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Optimization of Parameter Allocation System for LoRaWAN

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Abstract. This paper investigates the allocation of parameters of Long Range (LoRa) system and does some optimization to improve the performance. The objective of this paper is to adjust the assignment of parameters like spreading factor (SF), transmission power (TP), and bandwidth (BW) to foster the performance of packet error rate (PER), bit error rate (BER), and energy consumption. First, some models and basic relationships used in the simulation process have been shown in the methodology. Also, the process of the simulation and the parameter setup are displayed. The result, it is demonstrated the different parameter allocation systems for the networks of different densities. In the low-density network, using lower SF and a more specific allocation of TP and BW can improve the overall performance. In the high-density network, using a higher value will be the optimal option for the SF, adjusting the area of the SF according to the number of devices and allocating the parameters more specifically can also both get better performance of the LoRa, especially for the PER and BER. These findings can assist designers in developing more reliable LoRa wireless communication systems.

Keywords: LoRaWAN, Parameter allocation, Performance optimization

1. Introduction

LoRaWAIN, a low-power wide-area networks (LPWANs) protocol, facilitates extensive and low-bandwidth data exchange. Launched by the LoRa Alliance in 2015, it has emerged as a keystone for the global proliferation of Internet of' Things (loT) networks [1]. As loT development accelerates, the demand for robust, extensive-range and energy-efficient wireless communication protocols escalates [2]. Certainly, LoRaWAN is also facing challenges, like network congestion, limited data transmission rates, and energy management issues. This study aims to introduce an innovative optimization framework for LoRaWAN, enhancing its dependability and operational efficiency in extensive network implementations. While existing research has addressed the optimization of parameters such as spreading factor (SF), transmit power (TP), and bandwidth (BW), there is an unmet need for a more granular and precise calibration of these elements. Our research refines LoRa's energy efficiency, bit error rate (BER), and packet error rate (PER) by meticulously adjusting

SF, TP, and BW. Utilizing MATLAB for simulation, we have substantiated that our approach markedly elevates the operational excellence of LoRa systems. In the remaining parts will introduce our optimization method, the results, and the analysis.

2. Methodology

2.1. System model

2.1.1. Hata model for path loss of urban and suburban environment [3]

Hata model uses the following formulas to calculate path loss in urban and suburban environment. In urban areas, there is such a formula:

$$PL_{HU}\,[dB] = 69.55 + 26.16\log(f_c) - 13.82\log(h_t) - C_H + [44.9 - 6.55\log(h_t)]\log(d) \tag{1}$$

where d is the distance between receiver and a gateway in kilometers, and C_H is the antenna height correction factor, which can be calculated by

$$C_H = [1.11\log(f_c) - 0.7]h_r - [1.56\log(f_c) - 0.8] \tag{2}$$

Afterwards, path loss in suburban area can be calculated with the formula below:

$$PL_{HS}\,[dB] = PL_{HU}\,[dB] - 4.78[\log(f_c)]^2 + 18.33\log(f_c) - 40.94 \tag{3}$$

Also, signal to noise ratio can be calculated in a similar way. To be specific,

$$SNR\,[dB] = TP\,[dB] + G_{tx}\,[dB] - PL\,[dB] - N\,[dB] \tag{4}$$

In this formula, N means the received noise power. In AWGN noise floor,

$$N\,[dB] = -174 + NF + 10logBW \tag{5}$$

2.1.2. BER performance expression [4]

To confirm the accuracy of the numerical model, it is extremely important to adopt an analytic expression for the BER performance of the simulated LoRa system in AWGN channels. To fully consider the impact of bitrate parameters on several important BER performances, BER can be calculated as below:

$$BER = Q\left(\frac{log_{12}(SF)}{\sqrt{2}} * \frac{E_b}{N_0}\right) \tag{6}$$

where SF is the spreading factor and Eb/N0 is the energy per bit to noise power spectral density, which can be calculated as

$$\frac{E_b}{N_0}\,[dB] = SNR\,[dB] + 10\log_{10}(\frac{B_w}{R_b}) \tag{7}$$

for SNR a pre-defined signal-to-noise ratio in an AWGN channel and dB the decibel logarithmic unit. Neglecting channel coding, the bit rate shown in the equation above is defined as Rb = SF · BW/(2^SF) in b/s.

2.1.3. Three different models

Three models were used to show the influence of a single parameter (SF, TP, BW) on the LoRa performance that is also used in the simulation process.

1) Spreading factor

The following three figures demonstrate the impact of SF on the performance of LoRa systems: it can be seen that as SF increases, when the transmission power is low, the packet loss rate and collision probability of packages increase significantly under the same number of users, while the BER sharply decreases under the same SNR, indicating that a larger SF value is beneficial for reducing the bit error rate, but not conducive to reducing the packet loss rate and energy consumption when the transmission power is lower, nonetheless, the situation might have some difference when the transmission power increases, this will be discussed later.

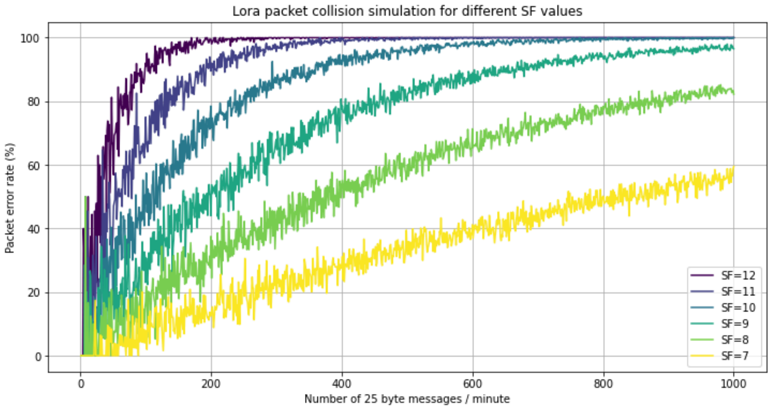


Figure 1. The relationship curve between SF and PER with low transmission power

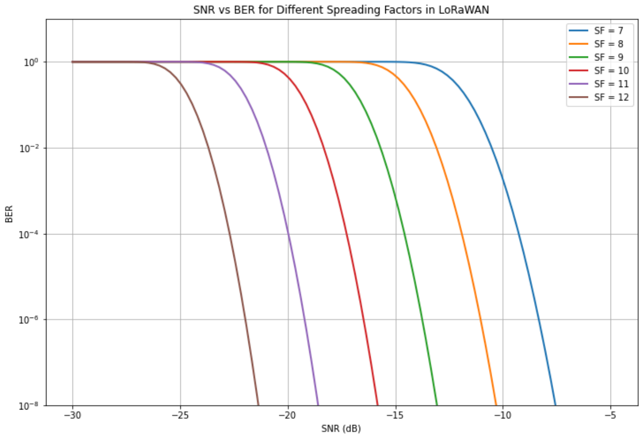


Figure 2. The relationship curve between SNR and BER with different spreading factors

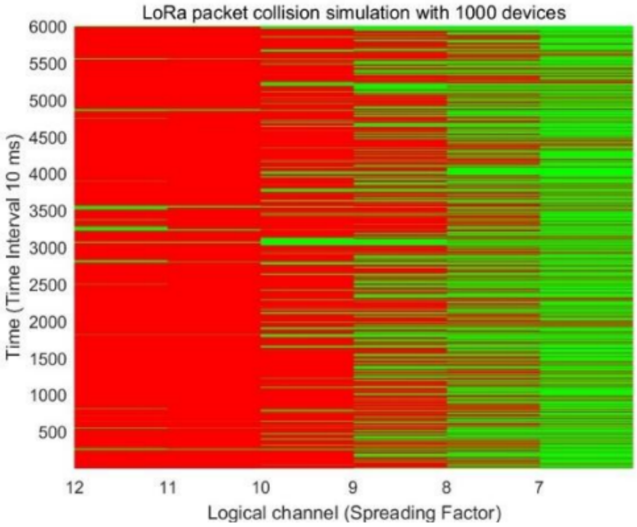


Figure 3. The relationship between SF and collision with low transmission power

2) Transmission power

The following figures show the impact of TP on LoRa transmission performance. Under the same SF conditions, higher transmission power can lead to lower packet loss rate and bit error rate, while inevitably causes greater energy consumption at the same time.

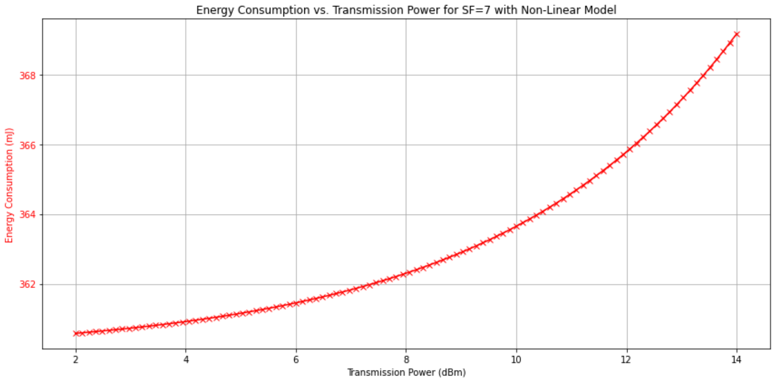


Figure 4. The relationship curve between TP and energy consumption

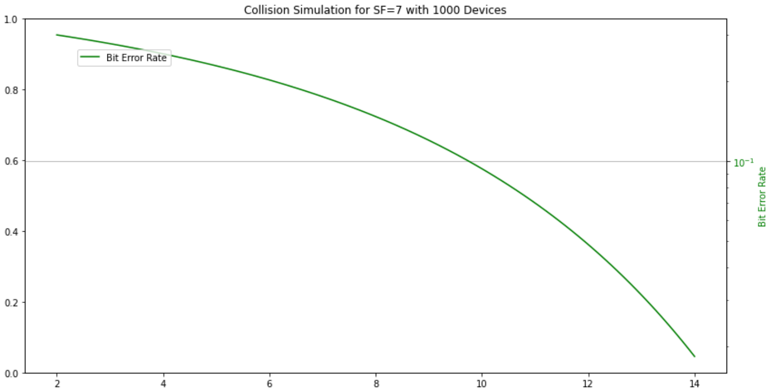


Figure 5. The relationship curve between TP and BER when SF = 7

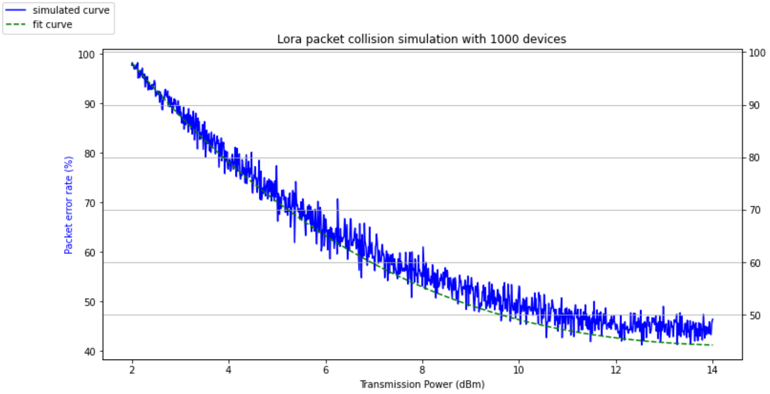


Figure 6. The relationship curve between TP and PER with random SF

3) Bandwidth

When it comes to bandwidth, the situation becomes even more obvious. Using higher bandwidth can apparently reduce energy consumption while increasing data rate. However, the range of SNR values will be limited to a certain extent after adopting high bandwidth, which indirectly leads to an increase in bit error rate as a result.

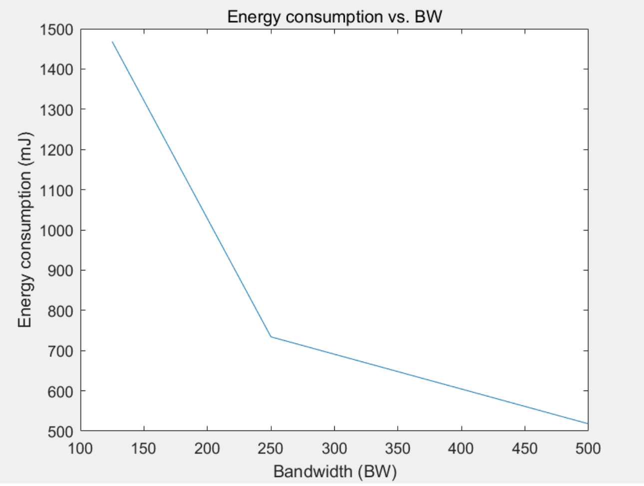


Figure 7. The relationship curve between BW and energy consumption

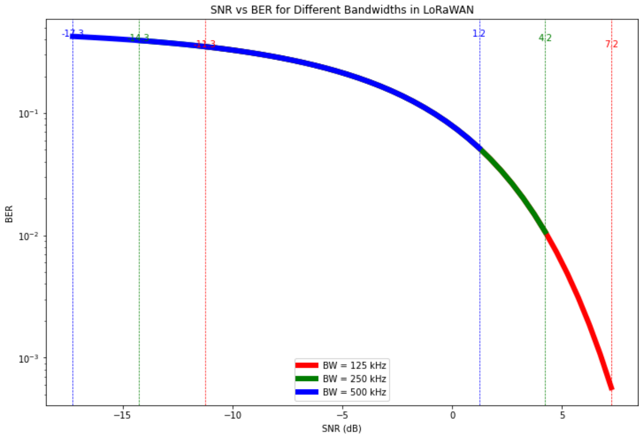


Figure 8. The relationship curve between SNR and BER with different bandwidth

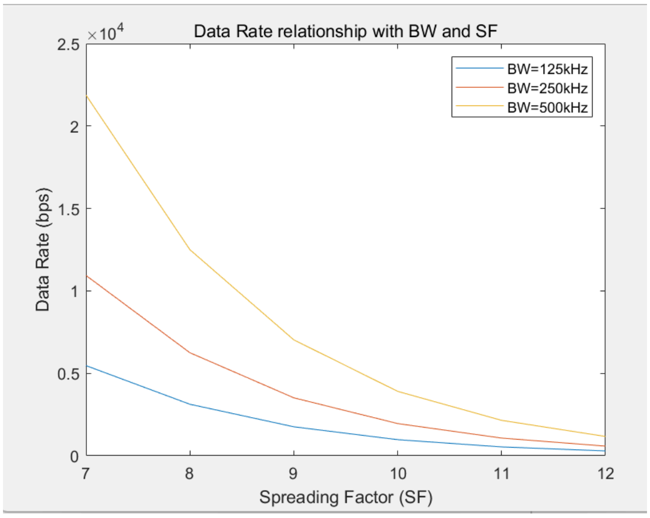


Figure 9. The relationship curve between SF and data rate with different bandwidth

2.2. Simulation setup and scenario

2.2.1. Parameter setup

This simulation concentrated on the single gateway system. The key parameters in the simulation are displayed in Table 1 and Table 2 presents the equivalent bit rate and the packet durations per 25 bytes (ms) of different spreading factors.

Table 1. Key parameters for the research based on Matthew Brandon Dani [5]

Fixed value	
base frequency(Hz)	868
coverage(km)	14
height of transmitted antennas(m)	30
height of received antennas(m)(m)	1.5
nf(dB)	6
timespan(ms)	60*1000
time_internal(ms)	10
number of channels	1
number of packets	1
gain of antenna(dB)	4
frequency_internal(Hz)	100
variable value	
Spreading Factor(SF)	7, 8, 9, 10, 11, 12
Bandwidth(BW) (kHz)	125, 250, 500
Transmission Power (TP) (dBm)	2-14

Table 2. Parameter of spreading factor in simulator LoRa based on Matthew Brandon Dani [5]

SF	Equivalent bit rate	Duration per 25 bytes (ms)
7	5478	36
8	3125	64
9	1757	113
10	976	204
11	547	365
12	293	682

2.2.2. Simulation setup

The research used the simulators that modified the Wireless LoRa Simulation-Matlab [5] from Matthew Brandon Dani showing the relationship between different spreading factors and the number of collisions and packet error rates with the change of the number of devices and the LoRa simulator from Riccardo Marini [6], which simulates the energy consumption with different parameters.

The main objective of the research is to allocate the parameters (SF, TP, BW) more specifically to get better performance in the low and high-density network environment to get the Lower PER, Lower BER, and Lower Energy consumption. Thus, the low-density and high-density network environments are set up using different hata models and various devices to simulate.

1) Low-density network cases: In the simulation process, the hata-suburban model was adopted to simulate the influence of the parameter allocation in the coverage of a single LoRa gateway on the bit error rate (BER), 100-200 devices were used to simulate the low-density network environment to simulate the impact of the parameter allocation on the packet error rate (PER) and the energy consumption.

2) High-density network cases: The simulation used the hata-urban model as the high-density network environment model to simulate the influence of the parameter allocation in the coverage of a single LoRa gateway on the bit error rate (BER). 1000-2000 devices were used to simulate the high-density environment to simulate the impact of the parameter allocation on the packet error rate (PER) and the energy consumption.

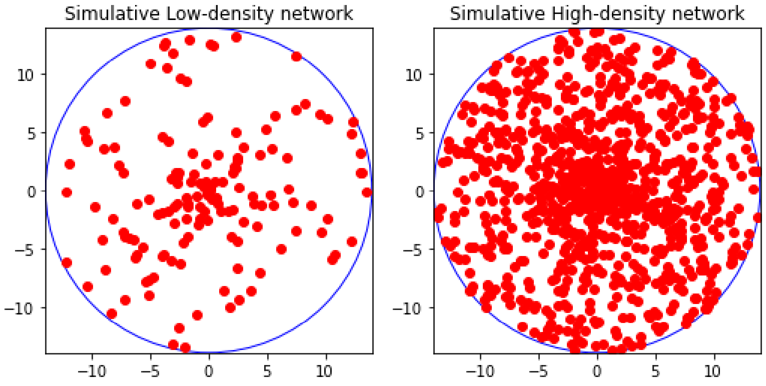


Figure 10. The simulation of the low and high-density network environment

To identify the best allocation of parameters, figuring out the range of different value ranges is important. However, if considering all of the values of various parameters, the process of optimization will be more complicated. In this research, the range of the spreading factors was first identified, because of the different coverage of the different spreading factors and the obvious influence of the spreading factors on the packet error rate in different network densities. After making the range of the spreading factor and the allocation of the spreading factors in the coverage (14km) clear, the next step is to adjust and allocate the transmission power (2dBm-14dBm) and bandwidth (125, 250, 500 kHz) of every SF area to get the best performance.

For the simulation of the energy consumption, similar to the simulation done on BER and PER, spreading factor, bandwidth, and transmission power are selected to be the variable parameters for energy consumption tests, with an existing LoRa simulator introduced in [2] to help perform the simulation. The CR is fixed to be 1, and two sets of experiments are done with 100 and 1000 devices respectively to simulate low-density and high-density Lora environment. The spreading factor will vary from 7 to 12, the range of transmission power is 2 to 14, and bandwidth will be selected between 125 kHz, 250 kHz, and 500 kHz. Five iterations will be done on each of the 126 combinations to ensure accuracy and reliability.

This 3-dimensional simulation aims to observe how changes in the three parameters impact the energy consumption performance of the selected Lora system, and also the potential effects caused by combining changes in different parameters. With the performance on energy consumption with different parameter combinations,

3. Results and discussion

3.1. Low-density network case

Table 3 shows the coverage of different spreading factors assumed, it is displayed that the essence of using different spreading factors is to make coverage bigger. The simulation of the relationship between the packet error rate and the transmission power with different spreading factors (Fig 11) illustrates that to ensure a low packet error rate in the low-density network, using SF7 and 8 is an optimal option. Through the comparison between the performance of SF7 and SF8, it is easy to see the smaller one is better, so increasing the coverage of the SF7 might have a better performance of the packet error rate.

Table 3. The coverage of different spreading factors in the low-density network environment

SF	Transmission coverage (km)
7	5-10
8	10-15
9	15-20
10	20-25
11	25-30
12	30-40

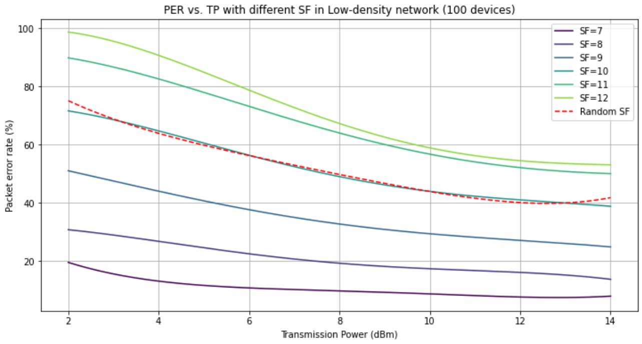


Figure 11. PER vs. TP with different SF in low-density network

Throughout some tests, the optimal spreading factors area allocation in the low-density network is SF7:SF8 = 9:5, which shows the lower BER and Energy consumption and the lowest PER compared with other allocative decisions. Then after the simulation of the different allocative combinations of transmission power and bandwidth, the final system for the low-density system (100-200 devices) is displayed in Fig 12.

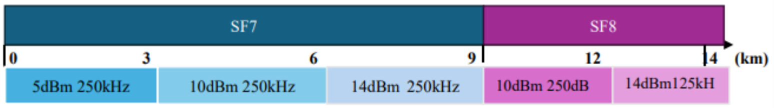


Figure 12. The optimal parameter system in the low-density network environment

Figure 13. The simulative conventional system

Compared with the simulative conventional system (Fig 13), which is without the specific parameter allocation, the performance of the PER and energy consumption both get excellent optimization results. In particular, the long-distance PER is reduced, as shown in Fig 14, the long-distance PER of the conventional system exceeds 5%, but because the optimized system adopts SF8 in the coverage of 9-14. Compared with the coverage of SF8 in a larger range of conventional systems, the new system takes advantage of the low interference of SF7 in low-density environments compared with SF8, increases the coverage of SF7, reduces the coverage of SF8, and optimizes the long-distance packet loss rate.

In Fig 15, it is easy to see that there is no distinct optimization for the BER. Nonetheless, to ensure the quality of the signal, the bit error rate should be lower than 10-6, for the conventional system, the long-range BER is higher than 10-6, the optimal system can solve this issue more flexibly, making the BER of the system within the high-quality range.

Table 4 compares the performance on the energy cost of the optimized LoRa system to the conventional system in a low-density environment. It can be observed that in low-density cases, the power consumption is solidly reduced, with only one exception in the region of 12-14 kilometers.

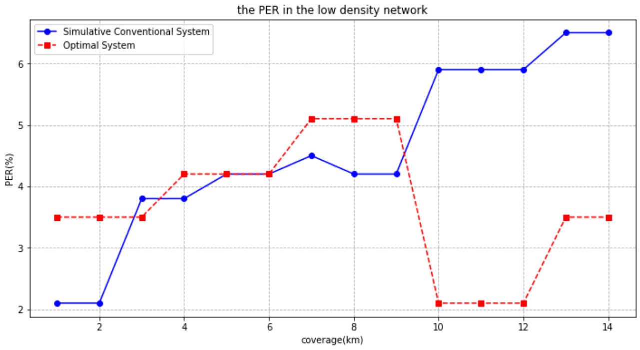


Figure 14. The comparison of the performance of PER in the low-density network

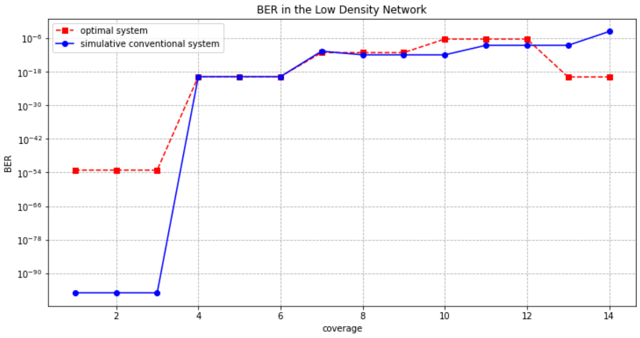


Figure 15. The comparison of the performance of BER in the low-density network

Table 4. Optimized system vs conventional system in energy cost (low-density environment)

Energy Consumption (mJ)			
Coverage(km)	Conventional	Optimized	Comparison
0~3	3693	3615	-2.11%
3~6	3693	3648	-1.22%
6~9	4123	3675	-10.87%
9~12	4338	4104	-5.39%
12~14	2892	2892	-

3.2. High-density network case

In the high-density network, the situation will be more complicated, with the increase of devices, the interference of different devices will be more and more, and the coverage of different SF areas will reduce (Table 5). Thus, more spreading factors should be used. Also, in the high-density network, the bigger spreading factor shows the better performance of PER compared to the smaller one, it is demonstrated in Fig 16. The PER of the SF12 has an obvious decrease with the increase of the transmission power, even getting better than the performance of SF9. Therefore, increasing the coverage of the higher SF area in the high-density network might have a better performance of PER.

Table 5. The coverage of different spreading factors in the low-density network environment

SF	Transmission coverage (km)
7	1-2
8	2-4
9	4-6
10	6-8
11	8-10
12	10-14

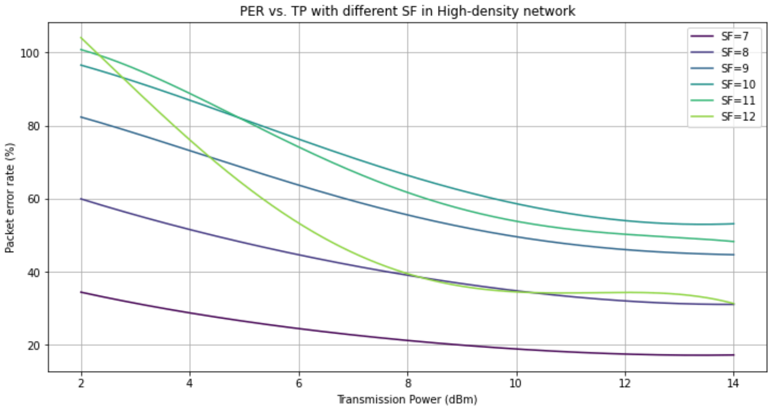


Figure 16. PER vs. TP with different SF in low-density network

After some complicated tests, the optimal system of the high-density network is displayed in Fig 17, compared with the simulative conventional system shown in Fig 18, the optimal system has a more specific parameter allocation of transmission power and bandwidth and a bigger area of SF12.

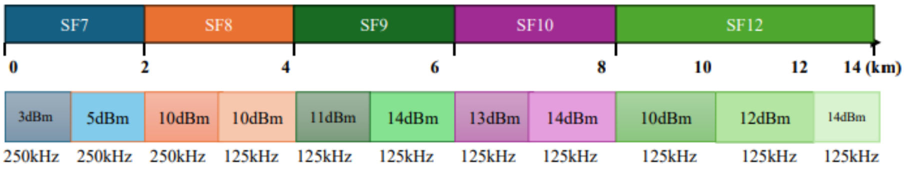


Figure 17. The optimal parameter system in the high-density network environment

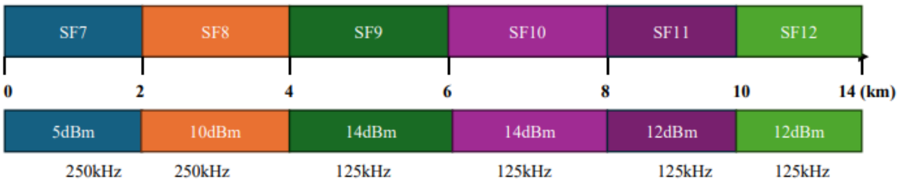


Figure 18. The simulative conventional system in a high-density network [7]

In Fig 19, there is a distinct optimization of the PER compared with the conventional one, especially for the long-range PER. In Fig 20, the optimal system also has some better effects on the performance of BER, although the BER of the simulative conventional system is also good. Table 6 compares the performance on the energy cost of the optimized LoRa system to the conventional system in a high-density environment. The improvement in energy cost is not that obvious. Although the total cost is still reduced, it can be seen that in the region of 12-14 kilometers, the energy cost increases by 5.38%. Such concession in parameter selection has a fair reason, it serves the purpose of improving the system's performance in domains other than power cost, like channel stability, as our initial goal is not to blindly cut down the system's energy cost but to optimize its overall efficiency while keeping energy consumption in an acceptable range.

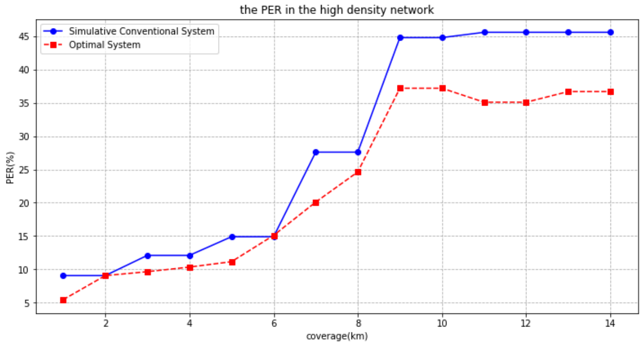


Figure 19. The comparison of the performance of PER in the high-density network

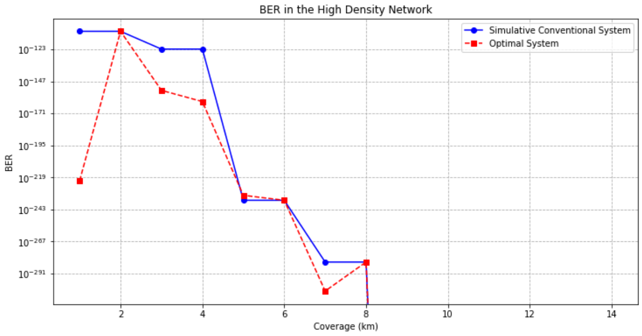


Figure 20. The comparison of the performance of BER in the high-density network

Table 6. Optimized system vs conventional system in energy cost (high-density environment)

Energy Consumption(mJ)			
Coverage(km)	Conventional	Optimized	Comparison
0~1	1167	1162	-0.43%
1~2	1167	1167	-
2~3	1298	1290	-0.62%
3~4	1298	1299	0.08%
4~5	1369	1316	-3.87%
5~6	1369	1369	-
6~7	1261	1240	-1.67%
7~8	1261	1261	-
8~10	1104	1069	-3.17%
10~12	1115	1115	-
12~14	1115	1175	(+5.38%)

Something here is interesting, so with the increase in the number of devices, the bigger spreading factors will have much better interference-resistance properties when the transmission power is high enough. The PER performance with different SF in higher-density network environments is shown in Fig 21, compared to Fig 16, this diagram is the result with double devices of Fig 7. It is easy to see that the PER of the high SF, including 10, 11, and 12 have a steeper decrease with the increase of the transmission power than the situation with fewer devices. Therefore, in contrast to low-density networks, in high-density networks, as the number of devices increases, it may be a good choice to increase the proportion of coverage of higher SFs.

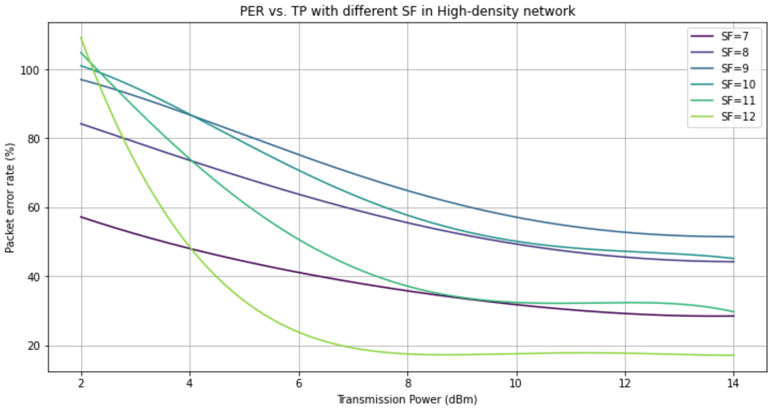
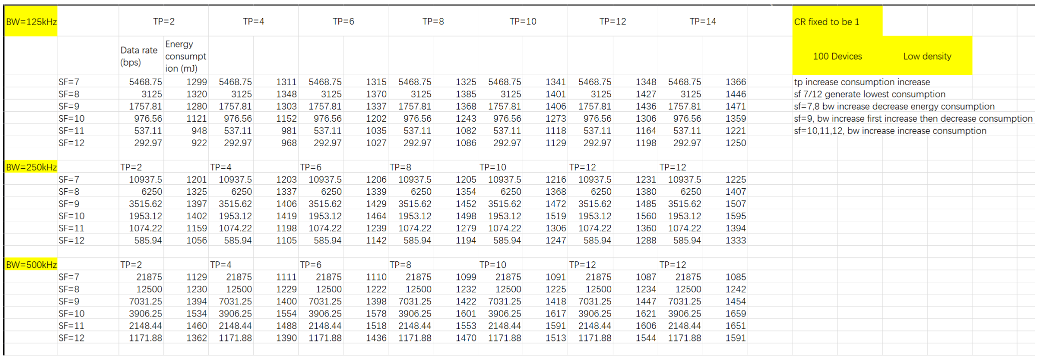


Figure 21. PER vs. TP with different SF in higher-density network

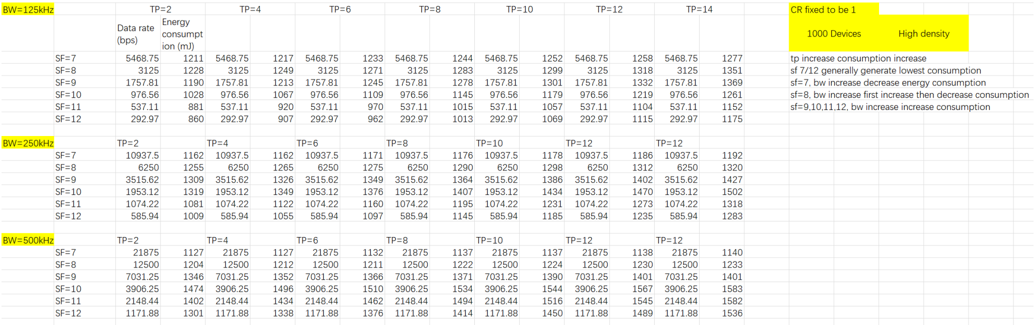
Figure 22 and Figure 23 provide the energy consumption simulation results for 100 device cases and 1000 device cases respectively. Several trends of energy consumption are observed while manipulating the three parameters, and both low and high-density cases share the same trend. The measure of adding more TP gradually increases the power consumption, indicating that if only considering the performance in energy consumption, a low TP will be a good choice.

On the other hand, in the simulation of energy consumption, the benefits of increasing the smaller spreading factor and the bigger spreading factor to satisfy the low-density and high-density network environment are shown as well. A different pattern is observed from increasing SF. The amplitude of energy consumption first increases and then decreases, resulting in the outcome that the most power-consuming case generally occurs in the range of SF from 8 to 10, while SF7 and SF12 generally produce the most energy-saving options. Thus, if only considering minimizing energy cost, either the lowest or highest SF will be a good option.



BW=125kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=14		CR fixed to be 1	
		Data rate (bps)	Energy consumption (mJ)													100 Devices	Low density
	SF=7	5468.75	1299	5468.75	1311	5468.75	1315	5468.75	1325	5468.75	1341	5468.75	1348	5468.75	1366	tp increase consumption increase	
	SF=8	3125	1320	3125	1348	3125	1370	3125	1385	3125	1401	3125	1427	3125	1446	sf 7/12 generate lowest consumption	
	SF=9	1757.81	1280	1757.81	1303	1757.81	1337	1757.81	1368	1757.81	1406	1757.81	1436	1757.81	1471	sf=7,8 bw increase decrease energy consumption	
	SF=10	976.56	1121	976.56	1152	976.56	1202	976.56	1243	976.56	1273	976.56	1306	976.56	1359	sf=9, bw increase first increase then decrease consumption	
	SF=11	537.11	948	537.11	981	537.11	1035	537.11	1082	537.11	1118	537.11	1164	537.11	1221	sf=10,11,12, bw increase increase consumption	
	SF=12	292.97	922	292.97	968	292.97	1027	292.97	1086	292.97	1129	292.97	1198	292.97	1250		
BW=250kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=12			
	SF=7	10937.5	1201	10937.5	1203	10937.5	1206	10937.5	1205	10937.5	1216	10937.5	1231	10937.5	1225		
	SF=8	6250	1325	6250	1337	6250	1339	6250	1354	6250	1368	6250	1380	6250	1407		
	SF=9	3515.62	1397	3515.62	1406	3515.62	1429	3515.62	1452	3515.62	1472	3515.62	1485	3515.62	1507		
	SF=10	1953.12	1402	1953.12	1419	1953.12	1464	1953.12	1498	1953.12	1519	1953.12	1560	1953.12	1595		
	SF=11	1074.22	1159	1074.22	1198	1074.22	1239	1074.22	1279	1074.22	1306	1074.22	1360	1074.22	1394		
	SF=12	585.94	1056	585.94	1105	585.94	1142	585.94	1194	585.94	1247	585.94	1288	585.94	1333		
BW=500kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=12			
	SF=7	21875	1129	21875	1111	21875	1110	21875	1099	21875	1091	21875	1087	21875	1085		
	SF=8	12500	1230	12500	1229	12500	1222	12500	1232	12500	1225	12500	1234	12500	1242		
	SF=9	7031.25	1394	7031.25	1400	7031.25	1398	7031.25	1422	7031.25	1418	7031.25	1447	7031.25	1454		
	SF=10	3906.25	1534	3906.25	1554	3906.25	1578	3906.25	1601	3906.25	1617	3906.25	1621	3906.25	1659		
	SF=11	2148.44	1460	2148.44	1488	2148.44	1518	2148.44	1553	2148.44	1591	2148.44	1606	2148.44	1651		
	SF=12	1171.88	1362	1171.88	1390	1171.88	1436	1171.88	1470	1171.88	1513	1171.88	1544	1171.88	1591		

Figure 22. Energy consumption with different BW, SF, and TP combinations in a low-density environment



BW=125kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=14	
		Data rate (bps)	Energy consumption (mJ)												
	SF=7	5468.75	1211	5468.75	1217	5468.75	1233	5468.75	1244	5468.75	1252	5468.75	1258	5468.75	1277
	SF=8	3125	1228	3125	1249	3125	1271	3125	1283	3125	1299	3125	1318	3125	1351
	SF=9	1757.81	1190	1757.81	1213	1757.81	1245	1757.81	1278	1757.81	1301	1757.81	1332	1757.81	1369
	SF=10	976.56	1028	976.56	1067	976.56	1109	976.56	1145	976.56	1179	976.56	1219	976.56	1261
	SF=11	537.11	881	537.11	920	537.11	970	537.11	1015	537.11	1057	537.11	1104	537.11	1152
	SF=12	292.97	860	292.97	907	292.97	962	292.97	1013	292.97	1069	292.97	1115	292.97	1175
BW=250kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=12	
	SF=7	10937.5	1162	10937.5	1162	10937.5	1171	10937.5	1176	10937.5	1178	10937.5	1186	10937.5	1192
	SF=8	6250	1255	6250	1265	6250	1275	6250	1290	6250	1298	6250	1312	6250	1320
	SF=9	3515.62	1309	3515.62	1326	3515.62	1349	3515.62	1364	3515.62	1386	3515.62	1402	3515.62	1427
	SF=10	1953.12	1319	1953.12	1349	1953.12	1376	1953.12	1407	1953.12	1434	1953.12	1470	1953.12	1502
	SF=11	1074.22	1081	1074.22	1122	1074.22	1160	1074.22	1195	1074.22	1231	1074.22	1273	1074.22	1318
	SF=12	585.94	1009	585.94	1055	585.94	1097	585.94	1145	585.94	1185	585.94	1235	585.94	1283
BW=500kHz		TP=2		TP=4		TP=6		TP=8		TP=10		TP=12		TP=12	
	SF=7	21875	1127	21875	1127	21875	1132	21875	1137	21875	1137	21875	1138	21875	1140
	SF=8	12500	1204	12500	1212	12500	1211	12500	1222	12500	1224	12500	1230	12500	1233
	SF=9	7031.25	1346	7031.25	1352	7031.25	1366	7031.25	1371	7031.25	1390	7031.25	1401	7031.25	1401
	SF=10	3906.25	1474	3906.25	1496	3906.25	1510	3906.25	1534	3906.25	1544	3906.25	1567	3906.25	1583
	SF=11	2148.44	1402	2148.44	1434	2148.44	1462	2148.44	1494	2148.44	1516	2148.44	1545	2148.44	1582
	SF=12	1171.88	1301	1171.88	1338	1171.88	1376	1171.88	1414	1171.88	1450	1171.88	1489	1171.88	1536

CR fixed to be 1
1000 Devices High density
tp increase consumption increase
sf 7/12 generally generate lowest consumption
sf=7, bw increase decrease energy consumption
sf=8, bw increase first increase then decrease consumption
sf=9,10,11,12, bw increase increase consumption

Figure 23. Energy consumption with different BW, SF, and TP combinations in a high-density environment

Lastly, the BW selection is found to be largely dependent on the SF that is selected, while the change in TP does not show a significant impact on it. Specifically, when SF is low, an increasing BW generates lower overall energy consumption, but as we increase SF, the pattern alters and eventually causes the power consumption to increase as we select greater BW. The initial pattern is understandable as a greater BW represents a wider channel, which reduces the chance of signal collision during LoRa operation, and as studied in [8], with less probability of collision the total energy consumption drops, because the system does not have to resend that much collided signal. For the altered pattern seen in higher SF cases, it can be explained that the measure of increasing SF brings more complex factors into the LoRa system, which can turn large BW features into a disadvantage. For instance, a wider BW may invite more potential interference from other signals, meaning the system might need to make adjustments or retransmissions, both of which can consume additional energy. Combined with the fact that a high SF often tends to generate a higher package error rate, large BW's negative side effect on channel stability is magnified in a high SF environment, and it overwhelmed the benefit gained from having a wider channel, leading to a higher total energy cost.

4. Conclusion

This study discusses the influence of system parameter optimization on the performance of remote (LoRa) systems in low-density and high-density network environments. By providing a specific introduction to the models and basic relationships used in simulations as well as offering solutions based on these simulations, this study proves that suitable configuration of LoRa parameters, particularly spreading factor (SF), transmission power (TP), and bandwidth (BW), can significantly affect critical performance indicators.

These indicators include packet error rate (PER), bit error rate (BER), and energy consumption. In low-density networks, using lower SF can improve signal quality, while adjusting SF according to the number of users can further improve system outcomes. On the contrary, expanding higher SF regions and allocating increased TP and BW to these regions can alleviate interference and improve performance in high-density networks.

In addition, the survey also makes a profound study on the impact of TP and BW selection on system performance. These findings provide valuable guidance for network designers and engineers to create more efficient and reliable LoRa-based wireless communication systems that can accommodate different network densities.

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