# MPCast: A Novel Downlink Transmission Technology for Low Power Wide Area Networks

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ICC 2021 - IEEE International Conference on Communications | 978-1-7281-7122-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICC42927.2021.9500584

*Abstract*—**In this paper, MPCast, a novel wireless transmission technology for the downlink of Low Power Wide Area Networks (LPWAN), is proposed. MPCast modulates data on the Zadoff-Chu (ZC) sequence, which generates a peak at the receiving side. Both the location and phase of the peak carry information. Also, multiple peaks are transmitted simultaneously at different power levels to be received by nodes with different channel conditions. A novel preamble design allows the nodes to detect the frame and synchronize with the AP at low computation complexity. MPCast has been validated with real-world experiments on the Powder platform. MPCast has also been evaluated with simulations under a challenging wireless channel model. The results show that MPCast achieves a physical layer data rate of 1.74 kbps in a 125 kHz channel when the Signal to Noise Ratio (SNR) is -7 dB, which is a 9 dB gain over LoRa SF 9.**

## I. Introduction

Low-Power Wide-Area Network (LPWAN) has attracted much attention recently as one of the key components in Internet of Things (IoT). An LPWAN may connect a very large number of low power devices to the Access Point (AP), where the devices may be scattered in a large area. While the main focus in LPWAN research has been the uplink, on which the nodes transmit data packets to the AP, the downlink also faces a number of unique challenges, namely, achieving a relatively high data rate at very low Signal to Noise Ratio (SNR), while maintaining low complexity for the nodes.

To elaborate, in an LPWAN, the downlink should carry the Acknowledgments (ACK) from the AP to the nodes, as well as allowing the nodes to synchronize with the AP. The ACK traffic can be quite heavy, demanding high data rates. For example, if the AP on average receives 50 packets per second from the nodes and every packet demands an ACK, assuming each ACK is only 24 bits, the downlink data rate should be at least 1.2 kbps, which is higher than most uplink data rates in most LPWANs. To decode the packet from the AP, the node must also detect the packet and lock to the beginning of the physical layer symbol. Note that an LPWAN is expected to operate on links with very low SNR, e.g., the AP may be required to receive packets from the nodes when the SNR is as low as -20 dB. To achieve this, the AP may employ multiple antennas and use sophisticated error correction codes, noting that the encoding process of an error correction code is typically simple and puts no burden on the nodes. The node, on the contrary, may only have a single antenna, and cannot use highly complicated algorithms for decoding and synchronization.

The challenge on the downlink can be partly addressed by allowing the AP to transmit at a higher power, e.g., 13 dB more, than the nodes [17], which raises the receiving threshold to -7 dB if the uplink threshold is -20 dB. Still, most LPWAN technologies today cannot meet the data rate requirement. In this paper, Multiple Peak Cast (MPCast), a novel LPWAN downlink transmission technology, is proposed. MPCast modulates data by varying the location and phase of the *peaks*, and achieves a Physical layer (PHY) data rate of 1.74 kbps. MPCast employs a relatively simple convolutional code for error correction that has also been used in other LPWAN technologies such as RPMA [15]. MPcast transmits multiple peaks in a symbol, hence modulates multiple packets in a single frame, where the packets are transmitted at different power levels for nodes with different channel conditions. As such, MPCast takes advantage of the broadcast nature of the donwlink and serves more than one node at a time, with very little sacrifice to performance. MPCast adopts a novel preamble design, which enables reliable synchronization at very low SNR. MPCast has been tested both with real-world transmissions over the air on the Powder platform [3], as well as simulations. The results show that MPCast enjoys 9 dB gain over LoRa SF 9 measured by the SNR value to achieve Packet Receiving Ratio (PRR) over 0.9, even with a 40% higher PHY data rate.

The rest of the paper is organized as follows. Section II discusses related work. Section III gives a quick description of the background information. Section IV gives an overview of MPCast. Section V explains the details of MPCast. Section VI describes the evaluation. Section VII concludes the paper.

## II. Related Work

Many LPWAN technologies have been proposed, including those designed for unlicensed band, such as LoRa [10], [17], Sigfox [4], Weightless-W/N/P [6], RPMA [15], [16], 802.11ah [7], IEEE 802.15.4g [11], as well as those for licensed band, such as NB-IoT [2], EC-GSM [8] and eMTC [8]. MPCast is designed specifically for the downlink of an LPWAN that may operate in an unlicensed band. As of today, LoRa appears to be the leading LPWAN technology for unlicensed band, although it still faces strong competitions in the market, such as from Sigfox, Weightless-W/N/P, and RPMA, etc. MPCast has been compared with LoRa and has demonstrated much higher physical layer reliability and higher speed. Sigfox downink message is up to 8 bytes, and may not

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sufficiently support certain applications. The communication range of Weightless is currently less than LoRa [18], therefore, will also be less than MPCast. The RPMA technology is proprietary, however, based on [15], RPMA likely has a fairly high complexity.

ZCNET [19] was recently proposed as an uplink technology for LPWAN. MPCast is designed for the downlink and complements ZCNET. MPCast shares certain common features with ZCNET, primarily the data modulation on the Zadoff-Chu (ZC) sequence, at the same time, solves many unique problems, such as synchronization under very strict complexity constraints.

## III. Preliminaries

A Zadoff-Chu (ZC) *root sequence* of length $L$, denoted as $Z$, is defined as

$$z_n = e^{-i\frac{un(n+1)}{L}} \tag{1}$$

for $n \in [0, L-1]$, where $z_n$ denotes element $n$ in $Z$ and $u$ is a selected integer [14], [12]. Currently, in MPCast, $L = 256$ and $u = 1$. Let $Z_h$ be $Z$ cyclically shifted by $h$ locations, which will be referred to as sequence $h$. A node may generate an OFDM symbol and use $L$ subcarriers to transmit $FFT(Z_h)$, where $FFT()$ denotes the FFT of a vector. Let $R$ be the complex vector observed at the $L$ subcarriers in the received symbol. Let the *signal vector*, denoted as $S$, be

$$S = IFFT[R^* \odot FFT(Z)], \tag{2}$$

where $IFFT()$ denotes the Inverse FFT of a vector, $R^*$ denotes the conjugate of $R$, and $\odot$ denotes the element-wise multiplication of two vectors. In ideal conditions, if $FFT(Z_h)$ is transmitted, a *peak* should appear at location $h$ in $S$. In practice, the peak location may be shifted due to synchronization error and Carrier Frequency Offset (CFO).

## IV. Overview

MPCast supports the downlink traffic from the AP to the nodes, where the AP is the transmitter and the nodes are the receivers. In this paper, the focus is the PHY layer. It is assumed that the AP has adopted a certain Medium Access Control (MAC) protocol to coordinate with other APs for medium access, for example, by exchanging information over the wired network. The bandwidth of the downlink channel is currently 125 kHz, the same as LoRa [17] and the uplink channel of ZCNET [19]. Each downlink time-domain ODFM symbol, referred to as *time symbol* in the following for simplicity, consists of 288 samples taken every 8 $\mu$s, in which 32 samples, i.e., 256 $\mu$s, are the cyclic prefix, which can accommodate large delay spread in long distance links.

In MPCast, the data is modulated by transmitting a peak at one of 64 candidate peak locations, as well as setting the phase of the peak to be one of 4 possible values. Therefore, each time symbol carriers 6 raw bits with peak location and 2 raw bits with peak phase. Convolutional code with rate 1/2 is used for error correction, therefore, each time symbol carriers 4 coded bits. As each time symbol is 0.002304 seconds, the PHY data rate is 1.74 kbps.

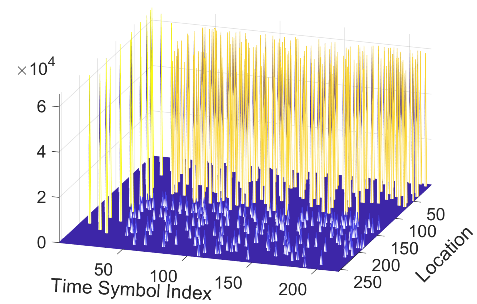

Figure 1. A typical modulated MPCast frame.

Each frame starts with the preamble, which consists of 32 time symbols, and allows the node to detect the frame and synchronize with the AP, i.e., finding the first sample of the frame. After the preamble, two packets are transmitted *in parallel*, each occupying half of the signal vector, resulting in more than one peak in the signal vector, giving MPCast its name. The packets are modulated following the same procedure described earlier. They are called the *Level 1* and *Level 2* packets, and are transmitted with 90% and 10% of the total power, respectively. Fig. 1 shows a modulated MPCast frame, where the preamble peaks are in the first 32 time symbols, followed by the peaks of two packets with different heights. The two packets carry distinct data to nodes with weak and strong channels, respectively, and allow MPCast to better adapt to the diverse channel conditions. With the current power allocation, the SNR of the strong nodes should be 10 dB higher than the weak nodes. Note that the strong nodes can still decode the Level 2 packet, while the weak nodes are hardly affected when decoding the Level 1 packet because only 10% of the power is diverted. The cost is that a node may have to decode both packets to find its data, which is still a good tradeoff between the complexity and overall network capacity. Lastly, each packet is expected to carry information to multiple nodes, because it is inefficient to transmit individual packets to each nodes due to the overhead.

## V. MPCast Design

In this section, the detailed design of MPCast is discussed.

### A. Frame Detection and Synchronization

Frame detection and synchronization are achieved by the same process at the node based on the frame preamble. In the rest of the paper, both will be referred to synchronization. Synchronization can be very challenging, especially for an LPWAN, which operates at very low SNR, at the same time, is constrained in complexity.

*1) The Preamble Construction:* The preamble consists of $M$ time symbols, each containing one peak, where $M = 32$. The peak location in time symbol $i$ is selected according to

$$q_i = \mod[\frac{i(i+1)}{2}, M]\kappa, \tag{3}$$

where $\kappa = 7$, so chosen because it is the largest prime number less than $L/M$.

MPCast adopts basically the same preamble peak generation method as in ZCNET [19] due to its desirable properties, such as evenly spreading peaks in the preamble, and high CFO estimation accuracy due to the randomization of peak locations. Eq. 3 is mathematically equivalent to that in ZCNET [19], but simpler. The following theorem is a new proof of the uniqueness of peak locations.

**Theorem 1.** $\mod [\frac{i_1(i_1+1)}{2}, M] \neq \mod [\frac{i_2(i_2+1)}{2}, M]$ *if* $i_1 \neq i_2$, *for* $i_1, i_2 \in [0, M-1]$.

*Proof.* In the appendix. □

As a result of Theorem 1, the preamble peak locations are unique with space $\kappa$ in between, therefore, are evenly spread in the entire signal vector,

*2) Synchronization Procedure at A High Level:* The node scans the received signal. It may start with an arbitrary point, and pass a segment of $\Upsilon$ time domain samples for synchronization, where $\Upsilon$ is the length of the minimum size frame in MPCast. Synchronization consists of two steps, namely the coarse and fine synchronizations, respectively. The location of the first sample of the frame will be estimated after fine synchronization. If a packet is decoded correctly based on the estimated location, synchronization is achieved. Otherwise, the node skips $\Upsilon/2$ samples and starts over again.

*3) Coarse Synchronization:* The coarse synchronization process takes an input of $\Upsilon$ time domain samples, and outputs a location, $Y_0$, which is expected to be close to the first sample of the frame. The idea is to scan the signal and compute signal vectors, which will be shifted according to the preamble peak locations. The shifted signal vectors will be added up into the *sum-vector*. When the scan reaches the actual preamble location, all $M$ peaks are aligned and the sum-vector contains a very high *aggregated peak*; otherwise, the peaks are not aligned and the peaks in the sum-vector are much lower. Therefore, the highest aggregated peak indicates the location of the preamble.

To elaborate, let $\eta$ and $T$ denote the lengths of the cyclic prefix and the complete time symbol, respectively, which are currently 32 and 288. Note that $\eta + L = T$. In the $\Upsilon$ samples, every $\eta$ samples is a *candidate starting point*. Starting at a candidate starting point, $MT$ time-domain samples are used to calculate $M$ signal vectors. The signal vectors will be reversely shifted according to the peak locations in Eq. 3, and the power of the signal vectors will be added up as the sum-vector. Note that the summation is not over the complex signal vectors, because the CFO has not been adjusted yet. The candidate starting point that produces the highest aggregated peak will be selected as $Y_0$, because the aggregated peak should be the highest if the first sample of the frame is within the interval of $[Y_0, Y_0 + \eta - 1]$.

*4) CFO Estimation and Fine Synchronization:* Fine synchronization outputs a location, denoted as $Y$, which is expected to be the location of the first sample of the frame. However, before fine synchronization, the CFO must be corrected, because CFO also leads to peak shift.

To find the CFO, the signal vectors of the preamble computed starting at $Y_0$ are examined. The complex signal values at the expected preamble peaks are extracted as a vector, denoted as $\zeta$. When the CFO is 0, the phases of the elements in $\zeta$ should be the same. However, with non-zero CFO, the phases will not be aligned. In MPCast, the set of possible CFOs, which are from $[-5\omega, 5\omega]$ at a step of $0.02\omega$, are tested, where $\omega$ denotes the subcarrier spacing. Let $f_i$ denote the $i^{th}$ possible CFO value. Let $\nu_i$ be the vector denoting the phase shift caused by $f_i$. Let $\gamma_i = \sum_{l=0}^{M-1} \zeta_l \nu_{i,l}^*$, where $\nu_i^*$ denotes the conjugate of $\nu_i$. Let $\gamma_{i1}$, $\gamma_{i2}$, and $\gamma_{i3}$ be the top 3 highest values, which will be considered the candidate CFO values. CFO values of $f_{i1}$, $f_{i2}$, and $f_{i3}$ will be applied to the time symbols of the preamble, and the one that produces the highest aggregation peak is used as the estimate of CFO.

Note that, ideally, the highest aggregation peak should be at location 0. If, instead, it is at location $d$ after CFO has been corrected, there must be a residual synchronization error. In most cases, $d < L/2$, and the output of fine synchronization is $Y = Y_0 - d$. Otherwise, $Y = Y_0 + L - d$.

*5) Complexity:* The computation complexity of synchronization is reasonably low in practice, first because during coarse synchronization, the main computation is to compute a signal vector every $\eta$ samples, which is only 9 times higher than during normal packet reception, because $T/\eta = 9$ with the current parameters. Second, during CFO estimation and fine synchronization, the main computation is to attempt the possible CFO values on $\zeta$, which however is still reasonably simple because the length of $\zeta$ is currently only 32. Also, note that the complexity discussed above is for the worst case, because it assumes that the node does not have any knowledge about the AP and is searching for the AP for the first time. After the node has associated with the AP, it can actually use the past history to simplify the synchronization process. For example, if the time drift is within a certain bound, the node does not need to try all candidate starting points, and may try only those agree well with the frames received from the AP in the past.

*6) Resilience Against Off-Sync Errors:* The preamble design also mathematically provides additional resilience against errors. Let $\tau$ denote the *off-sync value*, i.e., when the candidate starting point is $\tau$ time symbols earlier than the first sample of the actual preamble, noting that $\tau$ can also be negative. Let $V_\tau$ denote the *maximum overlapping preamble peak number*, i.e., the maximum number of peaks in the preamble that appear at the same location after the shift, when the off-sync amount is $\tau$. Clearly, $V_0 = M$. Theorem 2 establishes that $V_\tau$ is significantly less than $M$ for $\tau \neq 0$, hence, will not produce a peak higher than when $\tau = 0$.

**Theorem 2.** *Let* $\tau = \tau' 2^n$, *where* $\tau'$ *is an odd number. Then,* $V_\tau \leq \left\lceil \frac{(M-\tau)2^n}{M} \right\rceil$, *where* $\lceil\rceil$ *denote the ceiling of a real number.*

*Proof.* In the appendix. □

Based on Theorem 2, the maximum number of overlapping peaks with a non-zero off-sync value is $\frac{M}{4}$ when $\tau = \pm\frac{M}{2}$, making it practically impossible to produce an aggregated peak higher than when $\tau = 0$. It may be worth noting that the preamble in LoRa consists of 10 symbols, where peaks in the first 8 symbols take one location and those in the last 2 symbols take another location. Therefore, for LoRa, $V_1 = 8$, making it more vulnerable to timing errors. Also, the off-sync situation need not be considered in the uplink in [19], because the node is expected to have synchronized to the AP and should start the frame at an expected time symbol.

### *B. An Open-Loop Multiple Antenna Technique*

MPCast adopts a simple open-loop MISO technique, which is briefly explained here with the preamble as an example due to the space limitation. Let $A$ be the number of antennas at the AP. Let $S_k$ be the complex sinusoid on frequency $2\pi(k-1)/A$ for $k = [0, A-1]$. $S_k$ is referred to as *MISO code k*. Let $S_{k,l}$ be element $l$ in $S_k$. Let $W_h$ be the baseband waveform of time symbol $h$ in the preamble. The signal transmitted by antenna $l$ is $\frac{W_h S_{\lceil \frac{hA}{M} \rceil, l}}{\sqrt{A}}$. The benefit is that the received signal is the summation of signals from all transmitting antennas, which results in lower probability of deep fading. Note that traditional MISO techniques, such as the Alamouti scheme [9], need to learn the Channel State Information (CSI) from the training symbols, which may have to be frequently inserted in an LPWAN scenario due to the long symbol time, resulting in large system overhead.

### *C. Packet Transmission and Reception*

The packet consists of the PHY header and the data. The CRC is treated as part of the data.

*1) PHY Header Encoding and Decoding:* The PHY header contains 6 bits of data, which encodes the packet length information. The header also has a 4 bit CRC. The 10 bits are encoded according to a $(4, 2)$ RS code on $GF(2^6)$. The PHY header is modulated on 4 time symbols at the beginning of the packet. Each time symbol contains one peak with cardinality 64, mapping to one symbol of the RS code. Only 1024 codewords are used. The receiver decodes the header by trying all 1024 codewords. For example, if the number of antennas at the AP is 1, for each codeword, the complex signals at the expected peak locations are added up as the *weight* of this codeword. Note that the peak signal phases should have been aligned after correcting the CFO. Therefore, the actual transmitted codeword should have the highest weight. If the AP has 2 or more antennas and uses the open-loop MISO technique discussed in Section V-B, the first two and the last two time symbols use different MISO codes. Therefore, the complex values in the first two and the last two time symbols are added separately, and their power values are added as the weight.

*2) Data Modulation and Demodulation:* As mentioned earlier, MPCast modulates data on the phase and location of the peaks. With the current parameters, a peak may appear at 1 of 64 *candidate locations*. The candidate locations are evenly spaced in a range of 128 locations, with one point in between two candidate locations to better cope with larger delay spread. The phase difference between peaks in consecutive time symbols may be 1 of 4 values in $\{0, \pi/2, \pi, 3\pi/2\}$. However, every 50 time symbols, the phase of the peak is used as a pilot and does not modulate data, at which point the MISO code can be changed.

The packet from the upper layer is treated as a bit vector, and partitioned into two segments, denoted as $\Phi$ and $\Psi$, to be modulated with the peak location and phase, respectively. Both segments are encoded with the same convolutional code into codewords. Currently, the convolutional code is the same as that used in Wi-Fi with coding rate $1/2$, which is defined according to two polynomials $1 + x^2 + x^3 + x^5 + x^6$ and $1 + x + x^2 + x^3 + x^6$. Note that convolutional code has also been used in other LPWAN technologies such as RPMA [15]. The two codewords are separately interleaved. The interleaved location codeword is used to determine the locations of the peaks. The interleaved phase codeword is used to determine the phases of the peaks.

At the receiver side, the location codeword is first decoded. For each time symbol, the receiver first converts the *location symbol*, i.e., the observed power values at the 64 candidate peak locations, into the soft values of 6 individual bits, which are expected by the convolutional code decoder, according to a simple heuristic. For any bit, let the 0-locations be the locations with this bit being 0 in their binary indices, and 1-locations those being 1. Let $P_0$ and $P_1$ be the highest power values at the 0-locations and 1-locations, respectively. The symbol value is denoted as $y$, and satisfies

$$\frac{(y-1)^2}{(y+1)^2} = \frac{P_0}{P_1}, \tag{4}$$

i.e., the square of the distance of $y$ to the BPSK constellation points, which represents the noise power, is reversely proportional to $P_0$ and $P_1$. The choice of solution is

$$y = \frac{1 - \sqrt{\frac{P_0}{P_1}}}{1 + \sqrt{\frac{P_0}{P_1}}}. \tag{5}$$

Note that the main benefit of this approach is simplicity and compatibility with any FEC code developed for BPSK symbols. The soft values are then deinterleaved, and passed to decoding. Suppose the output is bit vector $\hat{\Phi}$, which should be identical to $\Phi$ if there is no error.

The receiver encodes $\hat{\Phi}$ and interleaves the codeword, after which the actual peak locations can be found. The phases values of the peaks will be read, which are standard QPSK, and will be passed to decoding. Suppose the output is bit vector $\hat{\Psi}$. The receiver concatenates $\hat{\Phi}$ with $\hat{\Psi}$ as the final output. The CRC will pass if there is no error.

## VI. Evaluation

MPCast has been experimentally validated with USRP X310 [1] in the Powder wireless platform [3] and tested simulations.

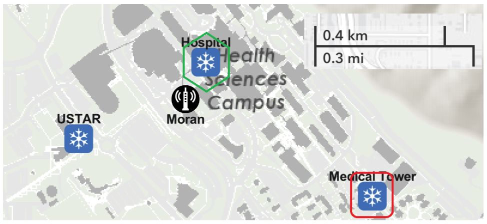


Figure 2. The radio locations in the experiments. Hexagon: transmitter (cbrssdr1-hospital). Square: receiver (cbrssdr1-smt).

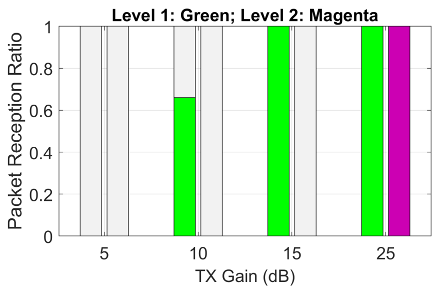


Figure 3. PRR of MPCast in the experiment.

### A. *Experimental Validation*

The experiments were conducted with the X310 USRP [1] in the Powder wireless platform [3], which hosts radios that can be reserved and controlled remotely. The transmitter and receiver locations in the experiments are shown in Fig. 2. The baseband waveform of 100 frames are first generated and saved in a file. As described in Section IV, each frame contains a Level 1 packet and a Level 2 packet, where both are 90 bytes in the experiment. The transmitter USRP basically plays the file. The receiver USRP receives the signals, which are saved as files and decoded by the decoding program. The carrier frequency is 3.675 GHz. Due to the minimum sampling rate limitation of X310, the sampling rate is raised to 500 kHz. The number of transmitter antenna is 1.

The PRRs of 4 transmissions are shown in Fig. 3, with the transmission power gains at 5, 10, 15, and 25 dB, respectively. It can be seen that successful transmissions have been achieved for both Level 1 and Level 2 packets. For example, when the transmission power gain is 25 dB, the PRRs of both Level 1 and Level 2 packets are 1. At lower transmission power gains, Level 2 packets cannot be received, but Level 1 packets can still be received. For example, when the transmission power gain is 10 dB, the PRR of Level 1 packets is 0.66.

The main limitation of the experimental validation is that the number of available links are small and are subject to interference, making it difficult to run a quantitative comparison. For example, the theoretical SNR threshold difference of Level 1 and Level 2 packets should be around 10 dB, which however has not been fully validated with the experiments. Therefore, the experiments mainly serve as a proof-of-concept demonstration of MPCast over a real-world wireless link. For a more quantitative evaluation, simulation is used, as described in the following.

### B. *Comparing with LoRa with Simulation*

MPCast is compared with LoRa with simulation in Matlab, where the channel model is the LTE ETU channel model, which represents challenging channel conditions with large delay spread.

*1) MPCast in the Simulation:* In the simulation, MPCast frames are generated in exactly the same manner as in the experiments. CFO randomly selected in $[-5\omega, 5\omega]$, where $\omega$ is the subcarrier spacing, is applied to the modulated frame. To test the synchronization of MPCast, an all-zero vector with length randomly selected in $[0, \Upsilon - 1]$ is added before the frame, where $\Upsilon$ is the length of the MPCast frame. The frame is then passed to the channel model, and added with noise. The number of antennas for MPCast is 2.

*2) LoRa in the Simulation:* LoRa implementation at [5], [13] is used in the comparison, with some additional CFO estimation code. The FEC code rate of LoRa is 4/7. LoRa supports multiple data rate by varying the Spread Factor (SF). SF 9 is used in the comparison because its PHY data rate is 1.25 kbps, which is lower than but closest to the data rate of MPCast. The number of antenna for LoRa is 1, because LoRa does not support a multiple antenna technique at the sender side. The same packet size as MPCast is used.

LoRa decoding is relaxed, which has significantly improved its performance. First, frame detection and synchronization are made perfect by informing the decoding program the actual starting point of the LoRa frame in the simulation. Second, it was found that, inside the same LoRa packet, some peaks are often off by just 1 position, while others are 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 in the simulation.

*3) Results:* Fig. 4 shows the PRRs of the two packet levels in MPCast and LoRa SF 9 as functions of the SNR. It can be seen that MPCast enjoys significant gain over LoRa. For example, suppose the PRR of a link should be 0.9 or higher to be considered functional. For MPCast Level 1, the SNR threshold is -7 dB, which is a 9 dB gain over LoRa, because the threshold of the latter is 2 dB. Note that this is achieved even when the PHY rate of MPCast is 40% higher than LoRa, and 10% of power has been diverted to the packet at Level 2. It can also been seen that, at sufficiently high SNR, the Level 2 packet of MPCast can be received correctly along with the Level 1 packet, and the gap is indeed about 10 dB.

## VII. Conclusions

In this paper, MPCast, a novel broadcast technology for LPWAN downlink, was proposed. MPCast modulates data by varying the location and phase of the transmitted peak, and achieves sufficiently high data rate to support the downlink traffic from the AP to the nodes. MPCast also adapts to the diverse channel conditions by transmitting two packets in parallel in a single frame at different power levels. A novel preamble design allows synchronization at very low SNR with reasonable decoding complexity. MPCast has been validated by real-world experiments performed on the Powder platform.

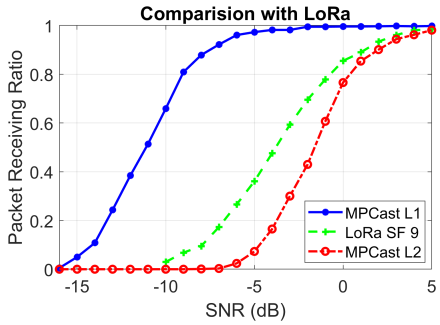

Figure 4. PRR of MPCast and LoRa SF 9.

MPCast has also been evaluated with simulations, and the results show that MPCast achieves 9 dB SNR gain over LoRa even when its data rate is 40% higher.

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## APPENDIX

*Proof of Theorem 1:* Suppose the theorem is not true, i.e., there exist $i_1 \neq i_2$ but

$$\frac{i_1(i_1+1)}{2} - \frac{i_2(i_2+1)}{2} = pM$$

for some integer $p$. As a result,

$$(i_1+i_2+1)(i_1-i_2) = 2Mp,$$

which is not possible. This because there is only one even number among $(i_1+i_2+1)$ and $(i_1-i_2)$, and without loss of generality, suppose it is $(i_1+i_2+1)$. As a result, $2M$, which is $2^6$, must be a factor of $(i_1+i_2+1)$. This is a contradiction because $(i_1+i_2+1) < 2M$. ■

*Proof of Theorem 2:* For simplicity, in this proof, it is assumed that the signal peak is at the expected peak location defined in Eq. 3, because although timing error and CFO may shift the signal vectors, the shift is same for all signal vectors, and the same proof applies to all possible shift values. Also for simplicity, the off-sync value is assumed to be positive, as a nearly identical proof can be used for negative off-sync values.

When the off-sync value is $\tau$, the signal vector of time symbol $i$ will be shifted according to the preamble peak location in time symbol $i+\tau$. Denote the peak location after the shift as $\lambda_{i,\tau}$. Refer to the shift as *Case 1* if

$$\mod\left[\frac{i(i+1)}{2}, M\right] > \mod\left[\frac{(i+\tau)(i+\tau+1)}{2}, M\right],$$

and otherwise, *Case 2*. In Case 1, after the shift,

$$\lambda_{i,\tau} = \mod\left[-i\tau - \frac{\tau(\tau+1)}{2}, M\right]\kappa,$$

otherwise, i.e., in Case 2,

$$\lambda_{i,\tau} = \mod\left[-i\tau - \frac{\tau(\tau+1)}{2}, M\right]\kappa + L - M\kappa.$$

The claim is that for $i_1 \neq i_2$, $\lambda_{i_1,\tau} \neq \lambda_{i_2,\tau}$ unless

$$i_1 = i_2 + p\frac{M}{2^n}$$

for some integer $p$. To see this, suppose the claim is not true, that is,

$$i_1 = i_2 + p\frac{M}{2^n} + x$$

for some integers $p$ and $x$, where $0 < x < \frac{M}{2^n}$, but $\lambda_{i_1,\tau} = \lambda_{i_2,\tau}$. Note that if one of $i_1$ and $i_2$ is in Case 1 and the other is in Case 2, $\lambda_{i_1,\tau} \neq \lambda_{i_2,\tau}$, because $L - M\kappa$ is not a multiple of $\kappa$. Consider when both $i_1$ and $i_2$ are in Case 1, because, clearly, the same proof applies when both $i_1$ and $i_2$ are in Case 2. Then,

$$(i_1 - i_2)\tau = yM$$

for some integer $y$. Note that

$$\begin{aligned}(i_1-i_2)\tau &= (p\frac{M}{2^n} + x)\tau \\ &= \tau' pM + \tau' 2^n x,\end{aligned}$$

which implies that

$$\tau' x = z\frac{M}{2^n}$$

for some integer $z$, which is impossible, because $\tau'$ is an odd number, while $0 < x < \frac{M}{2^n}$.

Therefore, at most, the shifted peaks may overlap every $\frac{M}{2^n}$ time symbols. ■