Performance Analysis of Single-Cell Adaptive Data Rate-Enabled LoRaWAN

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Abstract—LoRaWAN enables massive connectivity for Internet-of-Things applications. Many published works employ stochastic geometry to derive outage models of LoRaWAN over fading channels assuming fixed transmit power and distance-based spreading factor (SF) allocation. However, in practice, LoRaWAN employs the Adaptive Data Rate (ADR) mechanism, which dynamically adjusts SF and transmit power of nodes based on channel state. The community addressed the performance of ADR using simulations, but analytical models have not been introduced. In this letter, we seek to close this gap. We build over an analytical LoRaWAN model to consider distance-based spreading factor (SF) allocation. However, in over fading channels assuming fixed transmit power and stochastic geometry to derive outage models of LoRaWAN and propose a path loss-based method to define network geometry. Reynders et al. [5] propose a power and data rate (spreading factor, SF) allocation method based on clustering for the NS-3 simulator. Aligned to the problem we address, Abdelfadeel et al. [6] assess the performance of Adaptive Data Rate (ADR)-enabled LoRaWAN, achieving results similar to our theoretical analysis, and Li et al. [7] study ADR convergence, both through simulations.

In this work, we review the analytic models for single-cell LoRaWAN and propose an adaptation to include the ADR feature. Although multi-cell systems are likely to shape the topology of LoRaWAN networks in dense urban deployments, single-cell systems are still of interest for deployments in small town or villages, industrial plants, and in the agribusiness sector, where a dedicated single-cell LoRaWAN system may support a known number of users and applications. Analytic models allow for faster evaluation and insights that are hard to obtain from simulations. We validate our analytic model through Monte Carlo simulations. Following [3], we use our model to plan the network deployment to respect a maximum outage probability. We show that power control considerably reduces interference, increasing network capacity by up to 50% and reducing average transmit power by roughly 25%.

The main contributions in this letter are the performance analysis of ADR-enabled LoRaWAN and a simple closed expression for its outage probability in steady-state operation. We assume the network reaches steady-state when ADR converges for all nodes, and their SF and transmit power configuration remain unchanged, as defined in [7]. The performance analysis shows that ADR is an important feature of the technology and that it must be taken into account. The closed-form expression assumes, as in [7], that a network with static nodes converges to RSSI-based SF and transmit power figures, implementing, in practice, a truncated channel inversion scheme [8]. Also, transient periods occur when channel or network conditions change, and the time to return to steady-state depends on application and deployment scenario [7].

II. BASELINE LoRaWAN MODEL

LoRaWAN employs LoRa transceivers in the PHY layer, operating in sub-GHz frequencies (e.g., 868 MHz in Europe,
915 MHz in USA and Brazil) with Chirp Spread Spectrum modulation [9]. A key feature of LoRa modulation is the configurable SF rate. As shown in Table 1, higher SF rates increase signal robustness at the expense of transmission rate. Since LoRa is a form of frequency modulation, it features the capture effect, where the receiver retrieves a colliding packet if it is sufficiently above interference. The SIR for the successful reception of a packet is 6 dB [9]. A typical LoRa transceiver can use different transmit power (P). The Semtech SX1276 LoRa transceiver under European regulations admits 16 levels of transmit power between -1dBm and +14dBm, in 1dB steps.

### Table I

| SF    | ToA  | Bitrate | Receiver Sensitivity | SNR threshold |
|-------|------|---------|----------------------|---------------|
| i     | t_i  | Rb_i   | S_i (dBm)            | \( \phi_i \) (dB) |
| 7     | 51.46| 5.46   | -123                 | -6            |
| 8     | 102.91| 3.12  | -126                 | -9            |
| 9     | 185.34| 1.75  | -129                 | -12           |
| 10    | 329.73| 0.97  | -132                 | -15           |
| 11    | 741.38| 0.53  | -134.5               | -17.5         |
| 12    | 1318.91| 0.29 | -137                 | -20           |

In its most commonly used operating mode, known as class A, LoRAWAN implements a variation of unslotted ALOHA in a star network topology where nodes reach the gateway, which in turn connects to a network server via an IP network.

### A. Network Model

We model the spatial distribution and activity of LoRaWAN nodes with stochastic geometry [10]. We divide the network into SF rings according to the distance from the node to the gateway. The vector \( L = [l_0, \ldots, l_6] \), \( l_0 = 0 \), defines the SF ring edges, with \( R = l_6 \) as the coverage radius. For simplicity, \( S = \{1, \ldots, 6\} \) is the set of SF rings, and each ring uses a respective SF in the set \( \{7, \ldots, 12\} \). We consider that all nodes run the same application. Thus network usage differs for each SF because of different data rates (see Time-on-Air/ToA in Table 1). We also assume that devices generate a packet for transmission once every \( T \) seconds and that the packet is transmitted with a given probability according to the pure ALOHA protocol. The transmission probability is a vector \( p = [p_1, \ldots, p_6] \), \( p_i \in (0, 1) \) \( \forall i \in S \), and \( p_i = t_i/T \), where \( t_i \) is the 'ToA of the packet with the SF of ring \( i \). For example, Figure 1 presents a network configuration with \( N = 250 \) nodes and network geometry (L), obtained to ensure 0.99 connection probability according to the method we describe in Section IV.

Each SF ring constitutes a separate PPP \( \Phi_i \) with intensity \( \alpha_i = p_i \rho_i \), in its area \( V_i = \pi (l_i^2 - l_{i-1}^2) \), where \( l_{i-1} \) and \( l_i \) form its inner and outer edges. \( \rho_i = N_i/V_i \) is the spatial density of nodes in ring \( i \). The average number of nodes in \( \Phi_i \) is \( N_i = \rho_i V_i \). The average total number of nodes is \( N = \sum_{i \in S} N_i \). The coverage area is \( V = \pi R^2 \). For instance, take ring \( i = 5 \) (SF7) in Figure 1 defined by two circles of radii \( l_5 = 789.5 \) m and \( l_6 = 973.4 \) m. The ring area is \( V_5 = \pi (l_6^2 - l_5^2) = 1.02 \) km\(^2\). With \( N_5 = 50 \) nodes in the ring, the spatial density is \( \rho_5 = N_5/V_5 = 49.1 \) nodes/km\(^2\). If the transmit probability is \( p_5 = 0.01 \), then the intensity of \( \Phi_5 \) is \( \alpha_5 = p_5 \rho_5 = 0.49 \).

In our analysis, \( d_k \) is the Euclidean distance between the \( k \)-th node and the gateway, and \( d_1 \) denotes the distance of the node of interest to the gateway. We use the subscript “1” whenever a variable refers to the node under analysis. Nodes use a transmit power \( P_k \) to send signal \( s_k \), and both path loss and Rayleigh fading \( h_k \) affect the signal \( r_1 \) received at the gateway. Path loss follows \( g_k = \left( \frac{4}{\pi d_k} \right)^\eta \), with wavelength \( \lambda \), and path loss exponent \( \eta > 2 \). Therefore

\[
r_1 = s_1 \sqrt{P_1 g_k h_1} + \sum_{k \in \Phi_i} s_k \sqrt{P_k g_k h_k} + n,
\]

where the first term is the attenuated signal of interest, the second is interference, \( i \) is the ring of \( s_1 \), and \( n \) is the zero-mean additive white Gaussian noise (AWGN) of variance \( \sigma \).

### B. Outage Probability

We consider that communication outage occurs due to disconnection or interference, which are, respectively, conditioned on the realization of the SNR and the SIR of a transmitted packet. We base our analysis on the stochastic geometry model of the SINR of Poisson Bipolar Networks with Rayleigh fading in [10] Theorem 5.7. Disconnection depends on distance and happens if the SNR is below the threshold \( \psi_i \) (see Table 1). The disconnection probability is [3]

\[
H_0(d_1, P_1) = \mathbb{P}[\text{SNR} < \psi_i] = \mathbb{P} \left[ \frac{P_1 g_1 h_1^2}{N} < \psi_i \mid d_1 \right],
\]

with \( i \) indicating the SF ring in use by the node under analysis. With known \( d_1 \) and \( P_1 \), we condition \( H_0 \) to the probability of the Rayleigh fading power in \( |h_1|^2 \sim \exp(1) \), so

\[
H_0(d_1, P_1) = 1 - \exp \left( -\frac{\psi_i N}{P_1 g_1} \right).
\]

The outage due to interference (i.e., collision with other packets) considers the capture effect. Thus, the collision probability concerning the SIR threshold \( \delta \) is [3]

\[
Q_0(d_1, P_1) = \mathbb{P}[\text{SIR} < \delta \mid d_1] = \mathbb{P} \left[ \frac{P_1 g_1 |h_1|^2}{\sum_{k \in \Phi_i} P_k g_k |h_k|^2} < \delta \mid d_1 \right].
\]
III. POWER ALLOCATION FOR LoRAWAN

When considering transmit power allocation, $P_k$ may be different for each node. We assume that nodes at the edge of each SF ring use the highest available transmit power ($P_{\text{max}}$) to extend the coverage area. Considering a predefined target outage due to disconnection ($\gamma_{\text{th}}$), we define the network geometry by making $H_0(l_i, P_{\text{max}}) = \gamma_{\text{th}}$, so that

$$l_i = \frac{\lambda}{4\pi} \left( -\frac{P_{\text{max}} \ln(1 - \gamma_{\text{th}})}{N\psi_i} \right)^{\frac{1}{\eta}}.$$

(4)

We also use (2) to define the minimum transmit power the $k$-th device must use to ensure $\gamma_{\text{th}}$ as

$$P_{k_{\text{min}}} = -\frac{N\psi_i}{\ln(1 - \gamma_{\text{th}})g_k},$$

(5)

In practice, $P_{k_{\text{min}}}$ should be rounded up to the immediately higher value available. Additionally, we obtain the network average transmit power by averaging (5) over the area, i.e.,

$$P_{\text{avg}} = \frac{2\pi}{V_{\text{ln}}(1 - \gamma_{\text{th}})g_k} \sum_{i=1}^{n} \frac{N\psi_i d_k^2}{4\pi \eta} = \frac{2\pi N\psi_i}{V_{\text{ln}}(1 - \gamma_{\text{th}})g_k^2} \sum_{i=1}^{n} \frac{\psi_i d_k^2}{4\pi \eta} - T_{\text{th}}^{\eta+2} - T_{\text{th}}^{\eta+2}. $$

(6)

A. Outage Probability with Transmit Power Allocation

Rewriting the disconnection probability in (2) with the power allocation method defined by (5) yields

$$H_0(d_1, P_{1_{\text{min}}}) = 1 - \exp\left( -\frac{q_i N}{P_{1_{\text{min}}}} g_1 \right) = \gamma_{\text{th}}, $$

(7)

so that transmit power control compensates for path loss, makes $H_0$ independent of $P_1$ and $d_1$, and ensures $\gamma_{\text{th}}$ for all nodes. Similarly, rewriting (6) with (5) yields

$$Q_0(i) = \mathbb{P} \left[ \frac{\left| h_i \right|^2}{\sum_{k \in \Phi_i} \left| h_k \right|^2} < \delta \right],$$

(8)

and therefore $Q_0$ becomes independent of transmit powers and distances from the gateway, being only dependent on fading.

If we define $X_i = \sum_{k \in \Phi_i} \left| h_k \right|^2$ and $Y_i = \frac{\left| h_i \right|^2}{X_i}$, then $Q_0(i) = \mathbb{P} [Y_i < \delta] = F_Y(\delta), \text{with the cdf of Y}_i \text{ obtained as}$

$$F_Y(y) = \int_0^\infty F_{h_i}(xy) f_X(x) \, dx,$$

(9)

where $|h_i|^2 \sim \exp(1)$, $F_{h_i}(z) = 1 - e^{-z}$, $X_i$ is Gamma distributed, $X_i \sim \Gamma(N_{\Phi_i}, 1)$, $f_X(x) = \frac{1}{\Gamma(N_{\Phi_i})} x^{N_{\Phi_i} - 1} e^{-x}$, and $\Gamma(\cdot)$ is the Gamma Function [11]. Following the duality of notation of PPPs [10] Box 2.3, $N_{\Phi_i}$ Poisson random variable of mean $\beta_i = \alpha_1 v_i = \alpha_1 N_{\Phi_i}$ describing the average number of active interferers in PPP $\Phi_i$. Thus,

$$Q_0(i) = \mathbb{E}_{N_{\Phi_i}} \left[ \int_0^\infty (1 - e^{-\delta x}) \frac{1}{\Gamma(N_{\Phi_i})} x^{N_{\Phi_i} - 1} e^{-x} \, dx \right].$$

(10)

which is solved by distributing the multiplication, factoring out independent terms, and applying the identity $\int_0^\infty x^a e^{-ax} \, dx = \frac{\Gamma(n+1)}{a^{n+1}}$ [11]. Thus, the $N_{\Phi_i}$-dependent collision probability is

$$Q_0(i) = \mathbb{E}_{N_{\Phi_i}} \left[ 1 - (1 - \delta)^{N_{\Phi_i}} \right].$$

(11)

Since the pmf of $N_{\Phi_i}$ is $f_{N_{\Phi_i}}(z) = \frac{x^e e^{-x}}{e}$,

$$Q_0(i) = 1 - \exp\left( -\frac{\frac{x}{\delta + 1} \delta i \right).$$

(12)

Finally, the total outage probability for each SF ring $i$ is

$$C_{0}(i) = H_0 + Q_0(i) - H_0 Q_0(i).$$

(13)

Our model preserves the PPP properties for each point as long as the fixed communication distances and transmit powers satisfy $\frac{\gamma_{\text{th}}}{g_k}$ in (1) in (3), which is guaranteed by (5).

IV. NETWORK PLANNING

We use the outage probability in (13) as a tool to plan the deployment of single-cell LoRaWANs. We assume a target maximum outage $T_{\text{c}}$ for all nodes, $C_0(i) \leq T_{\text{c}}, \forall i$. We use this reliability constraint to maximize coverage radius and network usage. After a closer look at (13), we observe that, for each ring, $C_0(i)$ depends on the outer limit $l_i$ and the average number of active interferers $\beta_i$. Unfortunately, it is not possible to solve such optimization for both variables simultaneously, so, here, we explore the trade-off between coverage radius and network usage. Assuming that the larger coverage radius and higher network usage occur on the worst-case scenario where $C_0(i) = T_{\text{c}}, \forall i$, we represent the trade-off, following from (13), as

$$T_{\text{c}} = T_{\text{th}} + Q_0(i) - T_{\text{th}} Q_0(i),$$

from which we equate, either, the maximum $\beta_i$ assuming a given $T_{\text{th}}$ as

$$\beta_i = \frac{\delta + 1}{\delta} \ln \left( \frac{1 - T_{\text{c}}}{1 - T_{\text{th}}} \right),$$

(14)

or the maximum $T_{\text{th}}$ assuming a given $\beta_i$ as

$$T_{\text{th}} = T_{\text{c}} - Q_0(i) \frac{1 - Q_0(i)}{1 - T_{\text{th}}}. $$

(15)

Note that $\beta_i = p_i N_{\Phi_i}$, so we use (14) to obtain the maximum number of nodes in each ring, assuming that all nodes in a ring use the same duty-cycle $p_i$. Similarly, because of (4), we obtain the SF ring range $l_i$ with $T_{\text{th}}$ from (15).

V. NUMERICAL RESULTS

We assume the parameters in Tables I and II to mimic a suburban deployment of a single-cell LoRaWAN under European regulations. The figures show our theoretical model (solid lines) and Monte Carlo simulations (marks). Figure 2
shows the power allocation using (5) and the average power in the network. The dashed curve shows the continuous power allocation according to distance and considering different SFs. It shows that $SFi$ uses a wider range of transmit power because its nodes are closer to the gateway. The power variation is 3dB in $SFi8$, $SFi9$, and $SFi10$, and 2.5dB in $SFi11$ and $SFi12$. That matches the variation of the SNR threshold in Table 1 ($\gamma_i$) and is also aligned with the ADR power and SF allocation method defined by LoRaWAN. Still, in Figure 2 the dotted curve shows the discrete practical power allocation, obtained by rounding up the continuous values of (5). That mostly impacts the power of nodes closer to the gateway. Figure 2 also shows the average power in the network from (6) as 12.63 dBm – an average power reduction of 27%.

Figures 3 and 4 show results using two approaches: power allocation as in (5), and all nodes with maximum power (14 dBm). The most noticeable aspect is that proper power allocation allows all nodes in the network to experience similar outage probabilities close to the target $T_{C_0} = 0.01$. When nodes use constant power, $T_{C_0}$ is reached only on the edges of each SF ring. In the constant power scenario, the nodes closer to the ring inner edge use more power than needed, thus spending more energy and causing more interference.

The method in Figure 3 besides using less average power than that in Figure 4 also serves more users. We observe a gain of 9.3% in the number of supported users, on average, from 225 to 247 nodes. If we consider a scenario with fixed transmit power equal to the average power used in Figure 3 then power allocation leads to a gain of 56.7% in the number of users, from 157 to 247. Our results show that adequate power allocation in LoRaWAN contributes to the network capacity due to the interference reduction while being more energy-efficient.

VI. CONCLUSION

We modeled the performance of LoRaWAN with power allocation, considering two outage conditions: disconnection and interference. We determined the maximum number of users to ensure a maximum outage probability. Numerical results show that power allocation increases network reliability due to the reduction of interference while being more energy-efficient than fixed transmit power. In the future, we plan to investigate the performance of LoRaWAN with power control under inter-SF and external interference.

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