base station instead of via conventional multihop networks and gateways (Figure 1). Moreover, a sensor node that lost its connectivity with its native network or detected exceptions can report its abnormal states to a far away base station for timely maintenance. More broadly, if tremendous existing wireless devices (e.g., 4 billion Bluetooth devices) could be extended to access the network via a long range link (e.g., kilometers), it will bring benefits for many IoT applications such as smart cities, intelligent agriculture, and health monitoring, etc, especially when transmitting urgent/critical messages.

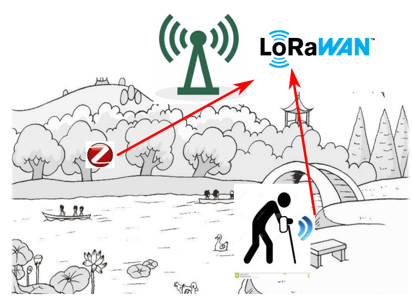

Fig. 1. Typical Scenario of Universal LPWAN

This vision can be possibly achieved through the newly emerged technology called cross-technology communication (CTC) [10], which enables devices of totally different technologies (e.g., WiFi, ZigBee) to communicate with each other directly. However, the existing CTC techniques such as signal emulation [10] and cross-decoding [11] are not suitable for this long range CTC scenarios, due to huge technical gaps between WPAN and LPWAN techniques.

To overcome this challenge, we leverage the narrow-band communication techniques in this CTC scenario, that is, BLE/ZigBee devices generate specific patterned signals (i.e., single-tone sine waves), which can be detected and demodulated by the Fast Fourier Transform (FFT) based demodulation

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scheme at the LoRa base station with a very high sensitivity. Using this CTC technique, the data packets sent by commercial BLE (or ZigBee) devices could be demodulated by highly sensitive LoRaWAN base stations, enabling a long range communication from BLE (or ZigBee) to LoRa. We note that with this technique, the increase of communication distance is at the expense of decreased data rate, which however, is acceptable since the increased transmission delay and overhead are much smaller than the delay and overhead introduced by relay nodes or gateways. Compared to other techniques such as adding FEC or using more sparse constellation points in modulation, this technique does not require any hardware or firmware modifications on the commodity devices, and is much more efficient and effective in extending communication range since it leverages the high receiver sensitivity at LoRa base station.

Another challenge of our system is the coexistence issue of these three techniques. On one hand, given the long communication range of heterogeneous radios, the chances of packet collision at the base station are increased. On the other hand, due to the incompatibility of heterogeneous technologies and the low-cost IoT devices, it is very challenging, even impossible, to implement sophisticated coordination and scheduling schemes (e.g., MAC protocol) for collision avoidance [3]. Therefore, to reduce collisions from heterogeneous radios, we aims to providing parallel communications from different technologies, which means concurrent transmissions from ZigBee, BLE, and LoRa can be all successfully decoded in parallel at the base station even if they are collided in the air. This technique not only improves the throughput of the whole system, but also greatly reduces the impact of other techniques to the existing LoRa communications.

In this paper, we take the first step towards this universal LPWAN*. Specifically, we propose Symphony, a novel LPWAN system implemented on existing wireless infrastructure including LoRa base station, commodity BLE, ZigBee and LoRa low-end devices. Symphony not only achieves a long range communications from low-power devices including BLE and ZigBee, but also enables concurrent communications from these heterogeneous devices even they are collided at base station. At the heart of our approach are two techniques: (i) Narrow-Band Communication, which enables WPAN transmitters (i.e., BLE, ZigBee) to generate some specific PHY signals being demodulated by a very high sensitive receiver (i.e., -134dBm), and (ii) Cross-technology Parallel Decoding, which means different type of wireless signals can be disentangled and decoded using an unified demodulation framework. Especially, BLE, ZigBee and Lora signals are disentangled by recognizing their respective peaks among FFT bins.

With such a universal LPWAN, several benefits can be enjoyed: (i) We can reduce the transmission delay and achieve a higher end-to-end reliability without relay nodes when a low-power WPAN device report its data to a far away base station. (ii) We can accelerate the application of LPWAN by reusing the already deployed BLE devices and ZigBee devices, saving the deployment cost of many LoRa nodes. (iii) We can reduce cross-technology interference through parallel decoding where low-power devices with diversified technologies communicate to a base station without coordination or scheduling.

The major contributions of Symphony are as follows:

- We design Symphony, the first framework towards universal LPWAN where WPAN devices (i.e., BLE, ZigBee) can connect to a LoRaWAN base station over a long range, and communicate to it simultaneously without interfering each other. With only one-hop, the existing BLE, ZigBee devices can upload their data to a far away base station quickly and reliably.
- In design of Symphony, we address three key challenges, namely (i) the long range communication from commodity BLE to LoRa, (ii) the long range communication from commodity ZigBee to LoRa, (iii) the parallel decoding for concurrent BLE, ZigBee and LoRa transmissions. These techniques may provide general guidance for future designs of more ubiquitous LPWAN technologies.
- We implement and evaluate Symphony on USRP-B210 (with LoRaWAN PHY), and commodity BLE chips (CC2540, CC2500), commodity ZigBee chips (AT86RF233) and commodity LoRa chips (Semtech SX1280). Our extensive evaluations demonstrate that Symphony can reliably transmit a frame from a BLE (ZigBee) sender to a LoRaWAN receiver with more than 500 meters, dramatically outperforming the native BLE (ZigBee) communication (30 meters) by about 16×. Moreover, Symphony achieves an universal communication system where BLE, ZigBee, LoRa sensors can communicate to a base station over a long distance simultaneously even under collision.

II. Symphony In a Nutshell

Fig. 2 illustrates the diagram of Symphony: (i) A BLE device transmits a BLE frame with *selected payload*, at the same time a ZigBee device also transmits a ZigBee frame with selected payload, and a LoRa client sends a normal LoRa frame. (ii) With selected frame payload, the BLE device generates specific signals (i.e., single-tone sine-waves) modulated by Gaussian Frequency Shift Keying (GFSK), the ZigBee device also generates specific signal (i.e., single-tone sine-waves) modulated by Offset Quadrature Phase-Shift Keying (OQPSK) and the LoRa device generates its normal signal modulated by Chirp Spread Spectrum (CSS). Those signals are all collided at the LoRa (or Symphony) base station. (iii) At the base station, the samples of the received signal are split into segments, and each segment is multiplied with a given template (for correlation) and then performing FFT, which will lead to three peaks (if ideally synchronized) in frequency domain. One corresponds to BLE, the second to ZigBee and the third to LoRa. (iv) According to these separable peaks, the base station can recognize and track the bit streams of BLE,

*To further improve the system, there are still many works to do. We will discuss some practical issues in Sec. VI, which will enlighten our future work.

ZigBee and LoRa respectively. (v) Finally, the base station decodes the streams and reassemble them into BLE, ZigBee and LoRa frames in parallel.

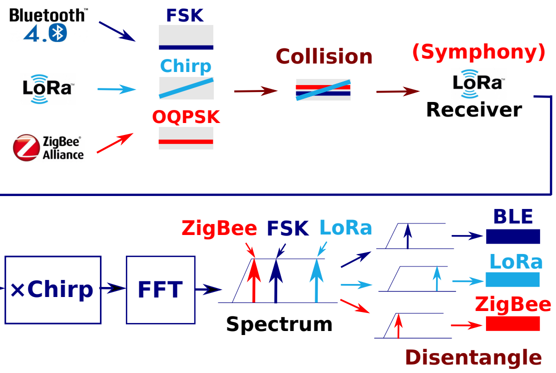


Fig. 2. Overview of Symphony

The key design of Symphony for long range communication is based on two observations: (i) the modulation schemes of BLE (GFSK) and ZigBee (OQPSK) can both generate some specific signals (i.e., continuous single-tone sinusoidal waves) by manipulating their frame payload; (ii) the FFT based demodulation at the LoRa receiver can be used to detect and demodulate the specific signals from BLE and ZigBee the same way as demodulating LoRa chirp signals. As we know, LoRa receiver can detect very weak LoRa (chirp) signals out of strong noises due to its high sensitivity. Therefore, using the same demodulator, LoRa base station can also detect and demodulate specific BLE/ZigBee signals even they are very weak over a long distance.

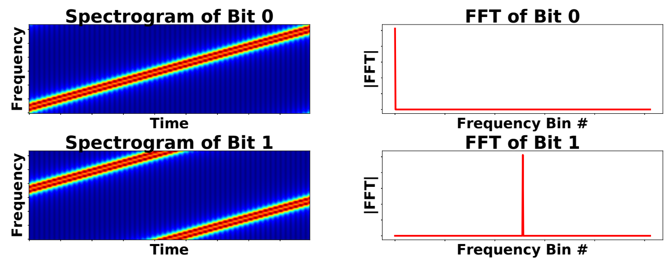
To be more specific, the frequency of a LoRa symbol (i.e., a chirp) varies linearly over time, indicating an ascending (or descending) line in spectrogram illustrated in Fig. 2. Meanwhile, the BLE signals can be manipulated to keep a fixed frequency in the same duration of a LoRa symbol if we carefully choose the payload bits, indicating a horizontal line in spectrogram illustrated as Fig. 2. Also, the frequency of ZigBee signals can be set constant by selecting ZigBee payload, the same way as BLE (Fig. 2) but with a different frequency.

At the LoRa base station, the received signal is multiplied by a specific signal (normally called as a correlation template), and then performed the FFT. Among the FFT bins, some peaks in the spectrum can be obtained. Note that the specific BLE signal corresponds to one peak in frequency domain if using a constant template, and the LoRa signal corresponds to another peak using a down-chirp template. Therefore, using a combined template, Symphony can obtain two peaks in frequency domain for the signals collided from BLE and LoRa. After disentangling these two peaks and tracking them, Symphony separates the collided signals into the BLE streams and the LoRa streams, and then decodes them individually.

For ZigBee, the OQPSK modulation also has the capability of producing the signals whose spectrum is a horizontal line in spectrogram (Fig. 2). Similar to the BLE signal, this specific ZigBee signal generates another peak in frequency domain at the LoRa receiver. Moreover, the locations of BLE peak and ZigBee peak are different because the frequencies of BLE signals and ZigBee signals are different, making it easy to disentangle the peaks coming from these heterogenous signals.

III. Wide-Area Connectivity for BLE

A. Primer of CSS (de)modulation



(a) Modulation (b) Demodulation

Fig. 3. Modulation and Demodulation of CSS

The LoRa physical layer modulates the information in the form of chirp pulses, where chirp is a kind of signal whose frequency varies linearly in time over the available bandwidth. Fig 3a shows the spectrograms of two chirps corresponding to bit '0' and bit '1'. The observation utilized by CSS demodulation is that the up-chirps with different initial frequencies will lead to the cross-correlation peaks at different locations, illustrated as Fig. 3b. In signal processing, the cross-correlation of the two signals is the sliding inner-product of one signal and the complex conjugate of another signal, and the multiplication in the time domain is the convolution in the frequency domain. Thus, the LoRa receiver demodulates the received chirps by first multiplying them with the down-chirp in the time domain and then performing an FFT. Due to conjugation with each other, the down-chirp and the up-chirp have a very strong correlation, so the operation of above FFT results in a peak at an FFT frequency bin. Therefore, the demodulation process of LoRa is depicted mathematically as:

$$\begin{aligned} D_L(t) &= L(t). \times Chirp_{Down}(t) \\ LoRaSymbol &= Loc(Peak(FFT(D_L(t)))). \end{aligned} \quad (1)$$

where $L(t)$ is the received LoRa signals, $D_L(t)$ is the multiplication results of $L(t)$ with another 'template' signal, and $Peak(v)$ is to get the peak in a vector v.

The demodulation result of the chirp signal corresponding to bit '0' results in a peak at the 0^{th} bin, while the peak for the bit '1' is located at the middle of FFT bins, illustrated as Fig. 3b. Thus, CSS demodulation, in a nutshell, localizes the peak on the result of FFT.

B. Specific BLE Waveforms for Symphony

To explain how Symphony works, first we show how a BLE transmitter produces a narrow-band time-domain waveforms (i.e., single tone sine-waves). With GFSK modulation, the data bits in a BLE frame are modulated into the physical signals as following:

$$I(t) = cos(\phi(t)), Q(t) = sin(\phi(t)) \quad (2)$$

$$\phi(t) = \pi h \int_0^t \sum_{i=0}^{\infty} d_i g(\tau - iT_b) d\tau,$$

where $I(t)$ and $Q(t)$ are the in-phase and quadrature branches of the BLE time domain signals. The d_i denotes the i_{th} data bit, T_b represents the duration of a BLE symbol, and g is the Gaussian function for pulse shaping. The modulation index, h, which controls the shape of the modulated signals, is 0.5 in BLE.

Using GFSK modulation, a BLE device is able to generate some specific time domain waveforms if the data bits fed into the modulator are chosen elaborately. For example, if the data bits of a BLE frame are all 1, the phase of the signal $\phi(t)$ will be $\pi ht/T_b$, then the time domain signal transmitted from the BLE modulator is given by $I(t) = cos(\frac{\pi}{2T_b}t), Q(t) = sin(\frac{\pi}{2T_b}t)$, i.e., a sine wave with single tone. Therefore, when a bit stream with all 1 is generated, a sine wave with a frequency shift as $\frac{\pi}{2T_b}$ (i.e., the right tone in Fig. 4) is produced. The same way, while for a bit stream with all 0, a sine wave with a frequency shift as $-\frac{\pi}{2T_b}$ (i.e., the left tone in Fig. 4) is produced. These signals are further shown in Fig. 5a, as horizontal lines in spectrogram.

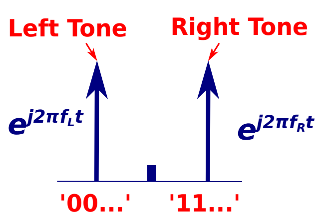


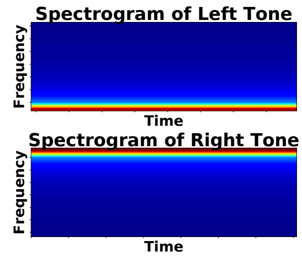
Fig. 4. Specific BLE Waveforms Utilized in Symphony

C. Demodulation of BLE Signals at LoRa Receiver

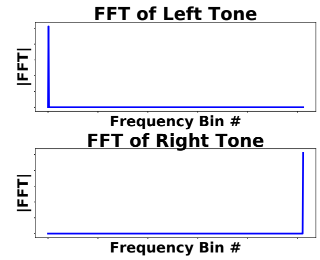
At the LoRa base station, the demodulation of a chirp is to correlate it with a given template (i.e., its conjugate signal). In the same way, the specific BLE waveform can also be demodulated at the LoRa base station, only with another correlation template. More specifically, as the spectrogram of BLE single-tone signal is a horizontal line (Fig. 5a), it can be recognized by multiplying a given template which is also a horizontal line in the spectrogram. For convenience, we choose the template as a constant signal, i.e., $\mathbb{1}(t)$, with which the multiplied result is still the input signal itself. Since the FFT result of a single-tone sine wave is a peak in frequency domain, the demodulation result of the specific BLE signals is given by:

$$\begin{aligned} D_B(t) &= B(t). \times \mathbb{1}(t) \\ BLESymbol &= Loc(Peak(FFT(D_B(t)))). \end{aligned} \quad (3)$$

where $B(t)$ is the received BLE signals. Fig. 5b illustrates the result of demodulation. We can see that one peak (left peak or right peak) is obtained by the LoRa demodulation with a template of $\mathbb{1}(t)$. And we can utilize the location of the peak (left or right) to decode the information sent from the BLE devices.



(a) Spectrogram of BLE Single-Tone Signal



(b) Chirp Demodulation with Template of $\mathbb{1}$

Fig. 5. Chirp Demodulation for BLE Special Signals

D. Configurations of BLE signals

For long range CTC, the BLE signal has to be demodulated by the LoRa base station. Therefore, the demodulation of BLE signals has to be totally compatible to the existing demodulation schemes. As we know, LoRa operates at configurable data rates by using different spreading factors, i.e., from 6 to 12. Considering a larger spreading factor leads to a longer communication range but a lowered data rate, we choose the spreading factor as 8 in Symphony to keep a good balance between communication range and speed. Moreover, the bandwidth (BW), within which the frequency of the baseline chirp increases linearly, is another physical layer parameter that determines the data rate of LoRa. Specifically, LoRa can operate with many bandwidth options, e.g., 200 kHz, 400 kHz, 800 kHz and 1600 kHz supported by SX1280 [12]. Notice that the frequency deviation of GFSK in BLE is $\pm$250 KHz, the overall bandwidth of BLE is 500 kHz. To accommodate both BLE and ZigBee band, we choose the chirp modulation with the bandwidth of 1600 kHz in Symphony. As defined in LoRa, a chirp with a spreading factor of SF has 2^{SF} samples, and the sampling rate is equal to its bandwidth. Therefore, if the above two fundamental parameters, i.e., SF = 8 and BW = 1600 kHz, is adopted in Symphony, the duration of a BLE single-tone sine-wave (denoted here as a BLE CTC symbol) is given by:

$$T_{symbol} = \frac{2^{SF}}{BW} = \frac{256}{1.6MHz} = 160\mu s \quad (4)$$

From the above equation we can see, to generate a continuous single-tone sine-wave, 160 BLE bits has to be used, as the BLE bit rate is 1 Mbps and the duration of a BLE bit is $1\mu s$. In other word, 160 consecutive BLE bits of '0's are used to produce the left tone signal which can be demodulated as symbol '0' at LoRa receiver, and 160 consecutive '1' bits are used to generate the right tone signal to represent symbol '1'. With this configuration, the data rate from BLE to LoRa is given by 6.25Kbps (=1000Kbps/160), which is a typical data rate for LPWANs.

E. Construction of BLE Payload

Specifically, to generate the desired signal, two steps are needed at the BLE side. The first step is payload encoding. As mentioned above, a symphony bit '1' is encoded as 160

BLE bits '1'. The second step is scrambling. As we know, in BLE, the payload bits has to be data whitened, i.e., XORed by a given pseudo-random noise (PN) sequence, before fed into the modulator [13]. The PN sequence is generated by a linear-feedback shift register (LFSR) and initiated by a scrambler seed which is set as the channel number (i.e., from 0 to 39). At the BLE side, we can obtain this scrambler seed, and then reversely construct the BLE payload bits by XORing the PN sequence with the desired bits into modulator. In this way, the desired single-tone waves will be generated.

IV. Wide-Area Connectivity for ZigBee

A. Specific ZigBee Waveforms for Symphony

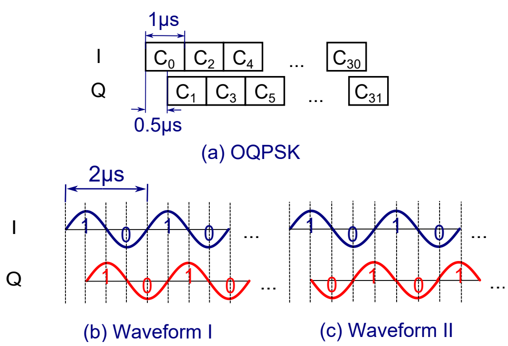


Fig. 6. Specific ZigBee Waveforms Utilized in Symphony

ZigBee utilizes OQPSK (Fig. 6) to modulate its chips. Specifically, the chips c_0, c_2, $\cdots$ are modulated onto in-phase component (I) and the chips c_1, c_3, $\cdots$ are modulated onto quadrature component (Q) one-by-one. As the chip rate of ZigBee is 2Mchip/s, the chip rate of each component (I or Q) is 1Mchip/s and the duration of each chip is 1μs. A half chip time offset, i.e., 0.5μs, exists between I and Q branches. After that, ZigBee adopts the half-sine pulse shaping to shape a chip into baseband samples. A chip '1' is shaped to a positive half-sine and a chip '0' is shaped to a negative half-sine as shown in Fig. 6.

By carefully choosing the input chips, two specific waveforms can be generated, shown in Fig. 6 (b) and (c). That is, when I-chips of '1010$\cdots$' are pulse shaped by half-sine waveforms, the I signals become a continuous sine wave with single tone. At the same time, the Q signals become a continuous cosine wave with the same tone, when the Q-chips are '1010$\cdots$' in Fig. 6 (b). Putting these two waveforms together, a complex exponential signal as $e^{j2\pi ft} = cos(2\pi ft) + jsin(2\pi ft)$ is generated, where f is equal to $1MHz$. This signal can be used to indicate the right tone in frequency domain the same as in Fig. 4. Similarly, in Fig. 6 (c), when chips of '10011001$\cdots$' are fed into OQPSK modulator, another complex exponential signal as $e^{-j2\pi ft} = cos(2\pi ft) - jsin(2\pi ft)$ is generated. This signal, in the same case, represent the left tone in frequency domain as in Fig. 4. In a nutshell, ZigBee is also able to generate a single-tone sine wave whose spectrum is one of the two pulses (Fig. 4).

B. Configurations of ZigBee signals

In default configuration, ZigBee utilizes Direct Sequence Spread Spectrum (DSSS) to spread a ZigBee symbol (four bits) into a specified 32-chip PN sequence. Since the chip sequence used for DSSS is predefined (i.e., PN sequence), we can not choose the chips arbitrarily to produce the desired signals as mentioned above.

However, as defined in IEEE 802.15.4g standard, commodity ZigBee radio chips (e.g., Atmel AT86RF233, Atmel AT86RF215) can provide flexible data rates, i.e., 250kb/s, 500kb/s, 1000kb/s and 2000kb/s. This is achieved by setting different spreading factors in DSSS. We note that when the chip rate is 2Mchip/s, the spreading factor is equal to 1, which means a chip is actually a bit. In this configuration, we can choose chips arbitrarily since we can select payload bits at will. Therefore, utilizing these configurable ZigBee RF radios, the specific waveforms can be generate to communicate with LoRa base station. Since the BLE (ZigBee) specific waveforms for long range CTC are manufactured only by choosing the payload bits of BLE (ZigBee) frame, a ultra-low cost payload encoding method is enough to achieve ubiquitous LPWAN, without any hardware modification on existing IoT devices.

C. Why Long Range Communication for BLE/ZigBee Specific Waveform?

In wireless communications, to support long range wireless communication, one can either (i) increase the transmission power or (ii) improve the receiver sensitivity (or do both). LoRa leverages the high receiver sensitivity to enable the long distant transmission. Specifically, the receiver sensitivity of LoRa can be as low as -134 dBm [4]. The key reason for such a good sensitivity is the spread-spectrum technique (i.e., Chirp Spread Spectrum (CSS)) provided by LoRa, where a narrow-band signal is deliberately spread into a wide-band transmission signal. At the receiver, the wide-band signal will be reversely changed into the narrow-band signal by a template correlation. Since both the noise and narrow-band interference are spread in a wide bandwidth, the narrow-band signal can be distinguished by FFT. In other word, the energy of this signal is gathered in a narrow-band by FFT, while the energy of noise and interference is wide spread in spectrum.

For the same reason, the specific waveform generated by BLE (ZigBee) achieves long range communication. During a FFT time window (i.e., the duration of a CTC symbol T_{sym}), the specific waveform (i.e., single tone sine wave) is a ultra narrow-band signal. At the receiver side, this single tone signal can be easily distinguished since the energy of the narrow band signal is gathered by FFT, while the energy of noise are wide spread in spectrum. Therefore, the weak signal deeply buried in noise can still be detected and demodulated by FFT at the LoRa base station. Fig. 7 clarifies this observation, where the single tone sine wave (top left of Figure 7) is able to be demodulated by FFT, and this demodulation can be more reliable with a larger FFT size.

Fig. 7 also shows that Symphony demodulation on BLE/ZigBee signals has almost the same performance as on

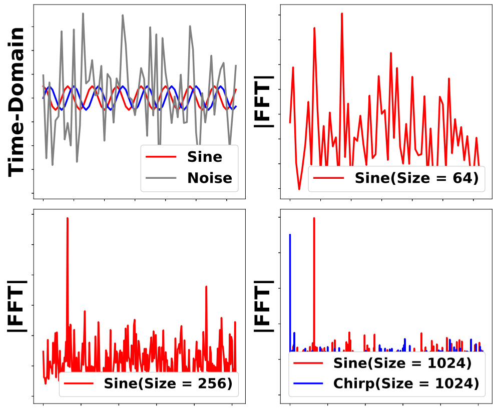


Fig. 7. Spectrum of BLE/ZigBee Specific Waveform with Noise

LoRa chirp. Specifically, when we demodulate a combined signal with a chirp and a BLE specific signal, the result at the bottom part of Fig. 7 shows that these two signals with the same FFT size leads to almost the same magnitude of FFT peak. Therefore, Symphony has the potential to achieve similar receiver sensitivity as LoRa. Notice that LoRa can achieve a receiver sensitivity as low as -134dBm, Symphony may also reach the link budget of 134dBm when the BLE/ZigBee sender transmits a frame with 0dBm, leading to a theoretical communication distance of over 10 kilometers.

V. Parallel Decoding

A. Unified Demodulation Framework

As we know, a LoRa receiver demodulates the wireless signal by multiplying it with a given template (shown in Fig. 2), and then performing FFT to find the peaks in spectrum. As Symphony aims at dealing with the collided signals, which are the superposition of three signals, the template for Symphony should also be the superposition of templates, i.e., the $Chirp_{Down}(t)$ for LoRa signal and the $\mathbb{1}(t)$ for the specific BLE (ZigBee) waveforms. Thus, in mathematics, the unified demodulation framework for the collided signals is given by:

$$\begin{aligned} D_C(t) &= R_C(t). \times (Chirp_{Down}(t) + \mathbb{1}(t)) \\ MixedSymbols &= Loc(Peaks(FFT(D_C(t)))). \end{aligned} \tag{5}$$

where $R_C(t)$ is the received collided signals, and $Peaks(v)$ is to get several peaks in a vector v.

According to the linear property of Fourier Transform, we have $FFT(D_C(t)) = FFT(R_C(t). \times (Chirp_{Down}(t)) + FFT(R_C(t). \times \mathbb{1}(t))$. The LoRa chirp in the collided signal (i.e., $R_C(t)$) has a high correlation with $Chirp_{Down}(t)$, but a very low correlation with $\mathbb{1}(t)$. Therefore, after FFT, the correlation results in spectrum is a high peak at some frequency (correlated with $Chirp_{Down}(t)$) and many extremely low components distributed in other frequencies (correlated with $\mathbb{1}(t)$). While for the BLE signal, it has a high correlation with the template $\mathbb{1}(t)$ and low correlation with $Chirp_{Down}(t)$, leading to a high peak at some frequency (correlated with $\mathbb{1}(t)$) and very low components distributed in other frequencies (correlated with $Chirp_{Down}(t)$). Similarly, the ZigBee signal also corresponds a peak. These three peaks can be detected and demodulated respectively if the FFT size is large enough.

In total, using the unified framework, the demodulation result is the superposition of three peaks generated from the BLE signal, ZigBee signal and LoRa signal respectively. Such analysis has been verified by the results obtained from the testbed (Fig. 8), where three peaks are obviously distinguished from other frequency components. Therefore, we can leverage these three peaks for collision recovery. In addition, since we just replace the correlation template from $Chirp_{Down}(t)$ to $Chirp_{Down}(t) + \mathbb{1}(t)$, only very limited modifications on the base station are required.

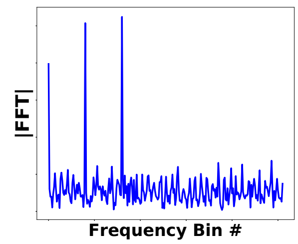


Fig. 8. Unified Demodulation of Collided Signals

B. Disentangle the Collision from BLE and ZigBee

Though both BLE and ZigBee generate the sine waveform with single tone in Symphony, the frequencies of these two waves are different. The frequency of BLE waveform f_B is ±250kHz because the frequency deviation used in GFSK is 250kHz. On the other hand, the frequency of ZigBee waveform f_Z is ±500kHz because the period of single tone shown in Fig. 6 is 2μs .

Since the BLE signal and the ZigBee signal generate different peaks at different frequency bins at LoRa receiver, we can disentangle them by the location of these peaks. For example, if we use the configuration parameters discussed in section III-D, the time window of FFT is $160\mu s$ (Eq. 4). Then the frequency resolution of FFT will be the reciprocal value of its time window, that is: $f_{res} = 1/160\mu s = 6.25kHz$.

Therefore, the locations of BLE peaks are given by $f_B/f_{res} = \pm 250/6.25 = \pm 40$ and those of ZigBee are $f_Z/f_{res} = \pm 500/6.25 = \pm 80$. Based on these two different peak locations (i.e., ±40 vs. ±80), Symphony is able to disentangle BLE signal from ZigBee signal in collision.

C. Disentangle the Collision from BLE (ZigBee) and LoRa

Symphony can also disentangle the collision from BLE (ZigBee) and LoRa. For a LoRa symbol, the number of possible peak locations depends on the symbol cardinality (size of symbol set). For example, if a LoRa symbol corresponds to two bits, the peaks will have four possible locations, i.e., the 0^{th} FFT bin, 64^{th} bin, 128^{th} bin and 192^{th} bin when FFT size is set to 256. The peak corresponding to BLE, on the other hand, only occurs at two possible locations (i.e., at the 40^{th} FFT bin or at the -40^{th} FFT bin). In this case, the BLE peaks will not be overlapped with LoRa peaks, and they can be easily distinguished. Fig. 9 illustrates the situation when the BLE peak and LoRa peak can be distinguished.

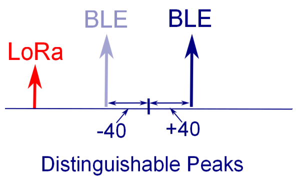


Fig. 9. Distinguishable Collisions of BLE and LoRa

D. Handling Timing Offsets

Our designs so far assumes that BLE, ZigBee and LoRa devices transmit their frames synchronously (i.e., the symbols are aligned) in time. However, such synchronization is impossible due to the lack of coordination. In this section, we discuss how to handle the interference among collided symbols, called as Inter-Symbol Interference (ISI).

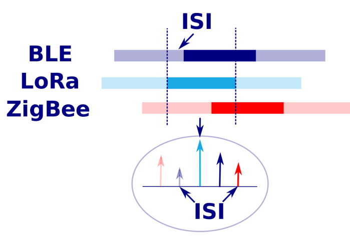


Fig. 10. Inter-Symbol Interference: Spectrogram of a collided symbol, and the corresponding Fourier transform peaks.

From Fig. 10, we can see that due to the misalignment of three symbols, it is quite possible that over the duration T of a symbol, one can observe as many as five distinct peaks instead of three. The reason is, when performing FFT for a BLE/ZigBee CTC symbol, both the signal from the previous symbol and from the current symbol are fed in. Therefore, two peaks may appear, one for the previous symbol and another for the current one. For example, the previous symbol is the left tone (corresponding to symbol '0') and the current symbol is right tone (symbol '1'), we have two peaks shown as Fig. 10. It is impossible to determine whether the left peak is corresponding to current symbol or the right one, making Symphony fails to demodulate this symbol.

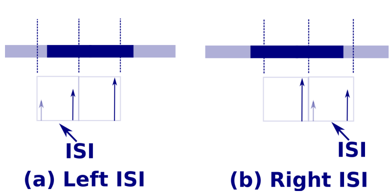


Fig. 11. Handling ISI by Choosing the Perfect Symbol

To solve this problem, we leverage a simple observation shown as Fig. 11. That is, if two identical BLE (ZigBee) symbols are sent continuously, there will be at least one symbol not influenced by ISI. This symbol, which is called as a *good* symbol, will generate a high peak among FFT bins. This good symbol may be the first symbol (left symbol) (Fig. 11 (b)) or the second one (right symbol, Fig. 11 (a)).

The key design is to find which symbol is the good one. We leverage a training sequence in the BLE (ZigBee) frame to decide whether the left symbol or the right one is good. A BLE device sends a training sequence as *0b11001100* (Symphony symbols) at the head of a Symphony frame. The LoRa server detects the pulses and demodulates them into a binary sequence, which would be *0b11001100* (Fig. 4) if ideally aligned. However, due to the timing offset as shown in Fig. 11, some uncertainties may be introduced in this binary sequence. Specifically, if left ISI occurs (Fig. 11 (a)), the received sequence will be *0bX1X0X1X0*, where 'X' denotes an uncertain binary digit. Or, if right ISI occurs (Fig. 11 (a)), the received sequence will be *0b1X0X1X0X*. We pick up the digits at odd positions or at even positions, then we can determine which symbols are good symbols. For example, if we extract *0b1X0X1X0X* at odd positions, and find out that the result matches *0b1010*, then we can decide that the left symbols are good. According to this, we can demodulate the following Symphony bits by all choosing the left symbols. Obviously, for reliable communication, the data rate is cut by half since each symbol has to be repeated once. However, this data rate, i.e., 3.125 Kbps = (6.25/2) Kbps, is still fast enough for LPWAN applications [1], [2], [3].

E. Symphony Demodulation

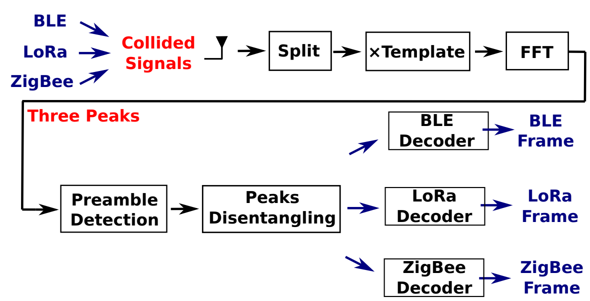


Fig. 12. Diagram of Symphony Demodulation

Putting all things together, we depict the whole procedure of Symphony demodulation in Fig. 12, that is: (i) The RF end down-converts and digitalizes the collided signal into the base-band samples. (ii) The Symphony receiver splits the samples into segments as native LoRa. (iii) Symphony multiplies each sample segment with a template (i.e., Equation 5) and performs FFT. Since Symphony leverages the same modulation schemes as the native LoRa except a slightly different correlation template, the overhead is kept minimal. (iii) After obtaining the frequency peaks from FFT, Symphony begins to detect the preamble of a LoRa/BLE/ZigBee frame according to the locations of the repeated peaks (Fig. 8). (iv) Once detecting the preamble, Symphony traces the corresponding peaks and demodulate them into symbols/bits in parallel, and then packs them into frames.

VI. Discussion

A. Two-way Communications

To achieve a real universal LPWAN, a downlink communication (i.e., from LoRa base station to low power devices) is required. Especially, we need an ACK as a feedback to enable reliable communication. This could be achieved by leveraging packet-level CTC (e.g., [14], [15]). For example, when the LoRa base station receives a data packet from a BLE/ZigBee device, it responds a normal LoRa ACK frame with fixed size. Then the BLE/ZigBee device samples RSSI to detect the existing of the frame, since we only need one bit information in ACK to tell the BLE/ZigBee sender whether the message has been successfully received. Although the transmission range is long, the transmission power of LoRa base station can be set large enough (e.g., 30dBm) to make the received signal detectable at BLE/ZigBee receivers [16].

B. Collision Avoidance among Homogeneous Devices

The mechanism of cross-technology parallel decoding can also be applied to solve the collisions from homogeneous signals. The base station performs FFT to distinguish signals from different frequencies. Therefore, if multiple BLE/ZigBee devices on different frequency channels transmit simultaneously, they can be separated by the FFT module at the LoRa base station. A typical LoRa base station is equipped with several RF radios operating at different frequency channels, which further enables Symphony to support concurrent transmissions from multiple BLE/ZigBee devices. If a collision still happens, the BLE/ZigBee devices will hop to other channels and retransmit the packet.

VII. Performance Evaluation

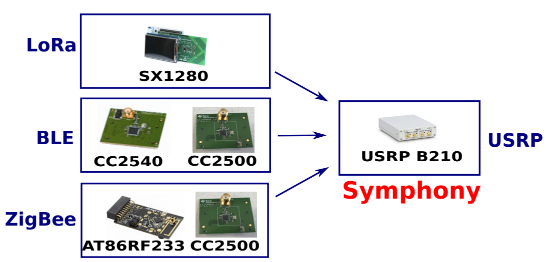


Fig. 13. Experimental Testbed of Symphony

Fig. 13 shows the testbed of Symphony. Specifically, we implement the Symphony base station on a USRP-B210 platform with LoRa PHY[17], and the Symphony sender (i.e., BLE/ZigBee/LoRa sender) on commodity chips (i.e., CC2540 (BLE), Atmel AT86RF233 (ZigBee), CC2500 (BLE/ZigBee)[†], and Semtech SX1280 (LoRa)). Moreover, we also use USRP as Symphony sender to generate collided frames. We compare the Symphony with two baselines: a native BLE communication on CC2540 transceivers, a native ZigBee communication on Atmel AT86RF233 transceivers. The default transmission power of the senders are all set as 0dBm, and the bandwidth of Symphony receiver (i.e., LoRa receiver) is set as 1.6MHz and spreading factor is set as 8. The channel frequency is set as 2.48GHz.

[†]We note that Symphony enables the long range communication with the cost of date rate, so the BLE/ZigBee chips need to send a long frame in Symphony. However, many low power chips such as CC2540 have buffer limit, so we utilize another similar commercial chip but with more flexible configuration (i.e., CC2500, which can be configurated as BLE or ZigBee chips) to generate the long frame for Symphony by decreasing its data rate. We utilize other BLE chip (CC2540) and ZigBee chip (AT86RF233) to measure some physical metrics including the BER, the locations of peaks, etc.

A. Long Range Performance

The evaluation of long range performance of Symphony mainly focuses on the link-layer metrics (e.g., frame reception ratio (FRR)) in long range communication. We do comprehensive experiments in two sites, including (i) a LOS site on an urban road, and (ii) a NLOS site in a campus.

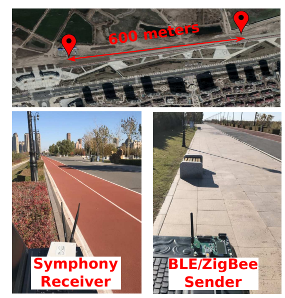


Fig. 14. Road Site.

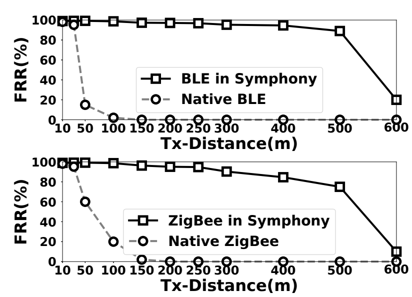


Fig. 15. Frame Reception Ratio with Tx Distances (Road).

We first evaluate the long range performance of Symphony at a site of an urban road (Fig. 14). We fix the transmission power of both BLE in Symphony and native BLE at 0dBm and only change the transmission distances. Fig. 15 shows the FRR of BLE in Symphony and native BLE. From the experimental results, we can see that Symphony achieves a good performance (FRR $>$ 90%) even the transmission distance is above 500 meters. In contrast, the FRR of native BLE drops to about 10% when the communication distance is above 50 meters. For short distance, the performance of BLE in Symphony approaches native BLE. While for long distance, the BLE in Symphony greatly outperforms the native BLE, indicating that Symphony enables a long range communication for BLE. The evaluation results from a ZigBee device to Symphony receiver in 15 also demonstrate that the ZigBee in Symphony has a very similar performance as those of BLE.

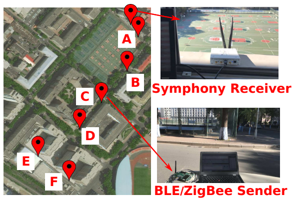


Fig. 16. Campus Site.

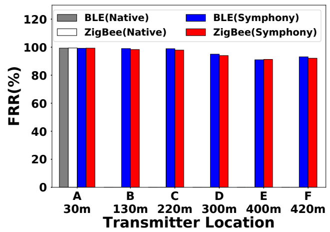


Fig. 17. Frame Reception Ratio with Tx Distances (Campus).

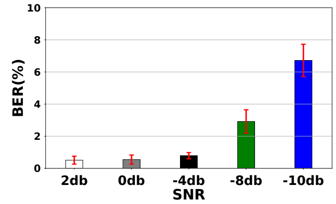


Fig. 18. BER of Parallel Decoding under Different SNR.

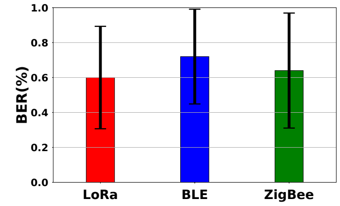


Fig. 19. BER of Parallel Decoding for Different Types of Frames.

We also evaluate the long range performance of Symphony in a non-line-of-sight (NLOS) scenario, i.e., a campus site shown in Fig. 16. We place the Symphony receiver (i.e., the LoRa base station) on a windowsill of a laboratory at the 8^{th} floor (the height is about 30 meters) of a building, and place the BLE/ZigBee senders at the location A, B, C, D, E, F illustrated as Fig. 16 respectively. The distances between the receiver and the transmitters are 30 meters (A), 130 meters (B), 220 meters (C), 300 meters (D), 400 meters (E) and 420 meters (F) respectively, and the testing locations D, E, and F are in NLOS conditions. The experimental results (Fig. 17) illustrate that the FRRs of Symphony, are more than 90% even the transmission distance is above 400 meters and the communication is under NLOS condition, indicating that Symphony can effectively support long range communications even under complex environments.

B. Parallel Decoding

Fig. 18 and Fig. 19 show the experimental results of performance where LoRa, BLE and ZigBee frames collide in an arbitrary way. In this experiment, we manufactured many collision situations using USRP in which the LoRa frame, BLE frame and ZigBee frame collided with each other at different positions, for example, the BLE/ZigBee frame collides with the payload of the LoRa frame, the BLE/ZigBee frame collides with the preamble of the LoRa frame, etc., and then send these collided frames. After the Symphony receiver demodulates and decodes these collided frames, we collect the decoded bits and obtain the bit error rate (BER).

Fig. 18 shows the BER of the BLE bits decoded by parallel decoding where the SNR (Signal-to-Noise Ratio) varies, and Fig. 19 shows the BERs of LoRa, BLE and ZigBee decoded bits when SNR is fixed as 0db. From the experimental results, we can see that Symphony is able to decode all three types of frames from the collided signals in a very reliable way (BER $<1\%$) (Fig. 19). At the same time, the performance of parallel decoding is good (BER $<8\%$) even with very low signal strength (SNR = -10dB) (Fig. 18). Symphony, thus, is shown to be able to disentangle and decode the collided signals in a long distance.

C. Experimental Insights

To understand the reason why Symphony works, we made another set of experiments to obtain several key physical-level metrics of Symphony. Specifically, we measure the receiver sensitivities of BLE, ZigBee and LoRa in Symphony, in comparison with that of native LoRa communication. Such measurements provide the insight into why Symphony can support long range communications for BLE, ZigBee and LoRa. We also measure the locations of FFT peaks from the specific BLE waveform and ZigBee waveform, since Symphony leverages the locations of peaks to disentangle and decode the collided heterogeneous wireless signals.

Firstly, we compare the performance of Symphony with native LoRa. To eliminate the influence of the irrelevant factors including the platform, radio, antenna, etc., we do the experiment where Symphony and LoRa work at the identical settings except the transmission power. Fig. 20 and Fig. 21 show the FRR of native LoRa and Symphony when the transmission power varies. For convenience, the transmission powers are expressed in 'dB' (relative power) instead of 'dBm' (absolute power). Fig. 20 displays the results at a LOS site, and Fig. 21 provides the results at a NLOS site. It is shown that the receiver sensitivity of LoRa in Symphony is about 5dB (LOS) and 6dB (NLOS) worse than those of native LoRa, and the receiver sensitivity of BLE/ZigBee in Symphony is about 4dB (LOS) and 5dB (NLOS) worse than those of native LoRa. Such results show that Symphony has only a small deterioration (about 5dB) in receiver sensitivity in comparison with those of native LoRa, and this deterioration is stable in different experimental scenarios. The reason for such a deterioration mainly lies in the change of the correlation template, which is suitable for both LoRa and BLE/ZigBee, but inevitably introduces additional loss for each of them. Also, we find BLE/ZigBee transmissions in Symphony performs even better than LoRa. The reasons are two folds. Firstly, the possible locations of BLE/ZigBee FFT peak are much less than that of LoRa, make it easier to be distinguished. Secondly, the repetition of BLE/ZigBee symbols eliminates the effect of time offset, and therefore is much more robust to synchronization errors than LoRa. Since the native LoRa typically has the receiver sensitivity of -135dBm [4], the receiver sensitivity of Symphony can be as low as -130dBm, enabling Symphony to achieve long range communication.

Fig. 22 illustrates the locations of BLE peaks when specific BLE waveforms are sent from the commercial chip (i.e., CC2540). The perfect match in this experiments (i.e., the y-axis of Fig. 22) means that the locations of the received peaks exactly match those calculated theoretically. From the results, we can see that almost all locations of received peaks

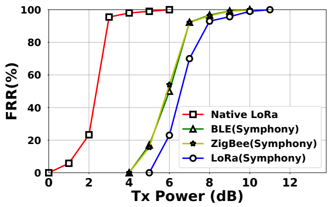


Fig. 20. FRR of Symphony vs. Native LoRa (LOS).

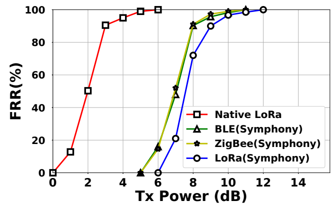


Fig. 21. FRR of Symphony vs. Native LoRa (NLOS).

can exactly match the theoretical ones (perfect match ratio approaches 99%). Moreover, the perfect match ratios for the left tones is almost the same as those for the right ones, where left tone is utilized to modulate the bit 0 and the right one for bit 1. At the same time, this perfect match ratio is very stable when the transmission power varies from 0dbm to -23dbm, meaning that the locations of the Symphony peaks is robust to the varying signal strengths (i.e., the different SNRs).

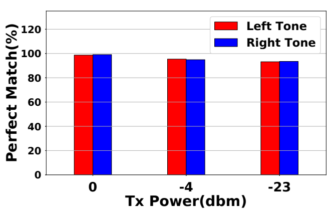


Fig. 22. Locations of Symphony Peaks Corresponding to Specific BLE Waveforms.

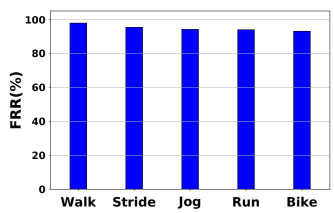


Fig. 23. Reliability of Symphony under Mobility (Mobile BLE Devices).

D. Performance under Mobility

We also evaluate Symphony with a mobile sender at the campus site (Fig. 16). In this experiment, the transmission distance is set as 220 meters (i.e., at location 'C' of campus site). Six levels of movements are evaluated in the experiments, namely, strolling, walking, striding, jogging, running and biking. Fig. 23 show that Symphony works well (PRR $>$ 93%) under different levels of mobilities for BLE devices. For mobile ZigBee devices, we obtain very similar results.

VIII. Related Works

Low-Power Wide-Area Network: LPWAN offers a promising capability, i.e., the wide-area connectivity for low power wireless devices. However, this capability, until now, can only be achieved by implementing newly designed wireless technologies and hardware, for example, the new commercial technologies like LoRaWAN [4], SigFox [5], LTE-M [6], NB-IoT [7]), and the researches such as SNOW [8], [18], TinyNode [19], etc. Although promising, these newly developed technologies bring in extra hardware costs and deployment complexities, especially when considering the large demanding on LPWANs from a wide variety of IoT applications. Our work, differently, provides a new direction to satisfy these requirements by directly connecting billions of existing WPAN devices into LPWAN.

Heterogenous Wireless System: Symphony is also a heterogeneous system because it enables a direct communication from BLE/ZigBee and LoRa. Recently, some researches on cross-technology communication [10], [20], [16], [21], [22], [23], [24] came out. For example, WEBee [10] emulates ZigBee signals using WiFi devices for direct communication. Inter-technology backscatter [25] uses WiFi to generate the signals detected by RFID, etc. However, none of the above researches takes the LPWAN into consideration. Recently, some works [26], [27], [28] leverage LoRa transmissions as the excitation signals, to enable long-range wireless connectivity for battery-less IoT devices. However, their applications could be seriously constrained since an excitation source has to be set very near to (e.g., $<$10 meters) the backscatter tag.

Parallel Decoding: To improve the communication efficiency, recent works explore the possibility of letting wireless devices transmit in parallel and decoding the collided packets at the receiver. Such technique, normally called as parallel decoding, has been studied in many types of wireless networks, such as cellular networks [29], [30], WLANs [31], RFIDs [32], [33], [34], [35], ZigBee [36] and LoRaWAN [3], etc. However, these parallel decoding systems only consider homogeneous signals. We note that the need for cross-technology parallel decoding becomes more and more urgent because today's wireless ecosystem is heterogeneous and the coordination among diversified technologies is very difficult. A few works have achieved parallel decoding from heterogenous devices via Multi-Input Multi-Output (MIMO) [37], [38] and Successive Interference Cancellation (SIC) [39]. These works, however, either are restricted by the number of receiver antennas, or depend on the assumptions that one signal has to be much stronger than the other one.

IX. Conclusion

This work presents Symphony, the first work that focuses on achieving a universal LPWAN on existing WPAN devices (i.e., BLE, ZigBee). To this end, Symphony addresses two challenges, that is, the long range cross-technology communication from BLE/ZigBee devices to LoRa base station, and cross-technology parallel decoding for concurrent transmissions from heterogenous devices. Our extensive experiments show that Symphony achieves about 3Kbps data rate over 500m distance for BLE/ZigBee communication with more than 90% reliability, extending the communication range about 16x that of the native BLE and ZigBee. Moreover, it is demonstrated that Symphony can demodulate the BLE/ZigBee/LoRa frames from the collided signals in parallel with less than 1% BER, showing that heterogeneous wireless technologies can not only cooperate with each other for better network performance, but also can coexist harmoniously in a system.

Acknowledgements

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