Investigating and Experimenting Interference Mitigation by Capture Effect in LoRa Networks

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LoRa-like CSS-based PHY layer, capture effect and Serial Interference Cancellation

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***Abstract*—Long Range communications are taking an important place in the IoT world. One Physical Layer solution is LoRa. It is based on Chrip Spread Spectrum. In this paper we review how this modulation technique carries information. However, a simple MAC layer, like ALOHA, will rapidly limit the capacity (in term of number of users) of such networks. However, sensing the channel will not resolve the collision problem because of the very wide coverage of access points. We study how capture effect and even more serial interference cancellation can drastically improve the performance. The position randomness of transmitters can allow to correctly decode simultaneous transmissions.**

***Index Terms*—Wireless Communications, LPWAN, $LoRa^{TM}$, LoRaWAN, Internet of Things (IoT), Wireless Sensor Networks,**

I. Introduction

In recent days, internet of things (IoT) is gaining huge interest as the internet users are shifting from persons to things. IoT paradigm offers the interconnection between physical objects that surround us, to send or receive (or both) information to or from the internet. These smart interconnected objects are not only able to sense and gather information from the environment but also interact and control the physical world [1]. Most of the time the connection takes place by making use of radio frequency (RF) based wireless communications.

To address diverse requirements of IoT's applications, LPWAN offers novel communication paradigm. LPWAN technologies (SigFox, LoRa, Weightless-W, etc.) successfully propose wide area connectivity from a few to tens of kilometers for low data rate, low-power, and low throughput applications [2]. Amongst the recently proposed and prominent LPWAN technologies, the semiconductor manufacturer Semtech has introduced extensive utilization of advanced spread spectrum technology with their Long Range $LoRa^{TM}$ product line. Unlike in direct sequence spread spectrum (DSSS) where message signal is modulated over a pseudo random code, LoRa uses sweep tone signal with frequency that either increases (up-chirp) or decreases (down-chirp) over time to encode the message signal. Multiple spreading factors and bandwidth settings enable orthogonal transmissions for LoRa end-devices, and this can prevent inter-network interference. However, dealing with the interference in case of simultaneous communications with the same SF or the same channel is still a significant challenge. In a LoRa system, it is considered that when two or more end-devices transmit their data simultaneously using the same spreading factor (SF), and over the same channel, a collision will occur at the receiver. This collision will result in loss of all colliding frames. However, thanks to capture effect, the receiver can sometimes successfully decode one frame even in the presence of a collision. Capture effect is the receiver's ability to receive one out of two (or more) colliding frames correctly. Moreover, when communication traffic increases, multiple signals from multiple end-devices collide, and thus communication reliability decreases. One solution is to utilize successive interference cancellation (SIC), which is widely studied as a technique to enable receivers to demodulate multiple signals from their received sum. The CE and SIC are successful only if the difference of the received power between signals in a mixed signal is greater than some threshold. LoRa systems can also benefit from the capture effect and successive interference cancellation, which would enhance the system's throughput performance. This article explores capture effect and successive interference cancellation for LoRa based systems. Contributions are:

- Capacity limitations of CSS based PHY layer are explored by calculating the packet reception rate (PRR) with varied network sizes.
- Capture effect and successive interference cancellation are incorporated in the LoRa based system and simulation results show significant improvement in the probability of successful reception rate.
- Moreover, as LoRa PHY is not openly available, this article provides a comprehensive analysis on technical features of the PHY layer associated with LoRa.

The rest of the article is categorized further into five sections. Section II and III describes some key features of LoRaWAN and LoRa technology consecutively. In Section IV capture phenomenon along with its different scenarios is defined. The Section V discusses the successive interference cancellation. Conclusive remarks are drawn at the end in Sections VI.

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Fig. 1. $LoRaWAN^{TM}$ network structure.

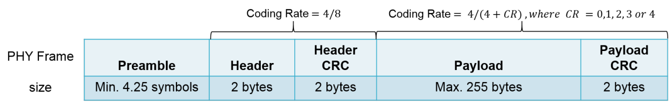


Fig. 2. $LoRa^{TM}$ PHY frame format

II. LoRaWAN

Long range wide area network $LoRaWAN^{TM}$ is an open standard which defines MAC protocol envisioned for LoRa. LoRaWAN specifications provide the ability to control SF and bandwidth BW utilization. LoRa network typically based on end-devices (sensors, actuators or both), gateways and a network server. End-devices in a LoRaWAN network follow the star of stars topology and connect to one or several gateways through LoRa wireless link. The gateways connect to the network server through an IP-based network and provide the bridging from end-devices to the IP world [3], as represented in Fig. 1. Orthogonal nature of spreading factors enables simultaneous and collision free communication in the network. However, [4] shows that these spreading factors are not perfectly orthogonal. Nevertheless, we are going to consider that different spreading factors do not interfere and we are interested in the limit in successful transmissions in a LoRaWAN system.

LoRaWAN defines three categories of end-devices, which are [3]:

- Class A: in this class, the communication is initialized by the end user, and they are allowed for bi-directional communications. End-devices can schedule an uplink transmission slot based on ALOHA protocol. Each uplink transmission is followed by two downlink receive windows. This class is considered more appropriate for energy constrained devices.
- Class B: in addition to random receive time windows, Class B devices also use scheduling methods. They receive a beacon from the gateway for the time synchronization.
- Class C: unlike class A and B, Class C end-devices have almost continuously open receive time windows. These windows only close while transmitting. This class is more energy consuming as compared with other classes.

Fig. 2 shows LoRaWAN frame format also used in our simulations. LoRaWAN offers maximum frame size of 256 bytes. The preamble field contains a sequence of constant up-chirps, two down-chirps and a quarter of an up-chirp for synchronization purposes [5]. The header field, when present, is transmitted with a code rate of $1/2$. This field specifies payload length, forward error correction (FEC) code rate (CR) value and presence of CRC at the end of the frame. The header also includes its cyclic redundancy check (CRC) field to protect the integrity of header. The payload field contains actual data, and optional CRC field is use for error protection in the payload [6].

The time on air for LoRa frame can be defined as:

$$T_{air} = T_s(n_{preamble} + n_{payload} + 4.25) \tag{1}$$

where $T_s = 1/R_s\ sec$ denotes symbol period , and $R_s = BW/2^{SF}\ symbols/sec$ is symbol rate. $SF = log_2(R_c/R_s)$ is the spreading factor and is the ratio between symbol rate (R_s) and chip rate (R_c). $n_{preamble}$ and $n_{payload}$ are the preamble and payload lengths. The constant value 4.25 shows the minimum length of preamble.

A. Probability of Successful Transmission

ALOHA based system allows the transmitters to transmit whenever there is a frame to send. LoRaWAN only employs ALOHA based MAC protocol for medium access. If we consider LoRa network consists of class A devices, corresponds to pure ALOHA, the throughput of such network is $S = Ge^{-2G}$, [7]. The term $P = e^{-2G}$ is called probability of successful transmission of a frame and $0 \leq P \leq 1$. For LoRa based network it can be defined as:

$$P_i = e^{-2p_i\lambda_i N T_{air_i}}, \qquad i \in SF \tag{2}$$

where T_{air_i} is the time on air of one LoRa frame (stated in (1)). λ_i is the frame generation rate with $SF\ i$ of all N end-devices in a network. p_i is the probability that an end-device is using $SF\ i$. Due to regional restrictions on operation in licensed free ISM bands, frame generation rate λ_i depends on the duty cycle D and time on air. If we assume that deployed network locates in Europe, then 1% duty cycle shall be applied on the usage of each sub-band.

$$\lambda_i = \frac{D}{T_{air_i}} \quad \text{or} \quad \lambda_i = \frac{1}{T_{off_i} + T_{air_i}} \tag{3}$$

$(T_{off_i} = (T_{air_i}/D) - T_{air_i})$ is the minimum period during which a device cannot access the medium because of duty cycle restriction.

III. LoRa TECHNOLOGY

LoRa utilizes wide band usually of $125\ kHz$ or more to broadcast a signal. Using Bands thar are not too narrow allows LoRa to exhibit some robustness against some characteristics of the channel (frequency selectivity, doppler effect). The transmitter generates chirp signals by varying their frequency over time and keeping phase between adjacent symbols constant. Receiver can decode even a severely attenuated signal 19.5 dBs below the noise level [8].

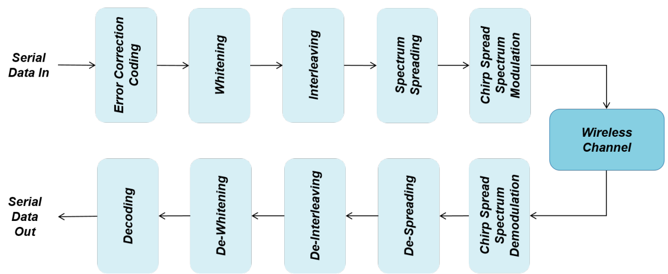


Fig. 3. $LoRa^{TM}$ PHY layer architecture

A. LoRa PHY Structure

Main characteristics of LoRa modulation depends on SF, CR, and BW. Spreading factor $(SF = log_2(R_c/R_s))$ is the ratio between symbol rate (R_s) and chip rate (R_c). LoRa employs six orthogonal spreading factors (7 to 12). SF provides a trade-off between data rate and range. Along with the spreading factors, forward error correction (FEC) techniques are used in LoRa to increase the receiver sensitivity further. Code rate CR defines the amount of FEC in LoRa frame. LoRa offers $CR = 0,\ 1,\ 2,\ 3$ and 4, where $CR = 0$ means no encoding. The choice of a higher SF and CR values also influence the T_{air}, and an increase in T_{air} will increase the off period T_{off} duration as well. Although, choice of higher BW will reduce the T_{air}, but lowers the receiver sensitivity. LoRa provides three scalable BW settings of $125kHz, 250kHz$ and $500kHz$. Taking these parameters into account, the useful bit rate R_b equals:

$$R_b = \frac{4 \times SF \times BW}{(4 + CR) \times 2^{SF}} \qquad (bits/sec) \tag{4}$$

The LoRa is a Semtech proprietary technology and is not fully open. This section gives the analysis on the working of PHY in LoRa, according to our understanding. Fig. 3 shows the block diagram of LoRa transceiver, which is briefly explained below.

Encoding

First, the binary source input bits passes through an encoder. The output of encoder depends on the choice of CR value. LoRa uses coding rates $(coding\ rate = 4/(CR+4))$ of $4/5$, $2/3$, $4/7$ and $1/2$. Which means, if the code rate is denoted as k/n, where k represents useful information, and encoder generates n number of output bits, then $n-k$ are the redundant bits. Encoding reduces the PER in the presence of short bursts of interference.

Whitening

The output of the encoder passes through the Whitening block. Whitening is an optional step in LoRa, which can be implemented by Manchester encoding to induce the randomness. Here, the purpose of whitening is to make sure that there are no long chains of 0's and 1's in the payload.

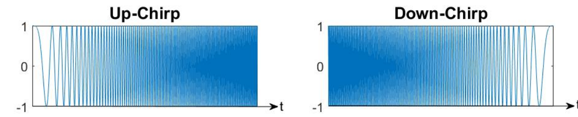


Fig. 4. Up-chirp and down-chirp signal.

Interleaving

The output of Whitening block passed to the Interleaving block. Interleaver uses diagonal placing method to scramble each 4+CR codeword, and sends it to spreading block.

Spreading and Modulation

This block here spreads each symbol over an up-chirp according the SF value used. For example, for SF = 7 and 12, 128 and 4096 $chips/symbol$ will be used, consecutively. The relationship between the symbol rate $R_s = BW/2^{SF}$ and chip rate R_c is:

$$R_c = 2^{SF} \times R_s, \qquad \text{and} \qquad R_c = \frac{\cancel{2^{SF}} \times BW}{\cancel{2^{SF}}},$$

so, $\quad R_c = BW\ chips/sec$

According to LoRa, SF settings are orthogonal in nature and allow simultaneous transmission of multiple frames in a network.

Then the spread data passes to the modulation. It takes much larger BW for transmission than required for the considered data rate.

Chirp signal is a sinusoidal signal with either linearly increasing or decreasing frequency. A linear chirp waveform can be expressed as:

$$c(t) = \begin{cases} exp(2\pi j(at+b)t), & \frac{-T_s}{2} \leq t \leq \frac{T_s}{2} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

with $at + b = f_{min} + \dfrac{f_{max} - f_{min}}{T_s} t$

where f_{max} and f_{min} are the maximum (125 kHz in our case) and minimum frequency, consecutively. T_s is the symbol duration. An up-chirp and a down-chirp is shown in Fig. 4.

In LoRa, a single chirp signal can be code for $SF = 7, 8, ..., 12$. Each symbol of SF bits can be represented by shifting the frequency ramp based on the symbol value. So, each coded chirp is obtained by a cyclic shift in an up-chirp, as illustrated in Fig. 5. Circular shift in raw up-chirp is expressed in (6).

where Δt is the shift in time that depends on the symbol value.

CSS Demodulation

The matched receiver for a linear chirp is performed by multiplication with the conjugate chirp, as shown in Fig. 5 and can be represent mathematically for $(\Delta t = 0)$:

$$y(t) = exp(2\pi j(at+b)t)\ .\ exp(-2\pi j(a(T_s-t)+b)(T_s-t))$$

$$y(t) = exp(2\pi j(2t(aT_s+b) - aT_s^2 + b)) \tag{7}$$

$$c(t) = \begin{cases} exp(2\pi \jmath(a(T_s + t - \Delta t) + b)(Ts + t - \Delta t)), & \frac{-T_s}{2} \leq t \leq \frac{-T_s}{2} + \Delta t \\ exp(2\pi \jmath(a(t - \Delta t) + b)(t - \Delta t)), & \frac{-T_s}{2} + \Delta t \leq t \leq \frac{T_s}{2} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

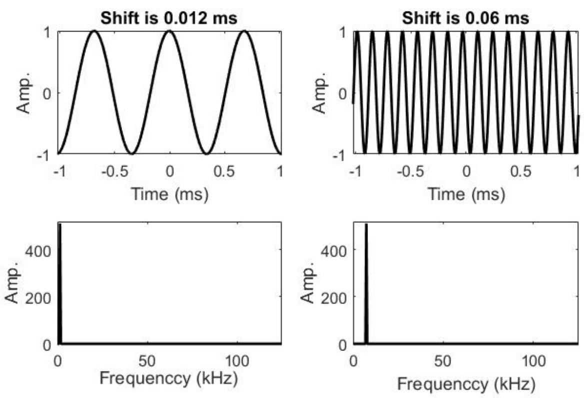


Fig. 5. Matched Filter Output

The matched receiver output for single symbol would be:

$y_i(t) = exp(2\pi \jmath(a(t + \Delta t) + b)(t + \Delta t))\ .\ exp(-2\pi j(a(T_s - t) + b)(T_s - t))$

$$y_i(t) = exp(2\pi \jmath(2tf_0 + \Phi) \tag{8}$$

here $f_0 = (a\Delta t + aT_s + b)$ is the frequency and $(\Phi = a\Delta t^2 - aT_s + b\Delta t - bT_s)$ is the phase of the received signal. Then, the output signal is analyzed to identify the presence of the sharp narrow peak in frequency domain, which is at 3 and 15 on Fig. 5. The sharp narrow peak occurs at the time index corresponding to the constant value of the coded chirp.

B. PHY Performance

Fig. 6 shows the BER performance of LoRa based PHY, plotted over the signal-to-noise ratio (SNR). Vertical axis show different bit error rate values and horizontal axis show SNR values. Fig. 6 shows that by increasing the spreading factor, BER decreases noticeably.

All the results have been produced with $CR = 0$ and $BW = 125kHz$.

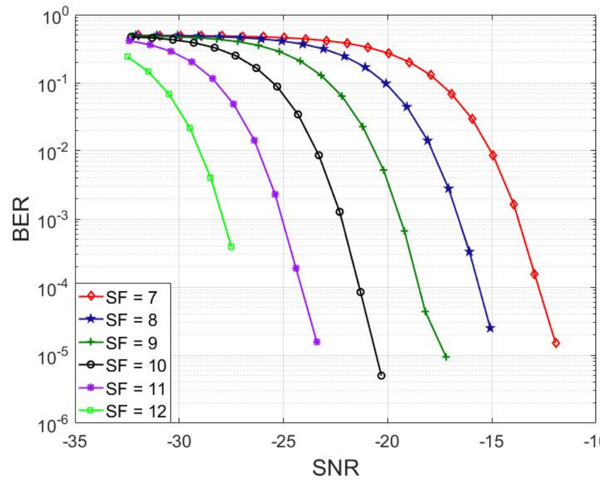


Fig. 6. BER performance of PHY layer based on LoRa with different SF values and $CR = 0$.

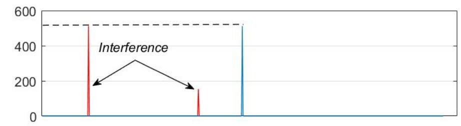
IV. Capture Effect

As mentioned before, LoRaWAN class A devices use pure ALOHA MAC protocol for medium access. One of the limitations of ALOHA based systems is its blind transmission strategy, which causes inefficient use of spectrum. Simultaneous transmission causes packet loss. Pure ALOHA based network can give 18.39% of maximum efficiency [7]. Moreover, when the collision occurs, all colliding packets are considered lost. LoRa PHY employs a modulation scheme that manifests capture effect. The receiver might be able to perform successful reception of strong packet in the presence of collision. This is shown in Fig. 7, where two interference symbols at the value of 30 and 100 add up in the transmitted symbol value of 128. The receiver can successfully differentiate between the interferers based on their received power values. The problem occurs when one or more interferers carry either the same value so that their power adds up or have an equivalent or more power than the useful one. In Fig. 7(a), first interferer has the same received power as the useful user and in Fig. 7(b), all interferers contain same value which cause an increase of peak value in frequency domain. The capture characteristics of any radio transceiver depend on the modulation, decoding schemes and its hardware design and implementation. Traditionally we consider that in a RF interference environment, a particular signal X can be successfully decoded if:

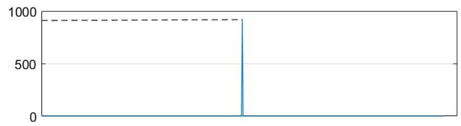
$$SINR_X = \frac{P_X}{\sum P_I + \sigma^2} > Th \tag{9}$$

where P_X is the source signal strength also depends on the duration of the collision, $\sum P_I$ is the aggregate interference strength from the other active users in the network, σ^2 is the channel noise power and Th is the minimum SINR threshold required to successfully decode signal X. For a LoRa modulation, as shown in Fig. 7, only the strength of the strongest interferer will matter as long as the simultaneous number of interferers is not to high and the probability to have interferers with shift that falls at the same time remains low. So (9) will become:

$$SIR_X = \frac{P_X}{P_I} > Th \tag{10}$$



(a)



(b)

Fig. 7. (a) FFT of Coded chirps at the values 30, 100 and 128 consecutively, with $SF = 8$. (b) FFT of 3 Coded chirps at the value 128, with $SF = 8$.

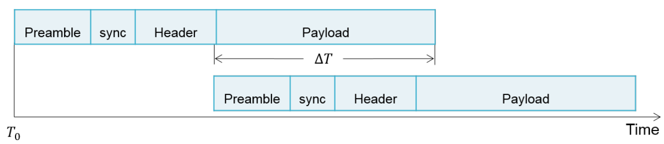


Fig. 8. Capture Scenario

We are going to characterize the capture effect in the next section (the probability for a packet to be decoded despite the presence of one interferer).

A. Capture Effect Scenarios

In the literature [9]–[11], usually, two capture scenarios are taken into account.

- Decoding the First: During the reception of a packet, a second packet arrives and creates collision. In this case, receiver already synchronizes with the first packet and tries to perform successful reception.
- Decoding the Last: Another scenario would be to decode the packet that arrives later. This necessitates to be able to detect the preamble of the second packet and then to correctly decode the packet.

We generate random collisions at receiver by generating two LoRa packets with the time difference $(T_0 \leq \Delta T \leq T_{air})$. First signal arrives at T_0 and second signal arrives after a random duration, within the T_{air} of first packet, as illustrated in Fig. 8. The transmission of interfering packet can start at any time and overlapping length ΔT of both packets varies randomly. The goal here is to identify under which power settings the collision detection and successful reception will work.

B. Capture Results

The packet structure used in all our simulations is shown in Fig. 2. We have used the minimum preamble size. However, increase in preamble duration can improve the detection probability. The payload is 20 $bytes$ long, with no channel encoding $(CR = 0)$ and $SF = 8$.

Fig. 9 presents the capture results. The probability of successful reception is calculated with 1000 packets transmissions

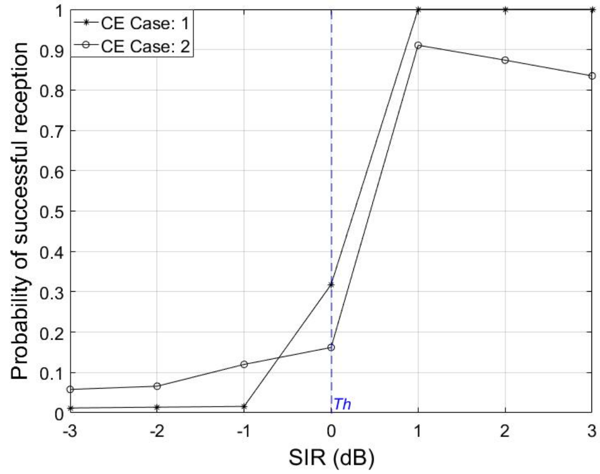


Fig. 9. Capture Results with $SF = 8; CR = 0$ and $BW = 125kHz$

for each power setting on random overlapping lengths ΔT. X-axis show signal to interference power (SIR) and Y-axis show probability of successful reception with capture. Note that, we do not assume that the received power ordering is known a prior at the receiver. From Fig. 9 we can assume that if the received power difference between two interferers are around $1\ dB$, the receiver can successfully decode the strong packet. Thus, (**??**) can be express as, $SIR_X = \frac{P_X}{P_I} \geq 1\ dB$.

V. Successice Interference Cancellation

As we have described earlier, in LoRa, collision occurs due the simultaneous arrival of two or more packets with the same SF at the receiver. According to capture effect, the strongest packet can be received successfully and other packets will be considered as interference. However, successive interference cancellation can allow to recover the weaker packets, as well. First, the stronger signal is decoded normally. The decoded signal is then subtracted from the combined received signal. In a second step, the weaker signal is extracted from the residue [12]. In case of multiple interferences, this can lead to an iterative process. The strongest signal is detected first from the received signal and then the next strongest and so on. After each signal's decoding, the received signal for that user can be reconstructed by recreating the transmit signal and applying an estimate of the channel to it. This can be subtracted from the composite received signal, which then allows subsequent users to experience a cleaner signal.

In this work, we have considered SIC as pure receiver technique, that means it does not require any type of modification on the transmitter. Let assume a LoRa network consisting on an gateway node (receiver) and N transmitters scattered around the gateway node in Poisson field $\Phi = \{(L_i, H_i)\} \subset \mathbb{R}^d \times \mathbb{R}^+$. Where L_i represents the location of each transmitting node, H_i is the channel attenuation coefficient. The SIR based successful decoding of single user is defined in (10). Which says that a particular signal X at $L \in \Phi$ can be decoded successfully if its SIR is greater than some threshold. Any

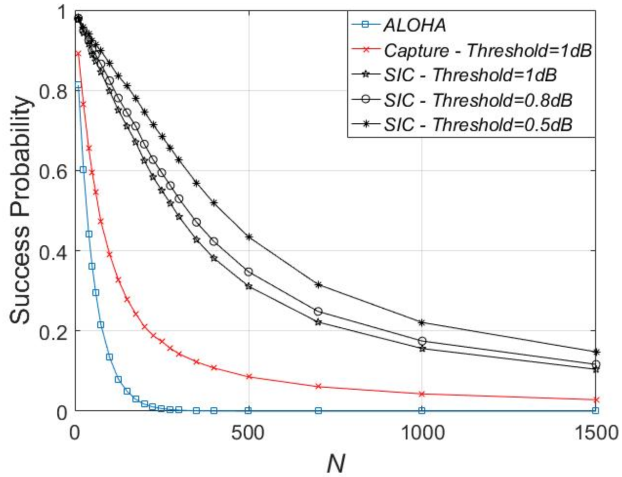


Fig. 10. Probability of Successful Transmission.

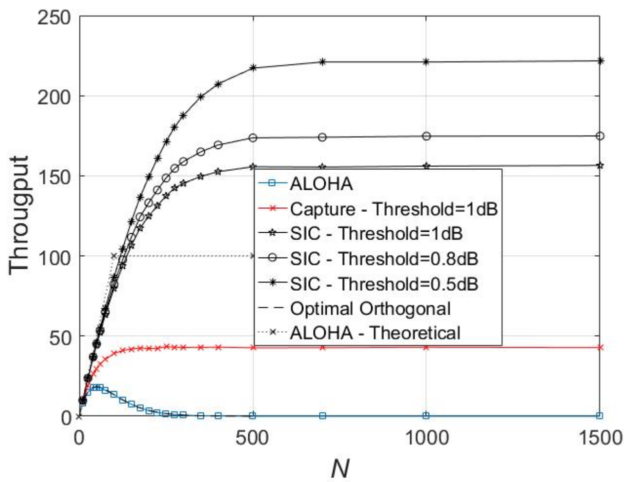


Fig. 11. Throughput

signal x_r can be decoded successfully from the residue of received signal $Y(t) = \sum_{active\ users} X_i(t)H_i(t)$, if its signal to residual interference plus noise power ratio SI_rR_x is:

$$SI_rR_x = \prod^{n}(\frac{P_i}{P_{i+1}}) \geq Th \qquad (11)$$

Fig. 10 and Fig. 11 show the probability of successful decoding of the packets and throughput of LoRa based system, with collisions. We have varied the network size N. The assumption is that all the nodes are using same SF but their packet generation rate is given in (3). It can observe that CE and SIC can significantly improve the performance for big networks. This studied case is in a sense of worst case scenario because no channel coding is used which would significantly improve the performance.

VI. Conclusion

This paper investigates the effectiveness of capture effect and successive interference cancellation for LoRa based system. The capture effect is receiver's ability to receive one of the dominant signals during a collision. While SIC first decodes dominant packets and subtract it from the residue and continue decoding next dominant packets. Although, these techniques are well explored in the communication literature, but are not yet applied in LoRa. This motivates us to observe the extent of possible LoRa's throughput gain with capture effect and SIC. Capture effect and SIC are combined with LoRa. And the simulation results show that receiver can decode one of the packet with CE or all packets with SIC, in the presence of a collision. It is also observed that overlapping length (ΔT) and interferer signal's received power affect the capture and SIC performance. It can be concluded that capture effect and SIC can play a significant role in performance enhancement of LoRa, and we propose to include it in the LoRa PHY. Moreover, we have also presented PHY performance of LoRa by replicating its features with our propositions.

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