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ZCNET: Achieving High Capacity in Low Power Wide Area Networks

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Abstract—**In this paper, a novel LPWAN technology, ZCNET, is proposed, which achieves over 40 times the network capacity of LoRa using similar or less resource under the most challenging channel conditions. The capacity boost of ZCNET is mainly due to two reasons. First, a ZCNET node transmits signals that occupy a small fraction of the signal space, resulting in a low collision probability. Second, ZCNET supports 8 parallel root channels within a single frequency channel by using 8 Zadoff-Chu (ZC) root sequences. The root channels do not severely interfere with each other, mainly because the interference power is spread evenly over the entire signal space. A simple ALOHA-style protocol is used for medium access, with which a node randomly chooses the root channel and the range it occupies within the root channel, while still achieving high packet receiving ratios such as 0.9 or above. ZCNET has been extensively tested with both real-world experiments on the USRP and simulations. ZCNET will likely better accommodate the explosive growth of IoT network sizes and meet the demand of IoT applications.**

I. Introduction

Future Internet of Things (IoT) applications may depend on the Low-Power Wide-Area Networks (LPWAN) to connect an extreme number of devices, which is very challenging, because the communication distance may be long, while the devices may be expected to run on a single battery for years [21], [12], [22]. Currently, LoRa [4] appears to have attracted most attention. In this paper, ZCNET, a novel LPWAN technology, is proposed, which achieves much higher capacity than LoRa with similar or less resource. For example, Table 1 shows a head-to-head comparison with LoRa under the most challenging channel conditions, under which the most robust Modulation and Coding Schemes (MCS) should be used, namely Spreading Factor (SF) 12 for LoRa and MCA A for ZCNET. It can be seen that the capacity of ZCNET is over 40 times of LoRa under the same Signal to Noise Ratio (SNR), even when ZCNET occupies less bandwidth and supports a higher Physical (PHY) layer data rate than LoRa.

	Bandwidth (kHz)	SNR (dB)	PHY Rate (kbps)	Capacity (kbps)
LoRa	125	-20	0.209	< 0.209
ZCNET	120	-20	0.237	> 8.42

Table 1
LoRa SF 12 and ZCNET MCS A

ZCNET achieves high capacity because it allows as many as tens of nodes to transmit packets simultaneously according to a simple ALOHA-style Medium Access Control (MAC) protocol without incurring high packet loss. Such a large number of simultaneous transmissions is made possible, roughly speaking, by creating a signal space much larger than that occupied by the transmitted signal. To elaborate, in ZCNET, data is modulated on the *Zadoff-Chu (ZC) sequence* [18], [15], which also inspired the name of ZCNET. A transmitted ZC sequence results in a peak in the received *signal vector*. In ZCNET, each node limits its peaks within a very small range, such as 4, while the length of the signal vector is 983. As a result, a node does not interfere with other nodes with high probability. In addition, ZCNET supports 8 parallel *root channels* in a single frequency channel, where each root channel can host multiple nodes simultaneously and cause small interference to other root channels. This is mainly because ZC sequences derived from a particular root appears as flat noise to other roots, i.e., the energy will be spread out almost evenly. Therefore, LPWAN nodes, which operate in the low SNR regime, cause low interference to nodes in other root channels. ZCNET has been extensively tested with both real-world experiments and simulations. The results show that ZCNET can indeed decode weak signals in the real-world, and can support multiple simultaneous transmissions from many nodes, each with randomly selected root channel and range.

The rest of the paper is organized as follows. Section II discusses related work. Section III gives a short description of the ZC sequence. Section IV gives an overview of ZCNET. Section V highlights the key features of ZCNET. Section VI explains the details of ZCNET. Section VII describes the evaluation. Section VIII concludes the paper.

II. Related Work

Many LPWAN technologies have emerged in recent years, among which LoRa appears to have attracted the most attention. ZCNET has been shown to outperform LoRa in this paper. Sigfox [8] supports packet size up to 12 bytes, and may not be optimal for certain applications. Weightless-W/N/P [10] were proposed by the Weightless Special Interest Group; however, according to Ubiik [25], a leading Weightless hardware manufacturer, LoRa still has advantage in the communication range. RPMA [7], [19] is similar in many ways to Spread Spectrum Aloha [23] but may suffer from high complexity. Other technologies, such as IEEE 802.11ah [11], and IEEE 802.15.4g [14], all still have an uphill battle competing against LoRa. ZCNET can be used in the unlicensed band and is therefore different from those designed for the licensed band, such as NB-IoT [5], EC-GSM [12] and eMTC [12].

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ZC sequence has been proven in LTE networks, such as in PRACH for initiating a connection [24]. ZCNET has to address new challenges of modulating the ZC sequences for data communications in the low SNR regime, noting that no data is modulated on the ZC sequence in PRACH. The modulation in ZCNET bears some similarities with Multi-Pulse Position Modulation (MPPM) in optical communications [20]. The main difference is that ZCNET decodes the peaks from many nodes at random locations, while MPPM only considers a one-to-one link.

There has been research on improving the capacity of LoRa, the most relevant appearing to be Chorus [17], which decodes simultaneous packets from multiple nodes by identifying the peaks based on features such as the carrier frequency offset. Chorus achieves impressive capacity gains over the original LoRa, however the capacity is still significantly lower than ZCNET, because its performance starts to deviate from the ideal when the number of nodes is 4-5 [17], while ZCNET can support much more simultaneous transmissions, such as over 40, while still keeping the packet receiving ratio above 0.9. This is, of course, not to diminish the contribution of Chorus, because ZCNET is a clean-slate design, while Chorus has to function within the limitations of LoRa.

III. Background of the ZC Sequence

Let Λ^r be a *root* ZC sequence, which is a complex vector of length L, where r denotes the root index [18], [15]. Λ^r can be used to generate L sequences with simple cyclic shifts. Let Λ^r_h be Λ^r cyclic shifted by h locations, which will be referred to as sequence h on root channel r. If a ZCNET node wishes to transmit Λ^r_h, it generates an OFDM symbol, in which L subcarriers are used to transmit $FFT(\Lambda^r_h)$, where $FFT()$ denotes the FFT of a vector. The receiver can extract R, which is the complex vector observed from the L subcarriers in the received signal. The *signal vector* of root channel r, denoted as S^r, is calculated according to $S^r = IFFT[R^* \odot FFT(\Lambda^r)]$, where $IFFT()$ denote the Inverse FFT of a vector, R^* denotes the conjugate of R, and $\odot$ denotes the pairwise multiplication of two vectors. In ideal conditions, if Λ^r_h is transmitted, a *peak* should appear at location h in S^r. In practice, the peak location may be shifted due to synchronization error and Carrier Frequency Offset (CFO).

Element n in a ZC root sequence is $z_n = e^{-i\frac{un(n+1)}{L}}$ for $n \in [0, L-1]$, where u is a selected integer. In ZCNET, u may take one of 8 values, i.e., u =1, L, 2, $L-1$, 3, $L-2$, 4, $L-3$, as the 8 roots. Lastly, if S^r is generated by u or $L-u$ where $u > 1$, the elements are reordered, because a non-zero CFO will otherwise split one peak into u peaks, separated by $H = \lceil L/u \rceil$ points. The reordering is basically to move the peaks back together: for $1 \leq x \leq H$ and $1 \leq y \leq u$, $S^r_{(x-1)u+y} \leftarrow S^r_{(y-1)H+x}$.

IV. Overview

In this paper, the focus is on the uplink, where a ZCNET Access Point (AP) receives packets from the ZCNET nodes.

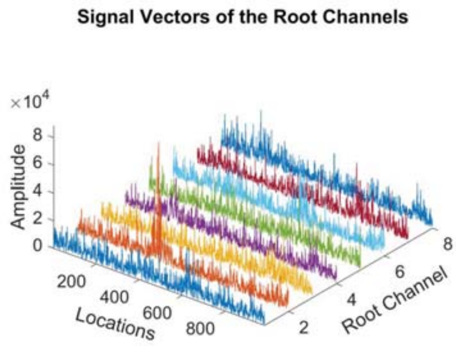

Figure 1. Signal vectors of 8 root channels.

A. Definitions

The main definitions are listed in the following:

- *Time Symbol*: The time-domain OFDM symbol.
- *Signal Vector*: A complex vector of length L. Currently, $L = 983$. If a node transmits sequence h, a peak will appear at location h in the signal vector under ideal conditions.
- *Peak Number*: The number of peaks transmitted by a node. A node can transmit multiple sequences, hence generate multiple peaks, by transmitting the summation of the time symbols of the individual sequences.
- *Range*: A continuous segment in the signal vector used by a node.

For example, Fig. 1 shows the signal vectors of all 8 root channels derived from a single time symbol, when there were 46 active packet transmissions. A number of peaks can be seen in most signal vectors. The peak number may be 1 or as many as 12, depending on the MCS. The peaks from the same node are confined in a small range.

B. ZCNET Nodes

The ZCNET node design is very simple. The MAC layer is an ALOHA-style protocol, i.e., the node simply picks a random root channel and a random range within the signal vector for the transmission of the packet. The packet consists of the preamble, the PHY header, followed by the data. At the PHY layer, the node may transmit one or multiple peaks in each time symbol. The data is modulated by changing the location and the phase of the peaks. For example, with MCS A, the node transmits only one peak, which is selected from 4 *candidate peak locations*. Clearly, two bits can be modulated with the location of the peak. In addition, the phase difference of the peak with that in the previous time symbol may be one of the 4 values in $\{0, \pi/2, \pi, 3\pi/2\}$, therefore, also modulates 2 bits. The data is encoded currently according to the Turbo code [13] for Forward Error Correction (FEC). However, other good code can be used as well with little change to the core of ZCNET.

Like most networks, the node should discover the AP and learn certain key network parameters, such as the frequency channel used by the AP. In particular, a ZCNET node should

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learn the frequency channel, the time symbol boundary, and the time symbol index. The time symbol boundary is needed to align the time symbols from multiple nodes within the tolerance level of the OFDM cyclic prefix. The time symbol index is needed because a packet transmission starts at a time symbol with index that is a multiple of 25 to simplify the packet detection in ZCNET. Such information can be easily learned from a beacon packet from the AP. The cyclic prefix of the time symbol is 256 μs to accommodate possible timing errors, drift, and large delay spread.

C. ZCNET AP

The ZCNET AP shoulders the main complexity of the network. The AP receives the composite time-domain signal, which may be the summation of the signals from tens of nodes on all root channels with no coordination. The AP must detect the packets and estimate key parameters, such as the beginning of the range and the CFO, to decode the packets.

The AP runs the same process to detect and decode packets for each root channel. The packets are detected based on the preambles. In the preamble, the node transmits one peak in each time symbol. The basic idea is to take the summation of the preamble signal vectors, because peaks from the same packet should add up constructively and stand out as a high peak, the location of which can be used to determine the beginning of the range of the packet. However, peaks from the ongoing packets, which are also in the signal vectors, may collide with the preamble peaks, and may even stand out after the summation, if their signals are strong. The solution is to randomize the locations of the preamble peaks and mask the ranges of the ongoing packets, which is explained in more details in Section VI-B, as well as the method to learn key parameters such as the CFO.

After a packet has been detected, the AP decodes the PHY header to learn the MCS and the length of the packet. When the packet transmission is completed, the signal vector values in the range of the packet are passed for decoding. After a successful decoding, all detected peaks of this packet are masked from the signal vectors.

V. Key Features of ZCNET

In this section, key features and design choices of ZCNET are explained.

A. Low Complexity of ZCNET Nodes

The MAC layer is clearly very simple. The PHY layer complexity is also very low, because the node can actually store pre-computed time symbols for each possible peak, therefore avoiding modulating OFDM signals in real time. If the node transmits K peaks, the baseband waveform is simply the summation of K pre-computed time symbols. For most MCSs, K is very small, such as 4 or less. The highest K is 12, which is still reasonable. Lastly, the encoding of typical FEC codes, such as the Turbo code, is very simple, and only involves linear operations.

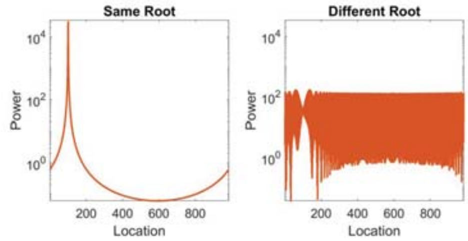

Figure 2. Power of signal vectors with the same and a different root.

B. Main PHY Parameters of ZCNET

Currently, the signal vector length is 983. The time-domain samples are taken every 2 μs. The time symbol contains 4224 samples, in which 128 samples are the cyclic prefix, and 4096 samples are passed to FFT. As only 983 points in the FFT output are used, ZCNET occupies 983/4096/0.000002=120 kHz of bandwidth. Note that the FFT size is about 4 times the signal vector length, which allows the time domain samples to be taken more frequently to better match the path delay. Clearly, the time symbol duration is 8.448 ms, in which 0.256 ms is the cyclic prefix.

C. Small Range

The range size in ZCNET is only 48 or less, compared to the signal vector length, which is 983. This is mainly because the *peak cardinality* is 4, i.e., when a node transmits a peak, it picks one from 4 candidates. In contrast, in LoRa SF 12, the cardinality is 4096. The main benefit of a small range is that multiple nodes can transmit simultaneously on the same root channel, significantly increasing the capacity of the network.

However, with a small cardinality, each peak carries much fewer bits, which may reduce the data rate. This is avoided, first, by modulating additional data on the phase of the peaks. Also, the duration of the time symbol of ZCNET is roughly 1/4 that of LoRa with SF 12, reaping a speed up of 4. A challenge, however, is roughly 6 dB loss in SNR, because only 1/4 samples are taken. Fortunately, a smaller cardinality also relaxes the SNR requirement, because the actual signal peak has less competitors. Measuring by the probability of the actual signal peak being the highest among all candidate peak locations, it was found that for white Gaussian noise, reducing the cardinality by half reduces the SNR requirement by roughly 0.5 dB. Additionally, ZCNET employs more advanced FEC code, which further compensates for the loss of SNR.

D. Parallel Root Channels

ZCNET achieves high capacity in large because the parallel root channels accommodate many simultaneous transmissions without severely interfering with each other. This is made possible by exploiting the inherent property of the ZC sequence, as well as interference cancellation.

1) Coping with Weak Interference: With the ZC sequence, a peak in one root channel does not generate high interference peaks in other root channels. Instead, it only evenly raises the noise floor. For example, Fig. 2 shows in log scale the power of the signal vectors calculated from the same time

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symbol containing one peak, one with the matching root and the other with a different root. It can be seen that the energy is concentrated with the matching root, however is flattened and more than 2 orders of magnitude lower with the different root. Therefore, weak nodes in ZCNET do not pose much challenge, because they introduce weak interference and only raise the noise floor by a small amount. For example, a node only increases the noise by 1% if its SNR is -20 dB.

2) Coping with Strong Interference: A process called SIMple Interference Cancellation (SIMIC) is used to cancel interference from strong nodes. Note that a strong signal in the matching root channel will manifest itself as a high peak, i.e., even before the data is decoded, the signal power is concentrated within a few points and can be easily identified, such as the peak in Fig. 2. Therefore, the signal around the peak can be carved out to reconstruct the time-domain signal. The reconstructed time-domain signal can be subtracted from the received time-domain signal, which will lead to a significant reduction of interference to other root channels. SIMIC is very simple, and is very different from typical interference canceling techniques, which require correctly decoded data, as well as accurate Channel State Information (CSI). Accurate CSI in the LPWAN environments can be difficult to obtain, because the channel coherence time can be comparable to the symbol time. Lastly, SIMIC only considers high peaks, because the signal distortion increases with the number of points carved out in the process.

E. ALOHA-Style MAC Layer

The MAC layer protocol of ZCNET is very similar to ALOHA, with the clear benefit of simplicity. ZCNET can afford to use ALOHA, because the load to any single root channel is quite low with the adoption of the small range and a relatively large number of root channels. The packet loss is actually dominated by noise and remaining interference from other root channels. In addition, with the help of the FEC code, packets can often be decoded correctly even with collision, especially if the collision affects only part of the transmission.

F. Co-existence of Multiple MCSs in the Same Root Channel

In ZCNET, multiple nodes can transmit at different MCSs simultaneously in the same root channel, and be received correctly, as long as their ranges do not significantly overlap. This is in contrast with LoRa, where each SF basically defines its own channel. Clearly, by decoupling the MCS from the root channel, ZCNET is more flexible in accommodating different traffic needs. For example, ZCNET can support many nodes with weak signals by spreading them to all root channels, while such nodes can only stay within the same channel with LoRa. The main challenge is to achieve high data rates, because all MCSs generate time symbols of the same duration, which is selected mainly for the lowest MCS to achieve long communication distance. ZCNET solves this problem by allowing a node to transmit multiple peaks.

VI. Details of ZCNET

In this section, the details of ZCNET are explained.

MCS	peak num.	peak cardi.	range	FEC rate	PHY rate (kbps)
A	1	4	4	1/2	0.237
B	2	4	8	1/2	0.473
C	4	4	16	1/2	0.947
D	6	4	24	2/3	1.89
E	12	4	48	2/3	3.79

Table 2
ZCNET Modulation and Coding Schemes

A. Modulation and Coding Schemes (MCS)

ZCNET currently supports 5 MCSs by varying the number of peaks and FEC code rates. Table 2 lists the parameters of each MCS. In ZCNET, regardless of the MCS, each peak modulates 4 raw bits, 2 with location and 2 with phase. The modulation with MCS A has been explained earlier. For other MCSs, each time symbol contains multiple peaks, one of which is used as the *pilot*. The phase offset of any peak with respect to the pilot modulates 2 bits. The pilot itself also modulates 2 bits with phase by adding a phase offset with respect to the pilot in the previous time symbol. The codewords are interleaved to cope with bursty errors in the channel. At the receiver, the data modulated on the peak locations is decoded first, after which the locations of the actual peaks are found based on the reconstructed codeword. The phase readings are then obtained to decode the data modulated on the phase. The PHY data rate can be calculated as follows. For example, with MCS A, in each time symbol, a node transmits one peak and therefore 4 raw bits. With 1/2 as the FEC code rate, each time symbol carries 2 data bits. As the time symbol is 8.448 ms, the data rate is 0.237 kbps.

B. Packet Detection and PHY Parameter Estimation

The first step of packet decoding is to detect the packet and learn the PHY parameters, such as the CFO, which are both based on the preamble of the packet. This process faces many challenges. For example, the preamble may collide with peaks from ongoing packets. Also, as the time-domain signal maybe the mixture of many packets, traditional CFO estimation methods, which may assume that the signal is from only one packet, cannot be applied.

1) Overview: The preamble consists of 16 time symbols, each with only one peak at a location with a known *offset* to the beginning of the range selected by the node. The preamble is transmitted at the beginning of a *SYNC epoch*, where each epoch has 25 time symbols. Note that the SYNC epoch is not a period set aside purely for packet detection. Instead, it is simply a logical unit with 25 time symbols. The packet length need not be a multiple of the SYNC epoch length.

To detect the packets, first, the ranges of the ongoing packets, which have been detected earlier, are masked, such that they do not interfere with the packet detection process. The signal vectors are then cyclically shifted according to the offset, such that the peaks in the preamble of the same packet are aligned, i.e., should appear at the same location. The offset values are chosen such that the preamble peaks are at evenly

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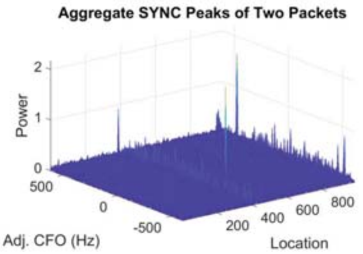

Figure 3. Power of aggregated SYNC peaks of two packets.

spaced locations in the signal vector, and therefore will not consistently collide with an ongoing packet. The summation of all shifted signal vectors is called the *SYNC vector*. The peaks in the same preamble should add up constructively, producing an *aggregated SYNC peak*, which should stand out even when the signal is weak. Currently, to be eligible for further packet decoding, the power of the aggregated SYNC peak should be over 16 times of the noise power in the SYNC vector. As there may be multiple new packets, the highest aggregated SYNC peak is selected first, after which the locations around the peak are masked, and the process is repeated, until there is no aggregated SYNC peak higher than the threshold. The location of the aggregated SYNC peak is clearly the beginning of the range of the packet.

The basic idea of CFO correction is to apply a set of *adjustment* CFOs to the time-domain signal of the preamble, and compute a SYNC vector for each adjustment CFO. Note that the preamble peaks have the same phase if the adjustment CFO completely cancels the actual CFO; otherwise, the phases are not aligned and the peaks will likely cancel each other during the summation. Therefore, during packet detection, the selected aggregated SYNC peak is the highest peak among all SYNC vectors. Once a packet is detected based on a peak in particular SYNC vector, the adjustment CFO that produces this SYNC vector is used as the estimate of CFO of the packet.

For example, Fig. 3 shows the power of the aggregated SYNC peaks of two packets. One peak is at location 387 with adjustment CFO -383 Hz, and the other at 951 and 442 Hz.

2) Preamble Peak Offset: Let q_i be the offset of the preamble peak with respect to the beginning of the range in time symbol i of the preamble. In ZCNET,

$$q_i = \{\frac{i(i+1)}{2M}\}MD, \quad (1)$$

where $\{\}$ denotes the fraction part of a number, M denotes the length of the preamble, and $D = 61$, which is the largest prime number below L/M. To see that the preamble peaks are evenly spaced, it suffices to prove that

$$\{\frac{i(i+1)}{2M}\}M$$

generates unique integers in $[0, M-1]$ with $i \in [0, M-1]$. Suppose this is not true, i.e., there exist distinct integers a and b, satisfying

$$\{\frac{a(a+1)}{2M}\} = \{\frac{b(b+1)}{2M}\}.$$

Denote the integer parts of those inside of $\{\}$ in the above equation for a and b as A and B, respectively, which are clearly different. As a result,

$$\begin{aligned} a(a+1) - b(b+1) &= (a+b+1)(a-b) \\ &= (A-B)2M. \end{aligned}$$

Note that there is exactly one even number among $(a+b+1)$ and $(a-b)$. On the other hand, $2M = 32$ and is greater than both $(a+b+1)$ and $(a-b)$, which is a contraction.

Clearly, if only to spread the preamble peaks evenly, one can simply let $q_i = iD$. The rationale behind the current solution, as well as why D is a prime number, is related to the CFO estimation, which will be explained shortly.

3) CFO Estimation: As mentioned earlier, the basic idea of CFO estimation is to apply a certain number of adjustment CFOs to the time-domain signals. It was found that the preamble peak phases are mostly random when the residual CFO after the cancellation is not a multiple of the subcarrier spacing, leading to very low height of the aggregated SYNC peak. However, care must be taken when the residual CFO is a multiple of subcarrier spacing. To elaborate, let the residual CFO be $\zeta\omega$, where ζ is an integer, and ω is the subcarrier spacing. Consider root u where $u \in [1, 4]$, because root $L-u$ can be treated similarly as root u. It can be verified that for element d in the signal vector, a residual CFO of $\zeta\omega$ will lead to a phase shift with respect to the first element by

$$\Phi(d) = 2\pi[\frac{\zeta d}{Lu} - \frac{\mod(\zeta d, u)}{u}]. \quad (2)$$

The two terms in $\Phi(d)$ explain the current choices of q_i and D. First, if the offset of the preamble peak is simply $q_i = iD$, clearly, the first term of $\Phi(d)$ introduces a constant phase difference of $2\pi\zeta D/(Lu)$ between consecutive peaks, which is a sinusoid. It will be matched and canceled with a certain adjustment CFO, after which the aggregated SYNC peak may be high. However, with Eq.1, the phases of the peaks is effectively randomized, and cannot be canceled by any adjustment CFO, which can only introduce a linear change to the phases. Similarly, unless ζ is a multiple of u, as D is a prime number, $\mod(\zeta q_i, u)$ generates roughly an equal number of integers within $[0, u-1]$, which further helps randomizing the phase values.

The adjustment CFO is from $[-5\omega, 5\omega]$ with a step of 0.02ω. The range is selected with the assumption that the CFO is within $\pm 5\omega$, which is basically the CFO estimation error of the nodes based on the downlink packets. It can be reduced if the estimation is more accurate. The computation complexity can also be significantly reduced by exploiting Eq.2, because the signal vectors for adjustment CFOs that differ by $\zeta\omega$ are different only by the phase values according to Eq.2 and a cyclic shift of $-\zeta$ points. Therefore, the computation is only for adjustment CFO in the range of $[0, 0.98\omega]$.

4) Timing-Offset (T-Off) Estimation: As mentioned earlier, to match the actual path delay at a finer granularity, the FFT size is slightly more than 4 times the signal vector length. The receiver can pick the beginning of a time-domain symbol with

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an offset of 0, 1, 2, or 3, referred to as the Time-Offset (T-Off). A good T-Off results in sinusoids that completes an integer number of cycles within the signal vector, and maximizes the height of the signal peak. A simple procedure is adopted T-Off estimation. That is, after the CFO has been found, the 4 possible T-Off values are applied to the time-domain signals of the preamble, and the value that generates the highest aggregated SYNC peak is used as the T-Off estimate.

5) Shortened Preamble for MCSs D and E: The preamble length is 16, which is selected to ensure a sufficient number of observed preamble peaks and sufficient energy for packet detection. A node with better channel conditions may use shortened preamble to reduce power consumption and air time. Currently, for MCS D and E, only the second half of the preamble is transmitted.

C. PHY Header

The PHY header consists of 6 time symbols, which carry 8 bits of information, namely, the MCS and the length of the packet, as well as 4 bits of CRC. The 12 bits are encoded according to an (6,2) Reed-Solomon (RS) code on $GF(2^6)$. A peak is transmitted in each time symbol, which can take one of 64 candidate locations according to the RS codeword. The range in successive symbols are cyclically shifted by 163 to avoid consistently colliding with an ongoing packet. The receiver calculates a weight for each possible codeword by taking the summation of the complex values in the signal vectors at the locations according the codeword, and selects the codeword that results in highest power. This approach is a reasonable tradeoff between performance and complexity.

D. SIMIC

With SIMIC, each time symbol is processed individually. First, for each root, the signal vector is calculated. Peaks higher than $\gamma\sigma$ are added to a list, where $\gamma = 16$ and σ is the noise power in the signal vector. The peaks found in all roots are sorted according their power levels. Then, starting from the strongest peak, the locations within $(\beta - 1)/2$ points to the peak, where $\beta = 7$, are masked in the corresponding signal vector, until the total number of masked locations in all signal vectors is above a threshold, currently 200, or until no peak is left. Lastly, for each root, the signal vector in the masked locations are carved out, and used to generate the time-domain signal by simply reversing the process described in the first paragraph of Section III. This time-domain signal will be subtracted from the received time-domain signal when computing the signal vectors of other roots.

E. The FEC Code in ZCNET

ZCNET uses an existing code that has been proven in practice, namely the Turbo code [13]. Note that the phase of the peaks are standard QPSK, therefore, the same Turbo code in LTE [24] is used for data modulated on the phase. The data modulated on the peak locations is coded with a customized Turbo code on $GF(4)$, which has gains over the typical Turbo code on the binary field. This is because $GF(4)$ represents better the *location symbol*, which refers to the vector of the power values at the 4 candidate locations of a peak. The power value is the summation from all antennas.

In the customized code, the base convolutional code has a memory depth of 2, which are both initially 0, and generates a parity checking symbol for every data symbol received. Let s_0 and s_1 be the symbols in the memory. When a new data symbol x is received, the new parity symbol y, as well as the new memory values are updated according to: $y = 3x + s_0 + 2s_1$, $s_0 = y + 2x$, and $s_1 = 2y + 3s_1$. Currently, the data symbols to the second encoder is permuted according to a random permutation. According to common practice, the data symbols are not punctured. The parity checking symbols are punctured periodically depending on the data rate.

The receiver converts the location symbol to probability values according to a simple heuristic, which assumes the power value of a transmitted peak follows the normal distribution. The mean of the power value is assumed to be the maximum value in the location symbol. The standard deviation of the power value is approximated as the the average of the location symbol, or the one fourth of the maximum value in the location symbol, whichever is smaller. The probability for each candidate location to be the transmitted peak is calculated according to the normal distribution, and then normalized.

VII. Evaluation

ZCNET has been tested with USRP X310 [3] in the Powder wireless platform [6] and simulations.

A. Implementation

For ZCNET, the packet baseband waveforms are first generated and saved as files. In the PHY layer experiments, the transmitter USRP basically plays the files. The receiver USRP receives the signals, which are saved as files and decoded by the decoding program. For comparison, the LoRa implementation at [9], [16] is used with additional code for CFO estimation and synchronization. Note that the timing offset is equivalent to CFO in LoRa and need not be separately estimated. The FEC code rate of LoRa is 4/7. Therefore, the PHY data rates of SFs 7 to 12 are 3.91, 2.23, 1.25, 0.700, 0.384, and 0.209 kbps, respectively. The packet sizes are all 20 bytes. It has been found that larger packets results higher gains of ZCNET over LoRa.

B. Real-World Experiments

Real-world experiments were conducted, as described in the following.

1) Experiment Settings: The experiments were conducted with the X310 USRP [3] in the Powder wireless platform [6]. The Powder platform hosts radios that can be reserved and controlled remotely, including a number of rooftop radios, some of which were used in the experiments. The results of one experiment with 4 rooftop radios are reported in this section, where the locations of the radios are shown in Fig. 4, with index from 0 to 3.

With 4 radios, 6 links were tested, including some long links such as link 01 and link 12 that were over 2 km. For each link,

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Figure 4. The radio locations.

100 packets were transmitted for each ZCNET MCS, as well as LoRa SF 12 and SF 9. The carrier frequency was 3.675 GHz. Due to the minimum sampling rate limitation of X310, the sampling rate of ZCNET and LoRa were 2 MHz and 500 KHz, leading to bandwidth usages of 480 KHz and 500 KHz, respectively. Note that like LoRa, ZCNET can also run on higher bandwidth, except that higher bandwidth also increases the noise power. The transmitter gains of links 01, 02, 03, 12, 13, and 23 were 30, 5, 25, 25, 7 and 2 dB, respectively, to achieve some level of connectivity, except for link 01, which did not work even with the highest gain.

In the experiments, LoRa decoding was relaxed, which has significantly improved its performance. It was found that, inside the same LoRa packet, some peaks were often off by just 1 position, while others were correct. With the relaxation, the peak position is still considered correct if it is off just by one. Note that the correct peak positions are known because the packets were generated offline with key information saved. It was found that without this relaxation, the Packet Receiving Ratio (PRR) can drop by over 30% even for strong links and over 60% for borderline links.

2) Experiment Results: The PRRs of 6 experiments are shown in Fig. 5. It can be seen that ZCNET MCS A outperforms LoRa SF 12, and ZCNET MCS D outperforms LoRa SF 9. For example, the PRRs of ZCNET MCS A and LoRa SF 12 on link 23 are 0.91 and 0.23, respectively. Also, the PRRs of ZCNET MCS D and LoRa SF 9 on link 12 are 0.99 and 0.65, respectively. Note that the PHY data rates of ZCNET MCSs A and D are 13% and 51% higher than LoRa SFs 12 and 9, respectively.

3) Discussions: The experiments confirm the practicability of ZCNET on decoding weak signals in the real-world, and that ZCNET is expected to outperform LoRa in range, while LoRa is actually known for its range among the existing LPWAN technologies. However, the experiments were not designed to determine the maximum range of ZCNET, because the transmission power was not maximized, the bandwidth was not minimized, and the carrier frequency was high. The wireless medium might occasionally be filled with interference from other experiments on the same platform, making it difficult to conduct a full quantitative comparison. Lastly, due to the limited number of available nodes, the experiments focus on the one-to-one transmissions, while the capacity gains of ZCNET, which require simultaneous transmissions of multiple node, has not be demonstrated.

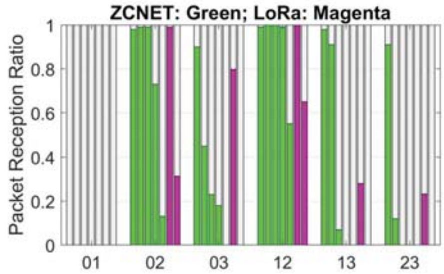

Figure 5. PRRs of 6 links in the real-world experiments. ZCNET, left to right: MCS A to MCS E. LoRa left: SF 12; LoRa right: SF 9.

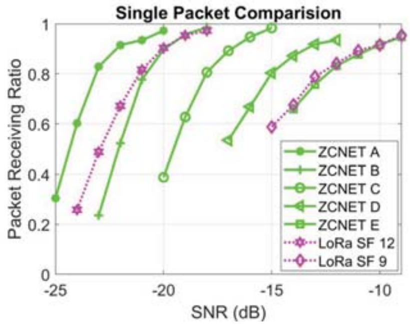

Figure 6. PRR as a function of SNR.

4) Summary: The experiments confirm the practicability of ZCNET on decoding weak signals in the real-world. The limitations also motivate the evaluation based on simulation to be discussed in the following.

C. PHY Layer Comparison with LoRa

For a quantitative evaluation, simulations were conducted to find the SNR decoding thresholds of ZCNET and LoRa.

1) Simulation Setup: In the simulation, ZCNET packets were randomly generated and passed to the LTE ETU channel model, noting that ETU has the largest delay spread in LTE channels [1], [2] and models challenging wireless environments. The number of receiving antennas of the model was 2. LoRa packets were similarly generated.

2) Results: Fig. 6 shows the PRR as a function of SNR for all MCSs of ZCNET, as well as SF 12 and SF 9 for LoRa. Not all results were included due to the limit of space in the figure. It can be seen that ZCNET has notable SNR gains over LoRa.

LoRa	SF 12	SF 11	SF 10	SF 9	SF 8	SF 7
SNR (dB)	-20	-16	-13	-10	-9	-8
ZCNET	A	B	C	D	E	
SNR (dB)	-22	-20	-16	-13	-10	

Table 3
SNR THRESHOLD AT 0.9 PRR

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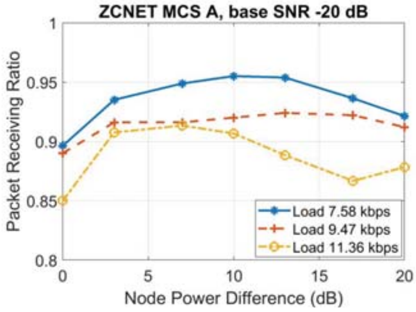

Figure 7. PRR of ZCNET with MCS A packets only.

For example, ZCNET MCS A exhibits about 2 dB gain over LoRa SF 12, even with a higher data rate. Also, the curves of ZCNET MCS E and LoRa SF 9 are very close, even when the data rate of the former is over 3 times of the latter. Using 0.9 as the required PRR, Table 3 shows the SNR thresholds. It can be observed that the SNR thresholds of different ZCNET MCSs are separated by around 3 dB, suggesting that the MCSs can offer options to nodes with different levels of signal powers.

3) Summary: The simulation results show that ZCNET can decode packets at lower SNRs than LoRa at similar or higher PHY data rates.

D. Link Capacity Comparison with LoRa

Another set of comparison is on the link level capacity with multiple simultaneous packets.

1) Simulation Setup: For ZCNET, time-domain signals were generated exactly as what would have been received in the real-world. That is, randomly generated packets were passed to the ETU model, scaled, and added to the background noise starting at randomly selected ZCNET SYNC epochs. To be more specific, the duration of each test was 2000 time symbols. A certain number of packets, such as 1000, were randomly assigned to each root channel to be started at random SYNC epochs. The SNR of a packet was randomly selected in $[B, B+\alpha]$ dB, where B and α are referred to as the *base SNR* and the *power difference*, respectively. The power difference models errors in transmission power control, which is a necessary procedure in most wireless networks and should limit the disparity of received signal power to a reasonable level. A difference of 20 dB should be a fairly large error.

2) Under the Most Challenging Channels: One interesting setting is when all nodes are under the most challenging channel conditions and must use the most robust MCS. For ZCNET, it would be MCS A, and for LoRa, SF 12. Note that this may be quite close to the reality in certain cases, as an LPWAN may cover a large area, with the majority of the nodes far from the AP. The base SNR was -20 dB, 2 dB higher than the decoding threshold of MCS A, to cope with the interference from other root channels.

Fig. 7 shows the PRR of ZCNET MCS A packets. For simplicity, in the figure, instead of the total number of packets, the traffic load is shown as the link layer load measured in kbps. For example, 1000 packets in 2000 ZCNET time

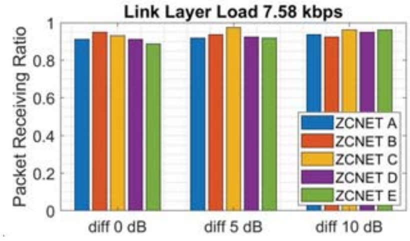

Figure 8. ZCNET with mixed load from all MCSs.

symbols is 9.47 kbps, because each time symbol is 8.448 ms and each packet contains 160 link layer bits. It can be seen that the regardless of the power difference, the PRR is always above or very close to 0.9 for load 9.47 kbps or lower. Therefore, ZCNET MCS A achieves a link layer throughput of at least 8.42 kbps even with a power difference of 20 dB. In contrast, the link layer throughput with LoRa SF 12 is capped at its PHY data rate of 0.209 kbps. The capacity gain is therefore over 40 times. Note that the actual gain can be even higher, due to the ALOHA MAC in LoRaWAN, which may lead to large loss due to collisions.

3) Mixed Load with Multiple MCSs: Another setting is with mixed load, i.e., when packets on all MCSs are transmitted. Similar to earlier tests, all packets were generated with random root channels and added to the time-domain signal starting at random SYNC epochs. Packets on MCSs A, B, C, D, E were scaled to random SNRs, with bases SNRs -20, -17, -14, -10, -7 dB, respectively, and the same power difference, which was 0, 5, or 10 dB in different sets of tests. Fig. 8 shows the PRRs when the load is is 7.58 kbps. It can be seen that the PRRs of all MCSs are close to or above 0.9, i.e., in 2000 time symbols, 160 packets were offered for each MCS, even when the power difference was 10 dB. Therefore, ZCNET will likely support packet transmissions in realistic scenarios. Note that the capacity is lower with mixed MCSs than only with MCS A, because higher MCSs introduce more interference.

Similar tests were conducted for LoRa. Signals of packets with SF 7 to SF 12 were scaled to certain SNRs and added to the time-domain signal at random times, where the base SNRs were -6, -7, -10, -13, -16, -20 dB, respectively, and the power difference was 0 dB. Note that the starting times of the packets were random, because LoRaWAN adopts the ALOHA protocol. Also note that packets transmitted simultaneously with different SFs may be received correctly in some cases, although the signals on different SFs are not orthogonal [16]. To the benefit of LoRa, packet detection and synchronization were made perfect by passing the actual starting time of packets to the decoding program. Fig. 9(a) shows the results, where it can be seen that at load 7.58 kbps, i.e., 133 packets on each SF within the same amount of time as the ZCNET tests, LoRa basically fails, especially for the higher SF. For example, the PRR of SF 12 is below 1%. This is because most packets were under heavy collision, as the time was enough for transmitting only 13 packets with SF 12. Even for lower SFs, the PRR suffers greatly due to collisions with packets with the same SF and the interference from other SFs. Only

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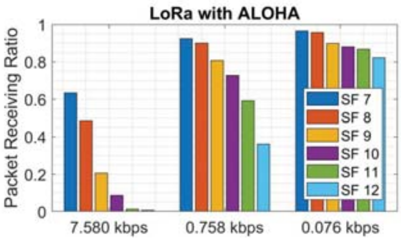
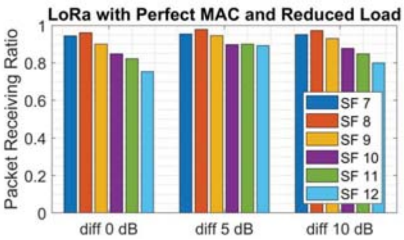


(a)



(b)

Figure 9. LoRa with mixed load.

when the load is reduced by 100 times, the PRRs of all SFs rise above 0.8.

To isolate the effects from ALOHA, another test was conducted for LoRa assuming perfect MAC, i.e., packet signals were added to the time-domain signal at random times so long as there was no collision within the same SF. The load was significantly reduced for higher SFs, as not all packets could fit in without overlapping. To be exact, the number of packets were 133, 133, 91, 54, 27, and 13, respectively, for SF 7 to 12. Fig. 9(b) shows the PRRs, where it can be seen that even with perfect MAC, LoRa can only support much lower load at lower PRR for weak nodes.

4) Summary: The head-to-head comparison between ZCNET MCS A and LoRa SF 12 confirms that ZCNET can achieve 40 times gain in capacity under the most challenging channel conditions. The test with mixed load show that ZCNET can maintain the PRRs close to or above 0.9 for load up to 7.58 kbps, where the load contains packets on all MCSs with random root channels, ranges, power levels, and starting times. LoRa, on the other hand, can reach PRRs above 0.8 with load 0.076 kbps, only 1% of ZCNET.

VIII. Conclusions

In this paper, ZCNET, a novel high capacity LPWAN technology, was proposed, which modulates data on the ZC sequences. High network capacity is achieved with a simple ALOHA-stype MAC layer, because each packet occupies only a very small range within the signal vector and enjoys low collision probability. In addition, ZCNET supports 8 root channels that do not severely interfere with each other, because weak interference is spread evenly over the signal vectors, while strong interference is removed with a simple interference canceling technique. ZCNET has been implemented and tested both with USRP in real-world experiments and simulations. The results show that ZCNET can achieve over 40 times the link layer capacity of LoRa under the most challenging channel conditions.

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