MIMO-LoRa for High-Data-Rate IoT: Concept and Precoding Design

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***Abstract*—Long range (LoRa) is a widely adopted modulation scheme for Internet of Things (IoT), but its data rate is low. To tackle this problem, in this letter, we introduce a novel concept of MIMO-LoRa: an integration of multiple-input multiple-output (MIMO) and LoRa for achieving high data rates. We also design a precoding for the proposed MIMO-LoRa system to further enhance the link reliability. The validity and effectiveness of the proposed MIMO-LoRa system are demonstrated through numerical simulations.**

***Index Terms*—Internet of Things (IoT), long range (LoRa), multiple-input multiple-output (MIMO), precoding.**

I. Introduction

Long range (LoRa), which is based on a chirp spread spectrum, has become one of the most popular and widely adopted solutions globally among low-power wide-area network (LPWAN) technologies developed for Internet of Things (IoT) [1]. Although the LoRa provides extensive coverage areas (up to a few 10 km), its data rate is low, which is a fatal drawback to supporting several important IoT applications requiring high data rates (such as emergent cases, multimedia IoT systems, video streaming, disaster monitoring, etc.).

Meanwhile, multi-antenna technologies have the outstanding capability to increase throughput and improve link reliability [2]. Thus, these technologies can provide great potential for LoRa. In the literature, such as in [3] and [4], multi-antenna technologies have been utilized in LoRa systems, but aimed only at enhancing the link reliability. Thus, the data rates of such LoRa systems are still low to support the high-data-rate IoT applications.

With the aim of breaking through such limitation, in this letter, we develop a novel integration of multiple-input multiple-output (MIMO) and LoRa system, namely, the MIMO-LoRa system, to achieve high data rates.[1] Two MIMO-LoRa system architectures are proposed: one with no precoding and the other with precoding. The former significantly increases the data rate of the LoRa modulation, while the latter balances between the data rate and link reliability. In addition, we demonstrate the superior performance and effectiveness of the proposed MIMO-LoRa systems through numerical results.

II. MIMO-LoRa

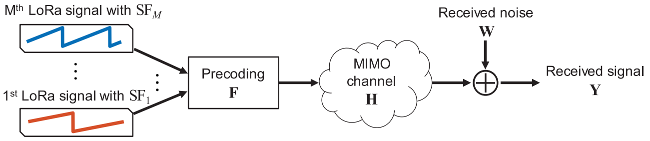

Fig. 1. System model of MIMO-LoRa.

TABLE I
Number of Information Bits of Various LoRa Systems

MIMO-LoRa (no precoding)	**MIMO-LoRa (with precoding)**	Non-MIMO-LoRa [5]	Conventional LoRa
$\sum_{i=1}^{M} \mathrm{SF}_i$	$\sum_{i=1}^{m} \mathrm{SF}_i$	SF_1+1	SF_1

We consider a point-to-point MIMO wireless communication link adopting the LoRa modulation. Suppose that a transmitter and a receiver are equipped M and L antennas, respectively.[2] The proposed MIMO-LoRa system is depicted in Fig. 1, which works as follows. Each transmit antenna carries a LoRa signal modulated with its own information symbol. To avoid interference among the LoRa signals, we choose different spreading factors (SFs) for the LoRa signals of different transmit antennas (although our analysis can be easily extended to the case when some of the LoRa signals have the same SF). Let SF_i be the SF used by the ith transmit antenna and suppose that $\mathrm{SF}_1 > \mathrm{SF}_2 > \cdots > \mathrm{SF}_M$. Then, the LoRa signal transmitted through the ith transmit antenna over $N \triangleq 2^{\mathrm{SF}_1}$ time slots can be expressed as [6]

$$x_i(n) = e^{j2\pi\left[\left(\frac{s_i}{N}-\frac{1}{2}\right)n+\frac{n^2}{2N}\right]}, \quad n = 0, 1, \ldots, N-1 \tag{1}$$

where $s_i \in \{0, 1, \ldots, 2^{\mathrm{SF}_i}\}$ is the information symbol. The received signal at the receiver is then given by

$$\mathbf{Y} = \mathbf{HX} + \mathbf{W} \tag{2}$$

where $\mathbf{H} \in \mathbb{C}^{L\times M}$ is the MIMO channel matrix and $\mathbf{W} \in \mathbb{C}^{L\times N}$ denotes the received noise matrix whose elements are identically and independently distributed with zero mean and variance σ^2. Also[3]

$$\mathbf{X} = \begin{bmatrix} x_1(0) & x_1(1) & \cdots & x_1(N-1) \\ \vdots & \vdots & \ddots & \vdots \\ x_M(0) & x_M(1) & \cdots & x_M(N-1) \end{bmatrix} \in \mathbb{C}^{M\times N}. \tag{3}$$

As shown in Table I,[4] the proposed MIMO-LoRa systems transfer more information bits (thus achieving a higher data rate) than the conventional LoRa system and the non-MIMO technique in [5] thanks to the use of multiple antennas. For example, when $M = 2$, $\mathrm{SF}_1 = 12$, and $\mathrm{SF}_2 = 11$, the conventional LoRa system carries 12 bits and the non-MIMO LoRa technique in [5] carries 13 bits, whereas the proposed MIMO-LoRa system conveys 23 bits (i.e., almost twice larger). For the MIMO-LoRa system with precoding, which will be presented in the next section, the number of information bits transferred is slightly reduced since $m \le M$ in general. The reduction depends on the channel condition and transmit power constraints. However, the link reliability [e.g., bit error rate (BER)] is substantially enhanced.

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[1] In [5], a non-MIMO technique has been developed to increase the data rate of the LoRa modulation, but the improvement is quite marginal even compared to the conventional LoRa system as shown in Table I.

[2] To save the power of IoT devices, the proposed MIMO-LoRa system can be operated only over a short time period or opportunistically.

[3] For synchronous transmission and high diversity gain, we form the transmission matrix $\mathbf{X}$ as in (3) such that the transmitted LoRa signals last for the same N time slots via proper signal repetitions. One can also construct $\mathbf{X}$ to accommodate the transmitted LoRa signals occupying different time slots.

[4] In LoRa modulation, the SF value denotes the number of information bits.

III. PRECODING DESIGN

The input–output relationship of the precoded MIMO-LoRa system is

$$\mathbf{Y} = \mathbf{HFX} + \mathbf{W} \tag{4}$$

where $\mathbf{F} \in \mathbb{C}^{M \times M}$ denotes the precoding matrix. The received signal-to-noise-ratio (SNR) can be derived as $[(\mathbb{E}[\|\mathbf{HFX}\|_F^2])/(\mathbb{E}[\|\mathbf{W}\|_F^2])] \approx [(\text{Tr}(\mathbf{F}^H\mathbf{H}^H\mathbf{HF}))/(MN\sigma^2)]$, where we have used the fact that $\mathbb{E}[\mathbf{XX}^H] \approx \mathbf{I}$ [7].[5] Let us define $\mathbf{G} \triangleq \mathbf{FF}^H$. We aim to design a precoding matrix $\mathbf{F}$ (or equivalently, to optimize the value of $\mathbf{G}$) to maximize the received SNR with total transmit power constraint and peak (or elemental) power constraint as follows:

$$\begin{aligned} (\text{P1}): \underset{\mathbf{G}}{\text{maximize}} \quad & \text{Tr}\Big(\mathbf{G}\mathbf{H}^H\mathbf{H}\Big) && (5)\\ \text{subject to} \quad & \text{Tr}(\mathbf{G}) \le \alpha && (6)\\ & \lambda_{\max}(\mathbf{G}) \le \beta && (7) \end{aligned}$$

where $\lambda_{\max}(\cdot)$ denotes the largest eigenvalue. Also, α and β denote thresholds for the total transmit power and peak power, respectively.

Let us denote the eigenvalue decomposition of $\mathbf{H}^H\mathbf{H}$ by $\mathbf{H}^H\mathbf{H} = \mathbf{U}\Lambda\mathbf{U}^H$, where $\mathbf{U} \in \mathbb{C}^{M \times r}$ is a semiunitary matrix with $\mathbf{U}^H\mathbf{U} = \mathbf{I}$ and $\Lambda = \text{diag}(\lambda_1, \lambda_2, \ldots, \lambda_r)$ is a diagonal matrix with $\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_r > 0$. Also, $r \triangleq \text{rank}(\mathbf{H}^H\mathbf{H})$. Let $\gamma_1 \ge \cdots \ge \gamma_M \ge 0$ denote the eigenvalues of $\mathbf{G}$. Then, since $\text{Tr}(\mathbf{G}\mathbf{H}^H\mathbf{H}) \le \sum_{i=1}^{r} \lambda_i \gamma_i$ [8], the optimal $\mathbf{G}$ to problem (P1) must take the following form[6]:

$$\mathbf{G} = \mathbf{U}\Gamma\mathbf{U}^H \tag{8}$$

where $\Gamma = \text{diag}(\gamma_1, \ldots, \gamma_r)$, that is, $\gamma_{r+1} = \cdots = \gamma_M = 0$. Consequently, (P1) becomes the following scalar optimization problem:

$$\begin{aligned} (\text{P2}): \underset{\gamma_1 \ge \cdots \ge \gamma_r}{\text{maximize}} \quad & \sum_{i=1}^{r} \lambda_i \gamma_i && (9)\\ \text{subject to} \quad & \sum_{i=1}^{r} \gamma_i \le P, \quad \gamma_1 \le \beta. && (10) \end{aligned}$$

Using the Lagrange multiplier method, it can be shown that the solution to problem (P2) is given by

1) For $q < r$

$$\begin{aligned} \gamma_1 = \cdots = \gamma_q = \beta, \quad & \gamma_{q+1} = \alpha - q\beta \\ \gamma_{q+2} = \cdots = \gamma_r = 0 & \end{aligned} \tag{11a}$$

where q is the largest integer not exceeding $\frac{\alpha}{\beta}$, i.e., $q = \lfloor \alpha/\beta \rfloor$.

2) For $q \ge r$

$$\gamma_1 = \cdots = \gamma_r = \beta. \tag{12a}$$

Once the solution to (P1) is obtained by (8) and (11), the corresponding optimal precoding matrix can be determined as

$$\mathbf{F} = \begin{bmatrix} \mathbf{U} & \mathbf{0} \end{bmatrix} \text{diag}\,(\gamma_1, \ldots, \gamma_m, 0, \ldots, 0) \tag{13}$$

where $m = q + 1$ if $q < r$ and $m = r$ otherwise. This means that only m transmit antennas out of M ones need to be active, and thus, total $\sum_{i=1}^{m} \text{SF}_i$ bits can be transferred simultaneously.

IV. SIMULATION RESULTS

In simulations, we consider a MIMO-LoRa system with $M = L = 3$, $\text{SF}_1 = 12$, $\text{SF}_2 = 11$, and $\text{SF}_3 = 10$. The elements of the MIMO channel matrix $\mathbf{H}$ (resp., the received noise matrix $\mathbf{W}$) are generated randomly according to the circularly symmetric complex Gaussian distribution with zero mean and unit variance (resp., variance σ^2). The SNR is defined as (α/σ^2). The bandwidth is set to $B = 500$ kHz.

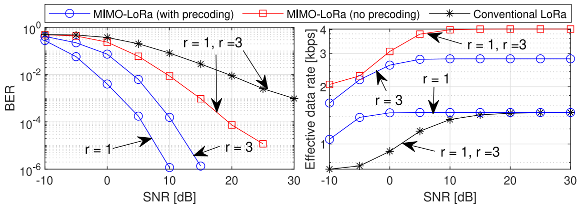

Fig. 2. BER and effective data rate versus SNR when $M = L = 3$, $\text{SF}_1 = 12$, $\text{SF}_2 = 11$, $\text{SF}_3 = 10$, $B = 500$ kHz, $\alpha = 1$, $\beta = 0.6$, and $r \in \{1, 3\}$.

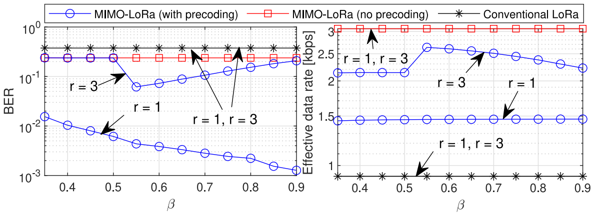

Fig. 3. BER and effective data rate versus β when the SNR is 0 dB, where the other parameters are set to be the same as those in Fig. 2.

Fig. 2 shows the performance of the various LoRa systems versus the SNR for different values of r when $\alpha = 1$ and $\beta = 0.6$. It can be observed that the proposed MIMO-LoRa systems significantly outperform the conventional LoRa system in terms of BER and effective data rate. The performance of the proposed MIMO-LoRa system with precoding relies on the channel condition (whereas the other two systems do not). Specifically, the performance improves when the channel is ill-conditioned, because much power can be allocated to LoRa signals exposed to better propagation environments.

In Fig. 3, the performance of the various LoRa systems is shown as a function of β when the SNR is 0 dB. As can be seen from Fig. 3, when the channel is ill-conditioned, the performance of the proposed MIMO-LoRa system with precoding improves as β increases; whereas, when the channel is well-conditioned, the performance improves and then degrades, meaning that there exists the optimal operating point with respect to β.

V. CONCLUSION

A novel MIMO-LoRa system has been introduced for high-data-rate IoT and the received SNR-maximizing precoding has also been designed to enhance the BER performance of the proposed system.

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[5] This property is valid in many cases and also enables a low design complexity with negligible performance loss in practice [2].

[6] This requires the channel estimation in practice with very little power consumption of IoT devices.