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LETTER

Channel capacity evaluation of 920-MHz band IoT platform via LEO satellite

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Abstract In a 920-MHz band Internet-of-Things (IoT) platform via a low Earth orbit satellite, signal collisions frequently occur between the desired satellite IoT (S-IoT) terminals and interference from terrestrial IoT (T-IoT) terminals accommodated in the T-IoT platform. In this letter, computer simulation is used to evaluate the capacity for S-IoT terminals per satellite that can be achieved by applying minimum mean squared error receiver beamforming in each case of using low power wide area terminals of LoRa, Sigfox, and ELTRES. The results show that a satellite can accommodate 1 million-order terminals by using multiple channels in the 920-MHz band.
Keywords: satellite IoT platform, LEO satellite, 920 MHz band, LPWA
Classification: Satellite communications

1. Introduction

Unlicensed-band low power wide area (LPWA) is widely used for the various Internet-of-Things (IoT) services that have been rapidly developing worldwide [1]. Although IoT services are being deployed over a wide area using LPWA methods such as LoRa [2], Sigfox [3], and ELTRES [4], which enable long-distance communication, there are still radio dead zones at sea or in mountainous areas. A low Earth orbit (LEO) satellite IoT (S-IoT) platform is being considered for collecting sensor data from IoT terminals everywhere on Earth, including areas that are difficult to cover with terrestrial IoT (T-IoT) platform [5, 6]. Hereafter, the desired 920-MHz band LPWA terminals to be accommodated by the S-IoT platform are referred to as the S-IoT terminals, and the terminals to be accommodated by the T-IoT platform are referred to as the T-IoT terminals.

In the S-IoT platform, each S-IoT terminal must perform uplink communication during the limited time that a LEO satellite passes overhead, so the probability of signal collisions increases with the number of terminals. Also, because S-IoT terminals use the same 920-MHz band as T-IoT terminals, interference signals from numerous T-IoT terminals are also received simultaneously when receiving the desired signals from S-IoT terminals. Therefore, spatial domain signal separation by receiver beamforming (RxBF) is important for high-capacity S-IoT terminals.

There are two main approaches to RxBF: methods that use known signals and blind methods that do not use known signals. We use the latter to prevent the loss of transmission efficiency caused by the addition of known signals. Multi-target constant modulus algorithm (CMA) [7], which can separate and detect signals from multiple desired terminals respectively, has been proposed as an extension of the well-known CMA as a blind method. In [7], it was reported that the signal-to-interference-plus-noise ratio (SINR) obtained by the multi-target CMA asymptotically approaches the SINR obtained by the minimum mean squared error (MMSE) algorithm that uses known signals.

Although the direct accommodation of LPWA terminals using LEO satellites has been investigated [5, 6], to the best of our knowledge, there are no reports that evaluate the capacity while taking into account the effects of interference from T-IoT terminals and RxBF. Therefore, the purpose of this letter is to clarify the order of the number of S-IoT terminals that can be accommodated by a satellite in S-IoT platform. Computer simulations show the number of terminals that can be accommodated by applying MMSE RxBF when many interference signals from T-IoT terminals are arriving. Note that the number of terminals accommodated was evaluated for the cases where LoRa, Sigfox, and ELTRES were each used as the LPWA method of the S-IoT terminals. We selected these methods for evaluation because they are widely used in Japan and around the world and can provide long-distance communication to LEO satellites.

2. Evaluation model

This chapter describes the system model and evaluation parameters assumed in the capacity evaluation.

For simplicity, it is assumed that S-IoT terminals are uniformly distributed within a circle with a radius of 1,000 km (roughly equivalent to Japan's territory and exclusive economic zone), and that the S-IoT terminals in the east and west areas of the circle are each accommodated by a satellite. In the following, we will limit our discussion to the evaluation of S-IoT terminals in the east area. The satellite orbit altitude is 570 km. When the satellite passes over the east area of Japan, it receives desired signals from S-IoT terminals (number of terminals: N_{Sall}) in the east area, as well as interference signals from T-IoT terminals distributed throughout the Japanese territory. The satellite receives signals from each terminal with N_R receiving antennas and transmits the received waveform data to the ground station (GS) via the feeder link. The GS performs off-line MMSE RxBF on the received signal waveform to separate the desired signals from the interference signals.

The following sections describe the evaluation parame-

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ters for the S-IoT terminal, T-IoT terminal, LEO satellite, and GS, the concept of the average number of simultaneous transmissions performed by the S-IoT terminals and T-IoT terminals, and the evaluation method of the communication success rate (CSR) in the GS.

2.1 Satellite IoT terminal

The S-IoT terminals are assumed to be 920-MHz band specified low-power radio station with a transmission power of 20 mW. The terminals have one circularly polarized patch antenna, and the boresight direction is in the 90° elevation direction. The antenna gain is 3.0 dBi, and the half-power beam width (HPBW) is 80°. The terminals are uniformly distributed within a circle with a radius of 1,000 km. It is assumed that among N_{Sall} terminals in the east area of the circle, those with an elevation angle of 48.7° or more to the satellite (the area within a 500-km radius from directly below the satellite) transmit signals. That is, because the area ratio $\alpha = 0.5$, the population of transmission terminals at each time is $\alpha \times N_{Sall}$. For simplicity, the average number of simultaneous transmissions was calculated assuming that each terminal transmits uniformly distributed during $T_{com} = 240$ sec, the time available for communication with the satellite per day.

The following describes the calculation method for the average number of simultaneous transmissions. Table I shows the number of channels N_{ch} (920-MHz band channel number [8]) used for each LPWA method, which was assumed when calculating the average number of simultaneous transmissions. Each terminal transmits one data (about 10 bytes) per day.

For LoRa terminals (LoRa modulation), the spreading factor (SF) in chirp spread spectrum (CSS) is set to 12 (this is the SF that enables long-distance communication to LEO satellites), and the signal bandwidth after spreading is 125 kHz [2]. In this case, on the basis of the transmission time limitation in [8], the available channel numbers are ch.24-38, so $N_{ch} = 15$. The frame length T_{frame} is 1 sec, and the number of identical data transmissions N_{frame} is 3. Thus, the average number of simultaneous transmissions per channel is $\alpha \times N_{Sall} \times N_{frame} \times T_{frame}/N_{ch}/T_{com}$.

For Sigfox terminals, only ch.37 is used according to [9], so $N_{ch} = 1$. The signal bandwidth is 100 Hz, and N_{subch}, the number of sub-channels in a 920-MHz band channel, is 1,920 [3]. The frame length is 1.3 sec, and the number of identical data transmissions is 3. Thus, the average number of simultaneous transmissions per sub-channel is $\alpha \times N_{Sall} \times N_{frame} \times T_{frame}/N_{subch}/T_{com}$.

For ELTRES terminals, the symbol rate is 6.35 kbaud, and the signal bandwidth after spreading by CSS is 160 kHz [4]. A 0.4-second frame is transmitted by randomly selecting one of the $N_{slot} = 576$ timeslots provided at 8-ms intervals in a $T_{period} = 5$-second period. Four identical data are transmitted, and frequency hopping is performed over a total of 23 channels from ch.39–61 [10] for each frame. Thus, the average number of simultaneous transmissions per channel is $\alpha \times N_{Sall} \times N_{frame} \times T_{period}/N_{slot}/N_{ch}/T_{com}$.

Table I Number of channels of S-IoT terminals

LPWA method, Transmission power	Number of ch. N_{ch} (Ch. number in 920-MHz band)
LoRa, 20 mW	15 (ch.24–38)
Sigfox, 20 mW	1 (ch.37)
ELTRES, 20 mW	23 (ch.39–61)

2.2 Terrestrial IoT terminal

T-IoT terminals have one dipole antenna with an antenna gain of 2.15 dBi. We assume that the horizontal plane pattern is omnidirectional and the 90° elevation angle direction is null. Based on the terminal diffusion forecast at year 2035 for the 920-MHz band active system in [11], it is assumed that there will be 128.46 million 20-mW terminals and 6.7 million 250-mW terminals. Then, based on [11], the terminal density is calculated from the population density of each region in Japan, and considering the average transmission cycle per terminal, the average duration of 10 ms per transmission, and Japan's land area, the average number of simultaneous transmissions is 16,401 for 20-mW terminals and 864 for 250-mW terminals. Note that, as in [11], the T-IoT terminals are distributed within the territory of Japan based on the assumption that the terminal density in each region is proportional to the population density. The ratio of the number of terminals for each LPWA method is assumed to be LoRa : Sigfox : ELTRES : other method = 3 : 2 : 1 : 4 for 20-mW terminals and LoRa : other method = 3 : 7 for 250-mW terminals. For simplicity, it is assumed that the terminals of each LPWA method transmit uniformly distributed over the channels shown in Table II. The average number of simultaneous transmissions per channel calculated by these assumptions is also shown in Table II. Note that the average number of simultaneous transmissions per sub-channel for Sigfox is 1.7.

2.3 LEO satellite

A LEO satellite has N_R circularly polarized patch antennas, and the boresight direction is geocentric. The antenna gain is 6.0 dBi, the HPBW is 80°, and the receiver noise figure is 4.0 dB. A satellite is assumed to accommodate the S-IoT terminals in the east area of the circle with a radius of 1,000 km. As mentioned previously, the orbital altitude is set to 570 km, and the available communication time per day between the satellite and the S-IoT terminals is 240 sec.

2.4 Ground station

At the GS, off-line MMSE RxBF is performed on the received waveform data transferred from the satellite to separate the desired signal from the interference signal. We

Table II Number of channels and average number of simultaneous transmissions of T-IoT terminals

LPWA method, Transmission power	Number of ch. N_{ch} (Ch. number in 920-MHz band)	Average number of simultaneous transmissions per ch.
LoRa, 20 mW	38 (ch.24–61)	129.5
LoRa, 250 mW	15 (ch.24–38)	17.3
Sigfox, 20 mW	1 (ch.37)	3,280.2
ELTRES, 20 mW	23 (ch.39–61)	71.3
Others, 20 mW	38 (ch.24–61)	172.6
Others, 250 mW	15 (ch.24–38)	40.3

evaluated the complementary cumulative distribution function (CCDF) characteristic of the SINR after RxBF by Monte Carlo simulation and then evaluated the CSR p (the probability of satisfying the required SINR for each LPWA method described below). The number of simultaneous transmissions of S-IoT terminals and T-IoT terminals in each trial (denoted N_S and N_G, respectively) were determined by the Poisson distribution, where the average number of simultaneous transmissions described in Sections 2.1 and 2.2 is the expected value.

The N_R rows $(N_S + N_G)$ columns propagation channel matrix $\mathbf{H}$ consists of only direct waves between the $N_S + N_G$ simultaneous transmission terminals and the N_R receiving antennas of the satellite is defined as

$$\mathbf{H} = \left[\boldsymbol{h}_1 \cdots \boldsymbol{h}_{N_S} \boldsymbol{h}_{N_S+1} \cdots \boldsymbol{h}_{N_S+N_G}\right], \tag{1}$$

where $\boldsymbol{h}_j$ is the propagation channel vector (column vector in N_R dimension) for the j-th $(j = 1, \ldots, N_S, N_S + 1, \ldots, N_S + N_G)$ terminal. The MMSE weight matrix $\mathbf{W}$ of $N_S + N_G$ rows and N_R columns is expressed as

$$\begin{aligned}\mathbf{W} &= \left[\boldsymbol{w}_1 \cdots \boldsymbol{w}_{N_S} \boldsymbol{w}_{N_S+1} \cdots \boldsymbol{w}_{N_S+N_G}\right]^T \\ &= (\mathbf{H}^H \mathbf{H} + \mathbf{A})^{-1} \mathbf{H}^H,\end{aligned} \tag{2}$$

where $(.)^T$ is the transpose, $(.)^H$ is the complex conjugate transpose, and $\mathbf{A}$ denotes the diagonal matrix of $N_S + N_G$ rows and $N_S + N_G$ columns where $P_n/P_{t,j}$ is the diagonal component. P_n is the noise power and $P_{t,j}$ is the transmission power of the j-th terminal. The SINR for the j-th S-IoT terminal after MMSE RxBF is expressed as

$$\mathrm{SINR}_j = \frac{P_{t,j}\left|\boldsymbol{w}_j^T \boldsymbol{h}_j\right|^2}{\sum_{k=1,k\neq j}^{N_S+N_G} \frac{P_{t,k}}{\beta_k}\left|\boldsymbol{w}_j^T \boldsymbol{h}_k\right|^2 + P_n \boldsymbol{w}_j^H \boldsymbol{w}_j}, \tag{3}$$

where β is the power correction factor due to spreading gain, as will be described in Sections 2.4.1–2.4.3.

The following sections describe the concept of interference signals and the method of calculating the CSR achieved by multiple transmissions of the same data in the capacity evaluation when LoRa, Sigfox, and ELTRES are each used as S-IoT terminals.

2.4.1 LoRa as S-IoT terminal

Capacity is evaluated considering the interference between S-IoT terminals and interference from T-IoT terminals of LoRa and other LPWA methods. That is, it corresponds to the evaluation in ch.24–36, 38. It is assumed that the LoRa T-IoT terminal transmits signals of any of SF 7–12 and that the proportion of each SF is equal. For SF 12, which is the same SF as S-IoT terminals, $\beta = 1$ because no spreading gain is available, and for SF 7–11, a spreading gain of $\beta = 2^{12}/12 = 341.3$ is considered. For the terminals of the other methods, β is set to 341.3. Substitute these β into Eq. (2) and (3) to calculate SINR. Then, the probability p of satisfying the required SINR 6dB is calculated from the CCDF of the SINR, and the CSR for three transmissions of the same data is calculated by $p' = 1 - (1 - p)^3$.

2.4.2 Sigfox as S-IoT terminal

Capacity is evaluated considering interference between S-IoT terminals and interference from T-IoT terminals of Sigfox, LoRa, and others. A transmitted Sigfox signal with a bandwidth of 100 Hz is spread to several hundred Hz due to the time variation of the Doppler shift caused by the high-speed movement of the LEO satellite, but it is assumed that the Doppler shift compensation at the GS compensates for the signal bandwidth so that it is less than 150 Hz [12] and the 150-Hz bandwidth is extracted by a filter. Note that for simplicity, it is assumed that the interference Sigfox signals are compensated to the 150-Hz bandwidth as well. Therefore, when calculating the SINR of a Sigfox terminal, it is assumed that, in addition to the interference signal transmitted simultaneously on the same sub-channel as the desired signal, 1/3 of the power of the interference signal transmitted simultaneously on the two adjacent sub-channels on both sides interfere. The signal bandwidth of the other method is assumed to be 125 kHz as well as LoRa method. For both systems, the 150-Hz bandwidth component out of the interference signal is assumed to interfere with the desired signal, so $\beta = 125{,}000/150 = 833.3$. The probability p of satisfying the required SINR of 9 dB is calculated from the CCDF of the SINR, and the CSR for three transmissions of the same data is calculated by $p' = 1 - (1 - p)^3$.

2.4.3 ELTRES as S-IoT terminal

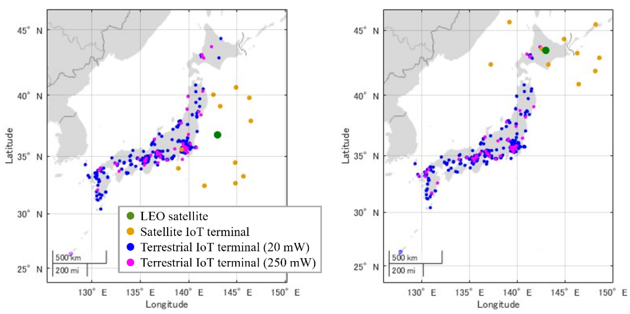
Capacity is evaluated considering the interference between S-IoT terminals and interference from the T-IoT terminals of LoRa and the other LPWA methods. Considering the spreading gain due to CSS for ELTRES, set $\beta = 160{,}000/6{,}350 = 25.2$ for LoRa and the other methods. ELTRES is characterized by transmitting the same data four times and performing maximum-ratio combining (MRC) of those four frames in the receiving processing. In this letter, the probability density function (PDF) of the SINR per transmission is evaluated, and the CCDF characteristic is obtained by calculating the SINR after MRC from each SINR of the four transmissions determined by a random number in accordance with the PDF. Then, from the CCDF, the probability of satisfying the required SINR of 7 dB is determined and set as the CSR p'.

3. Channel capacity evaluation

The CSR p' of S-IoT terminals when the satellite is located over the point shown in Fig. 1 was evaluated by Monte Carlo simulation with 10,000 trials. Figure 1 shows the positions of the satellite, S-IoT terminals, and T-IoT terminal that transmitted simultaneously in one trial. The evaluation of case 1 shown in Fig. 1(a) is when the satellite is located over a point at 36.8°N latitude and 143.0°E longitude, and interference signals arrive from many T-IoT terminals in urban areas such as Tokyo. Meanwhile, Fig. 1(b) shows case 2, when the satellite is located over a point at 43.5°N latitude and 143.0°E longitude, far from urban areas, and the impact of interference signals from T-IoT terminals is relatively small.

Figure 2 shows the capacity of each channel, i.e., the number of S-IoT terminals $N_{Sall,max}/N_{ch}$ that can be accommodated by one satellite per channel in the 920-MHz band. $N_{Sall,max}$ denotes the maximum number of N_{Sall}, provided that $p' \geq 0.99$ is satisfied. For $N_R = 9$ and case 1, the capacity is 300 terminals/channel when LoRa is used for S-IoT terminals, 160,000 terminals/channel when Sigfox is used, and 80,000 terminals/channel when ELTRES is used. Thus, for example, when using ELTRES, which has 23 channels available, N_{Sall} would be 1.84 million terminals. Also, a comparison of the capacity per channel between LPWA methods shows that Sigfox and ELTRES can be accommodated 533 and 267 times as many terminals as LoRa, respectively. The reason for this high capacity is that Sigfox can multiplex by 1,920 sub-channels per channel and ELTRES can multiplex by CSS per time slot at 8-ms intervals. Also, Fig. 2 shows that in case 2, the capacity is increased due to the reduced impact of interference signals from T-IoT terminals.

Figure 3 shows a comparison of the CCDF characteristics of the SINR with and without interference to evaluate the impact of interference between S-IoT terminals and interference from T-IoT terminals. As the figure shows, interference degrades the characteristics by 23 dB at CCDF = 0.8 for $N_R = 1$. In addition, when $N_R = 9$, the amount of property degradation due to interference is reduced to 16 dB for case 1 and 13 dB for case 2 due to the effect of RxBF. Note that the minimum SINR values for "w/o interference" when $N_R = 1, 9$ are 13.9 dB, 23.5 dB, respectively, which represent the SNR of the received signal from the S-IoT terminal at the area edge (elevation angle of 48.7°). As mentioned in Sections 2.4.1–2.4.3, the required SNRs for LoRa, Sigfox, and ELTRES are 6 dB, 9 dB, and 2 dB, respectively, indicating that it is possible to communicate to a LEO satellite even with 20-mW power.



(a) case 1 (b) case 2

Fig. 1 Position of LEO satellite, S-IoT terminals, and T-IoT terminals.

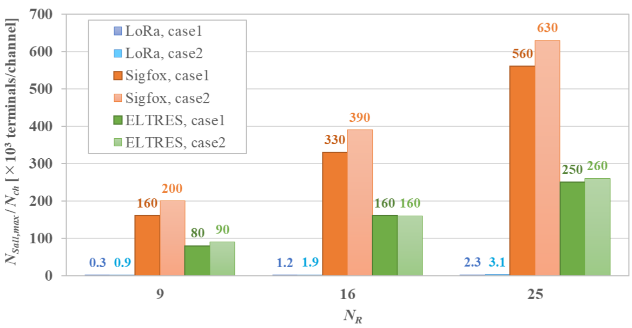


Fig. 2 Channel capacity comparison between LPWA methods.

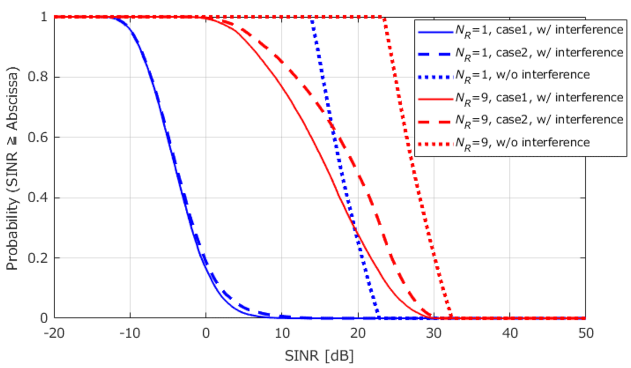


Fig. 3 CCDF performance of SINR.

4. Conclusion

To clarify the order of the number of S-IoT terminals that can be accommodated by a LEO satellite in a 920-MHz band S-IoT platform, the number of LPWA terminals accommodated by using MMSE RxBF was evaluated through computer simulations. We determined that when there are nine satellite receiving antennas, LoRa, Sigfox, and ELTRES can be accommodated by 300, 160,000, and 80,000 terminals per channel in a 920-MHz band, respectively. Thus, for example, when using ELTRES, which has 23 channels available in the 920-MHz band, a satellite can accommodate 1 million-order S-IoT terminals.

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