Letters

A New Index Modulation for LoRa

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***Abstract*—Long range (LoRa) is a widely adopted Internet of Things (IoT) technique, but its fatal limit is a low-data rate. In this letter, we propose a new index modulation for LoRa to increase the data rate, in which multiple quasi-orthogonal chirps modulated under different spreading factors (SFs) are concurrently transmitted, thereby leveraging the SF domain as a means to carry more information. Both the coherent and noncoherent detection algorithms for the proposed index modulation are also developed in efficient forms. Numerical results demonstrate that the proposed scheme notably outperforms the state-of-the-art techniques.**

***Index Terms*—Chirp spread spectrum, index modulation, Internet of Things (IoT), long-range (LoRa).**

I. INTRODUCTION

LONG range (LoRa) is one of the widely used techniques for Internet of Things (IoT), of which signal modulation is based on chirp spread spectrum. Though LoRa provides a balanced tradeoff between coverage and throughput, its data rate is generally low,[1] which is problematic in practical applications requiring higher data rates, such as energy management, multimedia service, surveillance/security, etc.

To struggle this limitation and increase the data rate, in the literature, several variants of LoRa have recently been developed, such as interleaved chirp spreading LoRa (ICS-LoRa) [2], slope-shift-keying LoRa (SSK-LoRa) [3], and frequency-shift chirp spread spectrum with index modulation (FSCSS-IM) [4]. In [2], [3], and [4], interleaved chirps, up/down chirps, and superimposed chirps were used, respectively, to carry more information than the conventional LoRa given the same bandwidth. However, the performance improvements of ICS-LoRa in [2] and SSK-LoRa in [3] are quite marginal as only one more bit is embedded. Although the FSCSS-IM in [4] achieves higher data rates than the ICS-LoRa and SSK-LoRa, its performance improvement is still marginal and a relatively high complexity is required for demodulation.

Motivated by these, in this letter, we propose a novel and high-performing index modulation scheme for LoRa, which exploits multiple quasi-orthogonal chirps with different spreading factors (SFs) as a means of conveying much information, substantially increasing the data rate. Both the coherent and noncoherent detection algorithms for the proposed index modulation are also presented in tractable forms. Numerical results demonstrate substantial performance improvements of the proposed scheme in terms of the data rate.

II. PROPOSED INDEX MODULATION FOR LORA

The key idea of the proposed index modulation is to concurrently transmit multiple quasi-orthogonal chirps modulated with different SFs, thereby effectively utilizing the SF values of the chirps as a new means to carry information (along with the initial frequencies of the chirps). Suppose that total K distinct SF values are available, where the kth SF value is denoted by S_k, $k = 1, 2, \ldots, K$. Also, $S_1 > S_2 > \cdots > S_K$. In practice, $S_k \in \{7, \ldots, 12\}$ [5].

In the proposed index modulation, total $\sum_{k=1}^{K}(N_1/N_k)S_k$ bits are carried via $\sum_{k=1}^{K}(N_1/N_k)$ chirps, where $N_k \triangleq 2^{S_k}$. Specifically, $\sum_{k=1}^{K}(N_1/N_k)S_k$ bits are divided into K blocks, where the kth block is assigned $(N_1/N_k)S_k$ bits. The kth block is further divided into (N_1/N_k) sub-blocks. The ith sub-block is assigned S_k bits that are mapped into a chirp $\boldsymbol{x}_k(i) \in \mathbb{C}^{N_k\times 1}$

$$\boldsymbol{x}_k(i) = \left\{ e^{j2\pi\left[\left(\frac{m_k(i)}{N_k}-\frac{1}{2}\right)n+\frac{n^2}{2N_k}\right]} : n = 0, 1, \ldots, N_k - 1 \right\} \quad (1)$$

for $i = 1, 2, \ldots, (N_1/N_k)$ [1], where $m_k(i) \in \{0, 1, \ldots, N_k - 1\}$ is the information symbol. The transmitted signal (or message) is then formed by superposing the modulated chirps over the whole K blocks as $\boldsymbol{x} = (1/\sqrt{K})\sum_{k=1}^{K}\boldsymbol{x}_k$,[2] where $\boldsymbol{x}_k = \left[\boldsymbol{x}_k^{\mathsf{T}}(1), \boldsymbol{x}_k^{\mathsf{T}}(2), \ldots, \boldsymbol{x}_k^{\mathsf{T}}([N_1/N_k])\right]^{\mathsf{T}} \in \mathbb{C}^{N_1\times 1}$ is the concatenation of all modulated chirps in the kth block.

III. DETECTION ALGORITHMS

Under the quasi-static block fading, the received signal is given by $\boldsymbol{y} = h\boldsymbol{x} + \boldsymbol{w} \in \mathbb{C}^{N_1\times 1}$, where $h \in \mathbb{C}$ and $\boldsymbol{w} \in \mathbb{C}^{N_1\times 1}$ are the fading channel and the received noise, respectively. The probability distribution function of $\boldsymbol{w}$ is $f(\boldsymbol{w}) = (1/[(\pi\sigma^2)^{N_1}])\exp(-[\|\boldsymbol{w}\|^2/\sigma^2])$.

A. Coherent Detection Algorithm

When the channel state information (CSI) is available (i.e., h is known) at the receiver, the coherent detection yields the optimal performance. For equi-probable messages, the optimal estimate of the transmitted signal with the minimal probability of detection error can be obtained according to the maximum likelihood (ML) criterion as follows:

$$\begin{aligned}\hat{\boldsymbol{x}} &= \arg\max_{\boldsymbol{x}} \left\{ f(\boldsymbol{y}|\boldsymbol{x}, h) = \frac{1}{(\pi\sigma^2)^{N_1}} \exp\left(-\frac{\|\boldsymbol{y}-h\boldsymbol{x}\|^2}{\sigma^2}\right)\right\} \\ &= \arg\min_{\boldsymbol{x}} \|\boldsymbol{y} - h\boldsymbol{x}\|^2 = \arg\max_{\boldsymbol{x}} \operatorname{Re}\left\{h^*\boldsymbol{x}^{\mathsf{H}}\boldsymbol{y}\right\} \end{aligned} \quad (2)$$

over all possible combinations of $\mathcal{M} \triangleq \{m_k(i) \in \{0, 1, \ldots, N_k - 1\} : i = 1, \ldots, (N_1/N_k), k = 1, \ldots, K\}$. Unfortunately, however, the naive ML detection in (2) requires an overwhelmingly high-computational complexity.

With the aim of addressing this complexity issue, in what follows, we develop a much more efficient version of (2) by exploiting the quasi-orthogonality of the modulated chirps in the proposed scheme

$$\boldsymbol{x}_k^{\mathsf{H}}\boldsymbol{x}_\ell \approx 0, \quad 1 \le k \ne \ell \le K \quad (3)$$

over all possible combinations of $\mathcal{M}$ [5]. Specifically, using (3), it can be shown that the ML detection in (2) can be decomposed into

$$\hat{\boldsymbol{x}}_k(i) = \arg\max_{\boldsymbol{x}_k(i)} \operatorname{Re}\left\{h^*\boldsymbol{x}_k^{\mathsf{H}}(i)\,\boldsymbol{y}_k(i)\right\}, \quad \forall i, k \quad (4)$$

each over $m_k(i) \in \{0, 1, \ldots, N_k - 1\}$, where $\boldsymbol{y}_k(i)$, $i = 1, \ldots, (N_1/N_k)$, are partitions of $\boldsymbol{y}$, each of size N_k, such that $\boldsymbol{y} = \left[\boldsymbol{y}_k^{\mathsf{T}}(1), \boldsymbol{y}_k^{\mathsf{T}}(2), \ldots, \boldsymbol{y}_k^{\mathsf{T}}(N_1/N_k)\right]^{\mathsf{T}}$. From (4), therefore, the

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[1] LoRa achieves a higher data rate with a lower SF, but this may not always provide the best solution because the improvement is still strictly limited.

[2] The peak-to-average power ratio of the transmitted signal $\boldsymbol{x}$ is no more than K.

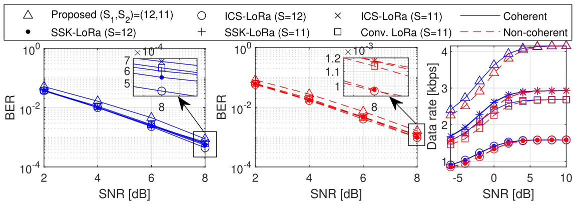

Fig. 1. Performance comparisons with the conventional LoRa, ICS-LoRa, and SSK-LoRa.

detection complexity can be substantially reduced. Intriguingly and importantly, it is possible to further reduce the detection complexity by leveraging the inherent property of the modulated chirps in (1) as follows.

Proposition 1: The coherent detection for the proposed index modulation can be performed efficiently via the following algorithm.

Step 1) Dechirp $\boldsymbol{y}_k(i)$ as

$$\tilde{\boldsymbol{y}}_k(i) = \tilde{\boldsymbol{x}}_k \odot \boldsymbol{y}_k(i) \quad \forall i, k \tag{5}$$

where $\tilde{\boldsymbol{x}}_k \triangleq \{e^{j2\pi[(n^2/2N_k)-(n/2)]}: n = 0, \ldots, N_k - 1\}$ is the base chirp for S_k (i.e., $\boldsymbol{x}_k(i)$ modulated with $m_k(i) = 0$).

Step 2) Take the discrete Fourier transform (DFT) of $\tilde{\boldsymbol{y}}_k(i)$ as

$$\tilde{Y}_{k,m}(i) = \sum_{n=0}^{N_k-1} \tilde{y}_{k,n}(i)\, e^{-j2\pi mn/N_k} \quad \forall i, k \tag{6}$$

where $\tilde{y}_{k,n}(i)$ denotes the nth entry of $\tilde{\boldsymbol{y}}_k(i)$.

Step 3) Detect the symbol of $\boldsymbol{x}_k(i)$ via

$$\hat{m}_k(i) = \underset{m \in \{0,1,\ldots,N_k-1\}}{\arg\max} \ \mathrm{Re}\left\{h^* \tilde{Y}_{k,m}(i)\right\} \quad \forall i, k. \tag{7}$$

Since the DFT in step 2) can be implemented via the fast Fourier transform (FFT), the computational complexity of the coherent detection algorithm in Proposition 1 is given by $\mathcal{O}(N_1 \sum_{k=1}^{K} \log N_k)$, which is much lower than that of the naive ML detection in (2).

B. Noncoherent Detection Algorithm

In certain situations, the CSI might not be available at the receiver such that the coherent detection cannot be used. To tackle this issue, we also develop a noncoherent detection algorithm for the proposed index modulation based on the generalized likelihood ratio test (GLRT) approach as follows: $\hat{\boldsymbol{x}} = \arg\max_{\boldsymbol{x}} f(\boldsymbol{y}|\boldsymbol{x}, \hat{h})$ over all possible combinations of $\mathcal{M}$, where $\hat{h} = \arg\max_h f(\boldsymbol{y}|\boldsymbol{x}, h) \propto \boldsymbol{x}^{\mathsf{H}}\boldsymbol{y}$ is the ML estimate of h. Thus, we have

$$\hat{\boldsymbol{x}} = \underset{\boldsymbol{x}}{\arg\max} \left|\boldsymbol{x}^{\mathsf{H}}\boldsymbol{y}\right| \tag{8}$$

over all possible combinations of $\mathcal{M}$. Note that (8) is a noncoherent version of the naive ML detection in (2), which requires no CSI but still incurs a very high-computational complexity due to the exhaustive searching. To address this issue, we propose a suboptimal, yet effective and efficient, noncoherent detection scheme for the proposed index modulation with a low complexity, which decompose (8) as follows:

$$\hat{\boldsymbol{x}}_k(i) = \underset{\boldsymbol{x}_k(i)}{\arg\max} \left|\boldsymbol{x}_k^{\mathsf{H}}(i)\, \boldsymbol{y}_k(i)\right|, \quad \forall i, k \tag{9}$$

each over $m_k(i) \in \{0, 1, \ldots, N_k - 1\}$. Also, using (1), a more efficient version of (9) can be developed, as presented in the following.

Proposition 2: The noncoherent detection for the proposed index modulation can be performed efficiently via the algorithm in Proposition 1 with step 3) replaced by the following.

Step 3) Detect the symbol of $\boldsymbol{x}_k(i)$ via

$$\hat{m}_k(i) = \underset{m \in \{0,1,\ldots,N_k-1\}}{\arg\max} \left|\tilde{Y}_{k,m}(i)\right| \quad \forall i, k. \tag{10}$$

The noncoherent detection algorithm in Proposition 2 requires a very low-computational complexity of $\mathcal{O}(N_1 \sum_{k=1}^{K} \log N_k)$.

IV. Numerical Results

First, through the simulations, the performance of the proposed scheme is evaluated and compared to that of the conventional LoRa, ICS-LoRa, and SSK-LoRa in terms of bit error rate (BER) and (effective) data rate versus signal-to-noise ratio (SNR) for a Rician fading channel with unit average power and the K-factor set to 10 dB. Also, the bandwidth, denoted by B, is set to 500 kHz and S denotes the SF value for the conventional LoRa, ICS-LoRa, and SSK-LoRa.

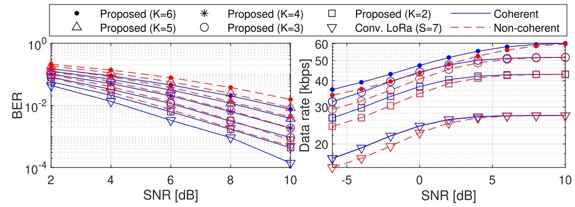

Fig. 2. Performance comparisons between the proposed scheme with various K and the conventional LoRa with $S = 7$.

TABLE I
Maximum Achievable Data Rates of Various Schemes [Bits/s]

LoRa	ICS-LoRa [2]	SSK-LoRa [3]	FSCSS-IM [4]	**Proposed**
$\frac{B}{N}S$	$\frac{B}{N}(S+1)$	$\frac{B}{N}(S+1)$	$\frac{B}{N}\lfloor\log_2\binom{N}{K}\rfloor$	$\sum_{k=1}^{K}\frac{B}{N_k}S_k$

In Fig. 1, the performance of the proposed scheme is compared to that of the conventional LoRa, ICS-LoRa, and SSK-LoRa when $(S_1, S_2) = (12, 11)$ and $S \in \{12, 11\}$. It can be seen that the proposed scheme achieves much higher data rates than the other schemes (by more than 151% improvement), thereby validating the effectiveness of the proposed scheme. The performance gap in terms of the data rate is observed to be more pronounced as the SF values decrease. While the BER of the proposed scheme is (slightly) larger than those of the other schemes due to the sensitivity issue.[3]

In Fig. 2, the performance of the proposed scheme with various K is compared to that of the conventional LoRa with $S = 7$. For the proposed scheme, we set $S_k = 7 + (K - k)$, $k = 1, \ldots, K$. From Fig. 2, we can observe that the data rate of the proposed scheme is much higher than the largest data rate of the conventional LoRa with $S = 7$. The difference between the data rates of the proposed scheme and the conventional LoRa increases as K increases. Even when K is small (e.g., $K = 2$), the proposed scheme still significantly outperforms the conventional LoRa in terms of the data rate.

Next, in Table I, we present the maximum achievable data rates of the various schemes to theoretically substantiate the superiority of the proposed scheme. For example, suppose that $B = 500$ kHz. Then, the conventional LoRa attains at most 2.69 kb/s when $S = 11$ and the ICS-LoRa or SSK-LoRa attains at most 2.93 kb/s when $S = 11$, whereas the proposed scheme even achieves at least 4.15 kb/s with $K = 2$ and $(S_1, S_2) = (12, 11)$,[4] yielding over 142% improvement.

V. Conclusion

The novel index modulation for LoRa, which significantly outperformed the state-of-the-art techniques, has been proposed, and efficient coherent and noncoherent detection algorithms have also been developed.

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[3]To be specific, S bits of the conventional LoRa and $S + 1$ bits of the ICS-LoRa or SSK-LoRa have the sensitivity corresponding to the SF value of S, while $\sum_{k=1}^{K}(N_1/N_k)S_k$ bits of the proposed scheme have the mixed sensitivity corresponding to multiple SF values of $S_1, \ldots, S_K$.

[4]For the same time interval as the proposed scheme with $(S_1, S_2) = (12, 11)$, the ICS-LoRa or SSK-LoRa with $S = 11$ accommodates two symbols with 24 bits, but its data rate still remains 2.93 kb/s.