# LoSee: Long-Range Shared Bike Communication System Based on LoRaWAN Protocol


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## Abstract

The development of LPWAN technology is gradually becoming an evolution of IoT (Internet of Things) applications, for its significant improvements of signal sensitivity and noise tolerance. At present, however, many IoT applications, such as shared-bike systems in China, are still using the communication technology of traditional mobile network, which consumes considerable power and suffers from high communication cost. In this paper, we present LoSee, a long-range shared-bike communication system, based on the LoRaWAN protocol. We clarify the system parameters of LoSee and determine its communication range. LoSee prototype system is implemented to track the bike route in real time. With the data collected from the prototype system, the relationship between the Packet Delivery Rate(PDR) and Signal to Noise Ratio(SNR) is built. Considering the impact of signal contention, a model is theoretically verified to decide the PDR under different node count and duty cycle. Finally, LoSee communication range is concluded and a solution is proposed for setting up a shared-bike system in the campus by LoRaWAN, which reduces power consumption and eases gateway deployment.


## 1 Introduction

IoT is another great innovation after Internet and Mobile Network in the information era. There will be approximately 24 billion IoT devices around the world till 2020. IoT extends the network node count drastically by connecting usual things in daily life by wireless networking and sensing technology. In a specific deployment of IoT devices (i.e., shared-bike) in large scale, a naive solution is utilizing traditional mobile network like 2G. This method is widely used but under costly consumption and maintenance. To help communication technology fit the large scale IoT applications better, LPWAN(Low Power Wide Area Network) protocols have come out.

LoRaWAN, as one of state-of-the-art open source LPWAN protocols, creatively introduces LoRa in its Physical Layer. LoRa[1] is based on CSS (Chirp Spread Spectrum)[6] modulation, efficiently avoiding the interference from both multipath transmissions and Doppler effect. As a result, the decode efficiency of signals is guaranteed. Take LoRa SX1276 transceiver as an example: its tolerance of LoRa signal RSSI and SNR are as low as -148dBm and -20dB respectively. Semtech, the patent holder of the LoRa chip, has been applying this technology to various IoT applications.

In this paper, we explore the feasibility of LoRaWAN to improve the cost of shared-bike system. We aim to answer three questions: First, how large can be the communication range of LoRaWAN to satisfy all the shared bikes in the campus? Second, how are gateways deployed to receive packets from bikes in the campus? Third, will the LoRaWAN system be better than the present mobile network?

We present LoSee, a novel shared-bike communication system in the campus based on LoRaWAN. We estimate the shared-bike demand in Tsinghua University. Based on the application of tracking bike routes, we design the duty cycle of LoRa nodes and choose communication channels with viable transmission parameters. In the implementation of prototype system, we use LoRa SX1276 with MCU STM32LO as nodes, Raspberry Pi 3 as a LoRaWAN gateway and NEO-7N GPS to get nodes' location. In the server end, we apply API of Baidu Map to display bike routes. Based on the prototype system, we collect data for modeling the relationship between PDR and SNR, based on LDPL[5] (Log-Distance Path Loss). Meanwhile, by theoretical analysis and simulation, we estimate PDR with signal contention. As a result, the communication range of LoSee is concluded. In the end, we propose LoSee, a feasible LoRaWAN-based shared-bike communication system in the campus. We show the LoRaWAN's advantages of low power and low deployment budget over traditional mobile networks. LoSee utilizes free ISM bands and efficiently distributes gateways to cover the whole campus, supporting all potential bikes.

## 2 System Preliminary

**LoRa** Based on CSS modulation, Semtech Company develops LoRa communication technology. CSS features a sinusoidal signal of increasing or decreasing frequency. LoRa uses a linear frequency modulated chirp. Any frequency drift


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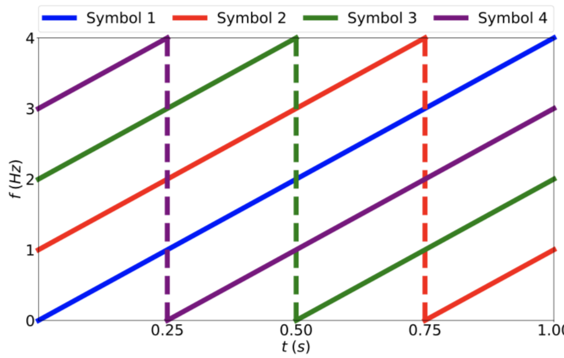


**Figure 1. Different Symbol Frequency(Hz) Modulation with Time(t)**

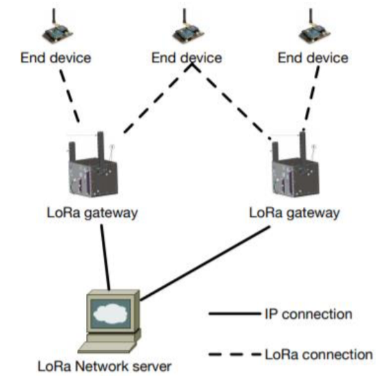


**Figure 2. LoRaWAN components**

between transmitters and receivers can be eliminated as time offset easily, even if the offset reaches 20% of the channel bandwidth. This technique provides LoRa with two main advantages: First, LoRa signals are not affected by Doppler effects; Second, no high-precision oscillator is required for LoRa nodes. Meanwhile, Forward Error Correction(FEC) is added in LoRa coding, helping noise cancellation. In LoRa, there are three parameters that can be set for specific applications: BW(Bandwidth), SF(Spreading Factor) and CR(coding rate). BW decides carrier signals' frequency range. SF decides how many bits can be comprised in one symbol. CR decides signals' redundancy in the coding process. These three parameters determine data transmission rate and receivers' tolerance of RSSI and SNR.

BW is one of the most important parameters in LoRa modulation. One chirp symbol consists of $2^{SF}$ chips, which cover the whole channel band. It starts with a continuous frequency increase to the upper bound of the band, with another increase from the lower bound following. As Figure 1 shows, four different symbol frequency modulations are given when $BW = 4Hz$ and $SF = 2$. These symbols stand for different bit information, ranging from 00 to 11, in total of $2^{SF}$ possibilities. Meanwhile, LoRa signals of different SFs will not collide with each other, making different orthogonal communication channels possible.

Following is how LoRa transmission rate is determined by BW, SF and CR.

LoRa chip duration $T_c$ depends merely on BW:

$$T_c = \frac{1}{BW} \tag{2.1}$$

Because one symbol consists of $2^{SF}$ chips, one symbol duration $T_s$ is:

$$T_s = \frac{2^{SF}}{BW} \tag{2.2}$$

One symbol contains $SF$ bits, so transmission data rate $R_b{}'(bps)$ is:

$$R_b{}' = \frac{SF}{T_s} = SF \times \frac{BW}{2^{SF}} \tag{2.3}$$

LoRa FEC makes redundancy CR of data transmission. As a result, payload rate $R_b$ is calculated as:

$$CR = \frac{4}{n+4}, n \in \{1,2,3,4\} \tag{2.4}$$

$$R_b = SF \times \frac{BW}{2^{SF}} \times CR \tag{2.5}$$

Give an example, when:

$$BW = 125kHz, SF = 7, CR = \frac{4}{5} \tag{2.6}$$

LoRa payload rate is:

$$R_b = 5.5kbps \tag{2.7}$$

**LoRaWAN** LoRaWAN protocol is an open-source MAC (Media Access Control) layer project built on LoRa physical layer. LoRaWAN is developed by LoRa Alliance. LoRaWAN protocol defines three main components of a typical LoRaWAN system: nodes, gateways and servers.

As Figure 2 shows, nodes are low-power sensors with LoRa radio. Gateways are packet forwarders, which collect LoRa packets from nodes and pass them to LoRa network servers by IP link. Gateways also listen to servers' commands and pass them to nodes. LoRa servers filter duplicated LoRa packets and integrate the valid ones into applications.

Different from traditional mobile networks, there is no binding between nodes and a specific gateway. Once LoRa packets are transmitted over the monitored channels of any gateway. The packets can be automatically captured and passed to servers. Servers will determine whether to accept packets from specific node MAC addresses. Packets are appended with information related to the link quality, such as RSSI and SNR, when passed by gateways.

Nodes can hop between several channels to improve the immunity from interference of busy channels. Different areas have different LoRaWAN channel options. Particularly in China, LoRaWAN stipulates all available channels ranging from $470MHz$ to $510MHz$, among which LoSee works.

**LDPL: Long Distance Path Loss** Compared with wired link, signal transmissions in wireless link face much more ambient interference, such as buildings' blocks and reflections. As a result, it is hard to accurately determine signal loss along the transmission distance. The LDPL model is widely adopted to estimate long-range signal transmissions, whose distance is much longer than the length of signal waves. In LDPL, received signal strength $Pr(dBm)$ is modeled as a logarithmic function of transmission distance $d(m)$:

$$P_r(d) = P_t - \overline{PL}(d_0) - 10nlg\frac{d}{d_0} - X_\sigma \qquad (2.8)$$

On the right hand side of the equation above, $P_t$ is transmission power of signals; $\overline{PL}(d_0)$ is average path loss when transmission distance is $d_0$; n is path loss coefficient; $X_\sigma \sim N(0,\sigma)$ refers to fluctuations of path loss.

Considering ambient noise $P_n \sim N(0,\sigma)$ is independent from $X_\sigma$, received signals' SNR(dB) can be estimated as:

$$SNR(d) = P_r(d) - P_n \sim N(\overline{SNR}(d), \sigma_{SNR}) \qquad (2.9)$$

where

$$\overline{SNR}(d) = b - 10nlgd \qquad (2.10)$$

$$\sigma_{SNR} = \sigma + \sigma_n \qquad (2.11)$$

In the equation 2.10, $b$ and $n$ can be estimated by utilizing linear regression towards SNR and transmission distance. In the equation 2.11, $\sigma_{SNR}$ can be calculated utilizing Gaussian Distribution Estimate of the gap between measured SNRs and estimated ones. Then probability that SNR is not lower than threshold $\gamma$ is:

$$P(SNR(d) \geq \gamma) = Q(\frac{\gamma - \overline{SNR}(d)}{\sigma_{SNR}}) \qquad (2.12)$$

where

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty e^{-\frac{x^2}{2}dx} \qquad (2.13)$$

This probability reflects the range of receivers' communication range to ensure the link stability.

# 3 Application Demand and Requirement

Typically, a complete shared bike system functions locking, unlocking and tracking bikes, so data transmitted includes GPS of one bike, control command of locks and some necessary ACKs. For high networking requirements of tracking bike routes in real time, we decide to focus on the tracking function of the shared-bike system.

## 3.1 Demand Analysis of Shared Bikes

Demand analysis of shared bikes is the basis of designing a LoRaWAN deployment scheme. We estimate the demand, indicated as $Dem$ based on the number of potential users $P$ and redundancy ratio $R(\%)$ during the rush hour:

$$Dem = P \times (1 + R) \qquad (3.1)$$

with

$$P = A \times B \times C \qquad (3.2)$$

where A is 47762, the quantity of Tsinghua University students; B is 20%, the ratio of students who have classes early in the morning; C is 5%, the estimated ratio of students who ride shared bikes during this time. $R$ is set to be 20%.

**Table 1. One LoRa Packet Transmission Time on Different SFs**

| SF | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| $T_{tx}(ms)$ | 57 | 102 | 185 | 340 | 630 | 1177 |

**Table 2. Maximized Transmission Intervals and Corresponding Duty Cycles of Different SFs**

| SF | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| $\tau$ | 321 | 179 | 99 | 53 | 29 | 15 |
| $du(\%)$ | 0.3 | 0.6 | 1 | 1.9 | 3.4 | 6.4 |

As a result, P is 478 and $Dem$ is 573. Since the whole campus area is about $4.5 \times 10^6 m^2$, shared-bike demand density is $\rho = 1.27 \times 10^{-4} bikes/m^2$, equally 1 shared bike per $7860m^2$ on average.

## 3.2 Data Transmission

For the real time of "bike route tracking", ACKs from the network server are not required by LoRa nodes. Otherwise, once GPS or ACK information is lost along the transmission path, retransmissions may lead to serious time offset of geographic positions.

LoRaWAN has three types of communications between nodes and gateways. Class A is similar to ALOHA, Class B is appended with regular beacons and Class C keeps nodes monitoring commands all the time. "Bike route tracking" only needs the uplink channel of nodes to upload GPS. Class A not only satisfies bike tracking function, but also guarantees low power of nodes.

## 3.3 Node Duty Cycle

To analyze the duty cycle to transmit packets, there are two questions: What is the size of a LoRa packet? How often at most should a bike report its location in the campus to ensure smooth bike tracking?

A NEO-7N GPS module provides 128-bit longitude and latitude data. Assembled with non-payload information in the LoRaWAN frame, one LoRa packet is 268-bit long. Combined with data transmission rate calculated when $BW$ and $CR$ are set as 125kHz and 4/5, one LoRa packet takes different duration to transmit on different SFs, as Table 1 shows.

As for the transmission interval, the road layout of Tsinghua University is extracted from OpenStreetMap by the road analyzer osmnx[2]. As Figure 3 shows, nodes are intersections or ends while edges are road segments without any bifurcation. There are 1237 road segments in total, with the average length of 73.4 meters. Assuming bike speed is 4 m/s, it takes 18.35 seconds to ride through one road segment. To ensure smooth tracking, there are at least $\tau$(the duty cycle factor) location packets transmitted. So the transmission interval is:

$$T_\tau = \frac{18.35}{\tau} (\tau \in N^+) \qquad (3.3)$$

Since duty cycle $du$ should be less than 100%, maximized transmission intervals and corresponding duty cycles of different SFs are listed as Table 2 shows.

**Figure 3. Campus Roads in Tsinghua University**

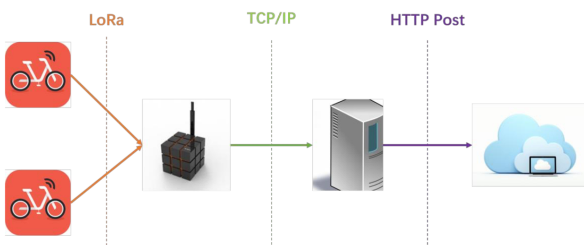


**Figure 4. LoSee Prototype Architecture**

## 4 Prototype Implementation

On account of the requirements of Section 3, we build the prototype of LoSee, whose architecture is represented as Figure 4. Bike locations measureed by GPS are transmitted to the gateway and passed to the LoRa server through IP link. The LoRa server integrate packets' data into JSON files and HTTP post to the application in the cloud for visualization. Following are implementations of three main components in the architecture.

### 4.1 Nodes

In the implementation of nodes, we use STM32L0 as MCU, single SX1278 as antenna and NEO-7N as GPS, as Figure 5 (left) shows. Packet transmitter code is based on the Github project LoRaMac-node. Transmission channels, BW, SF, CR and MAC verification parameters are configured in the LoRa nodes through J-link fire. Nodes are placed in the bike baskets, equivalent to e-locks of shared bikes.

### 4.2 Gateways

In the implementation of nodes, we use STM32L0 as MCU, single SX1276 as antenna and Raspberry Pi 3 for programming remotely, as Figure 5 (right) shows. Packet concentrator code is based on the Github project lora_gateway and packet_forwarder. By configuring LoRa network IP addresses and monitored channels of LoRa gateways, LoRa packets can be passed to the cloud successfully.

### 4.3 Network and Application

The LoRa Network and the monitor application are deployed on the Digital Ocean Cloud. Nodes, gateways and applications are registered on the LoRa Network. When the system is running, the network captures all packets transmitted by the registered nodes from known gateways. Each packet's LoRaWAN physical-layer payload is shown as Figure 6 for debugging, later HTTP posted with link quality to the monitor application. As Figure 7 shows, the monitor application is based on Django 2.0.4 Web Framework, using Baidu Map JavaScript API 3.0. In the node information display, besides SNR and RSSI, the distance between nodes and the LoRa gateway is logged. Frame counts are used for calculating PDR(Packet Delivery Rate), which is equal to the ratio of the captured count to the total count including missing packets. Timestamps are logged to help plot bike routes of any specific node.

**Figure 5. LoRa Nodes(left) and Raspberry Pi Gateways(right)**

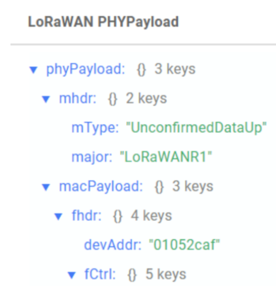


**Figure 6. Packets' LoRaWAN Physical-Layer Payload**

## 5 System Measurement and Implication

Based on LoSee, implemented as Section 4, LoRaWAN gateway communication range can be concluded using ex-

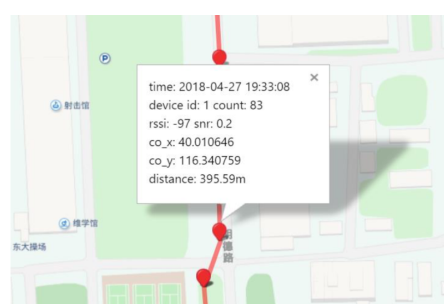


**Figure 7. Location Visualization of LoSee Monitor Application**

perimental results. Following are the definition and the estimate of the gateway communication range.

## 5.1 Communication Range

To determine an effective range of one gateway is a necessity of the deployment of a starlike network. In LoSee, we assume the range is a circle area with the radius r and the total number of bikes are statically nearly the demand. The communication radius r is strictly defined as: any bike nearer than r from the gateway can have at least one packet accepted along any road segment.

Having one packet accepted is based on two independent conditions: SNR is not lower than the gateway tolerance; No other signals with the same SF in the same channel are interfering the decode. As Section 2 shows, SNR is related to LoRa chirp SF and the distance d. $Y_1(d,SF)$ defines the probability(Packet Delivery Rate) when the first condition is satisfied. Signal contention is related to the total node number n, the duty cycle factor $\tau$ and SF. $Y_2(n.\tau,SF)$ defines the probability when the second condition is satisfied. To ensure a bike node connecting to the gateway(at least one packet accepted along any road segment), the inequation below needs to be satisfied:

$$Y_1(d,SF)\times Y_2(n,\tau,SF)\times\tau\geq 1 \quad (5.1)$$

$Capacity(d)$ refers to validly connected nodes in the range of radius d of one gateway. $Demand(d)$ refers to the demand of bikes in the range of radius d of one gateway. Based on the inequation above and analysis in the section 3.1, we can get:

$$Capacity(d)=\sum_{SF=7}^{12}\max_{\tau\geq 1}Y_2{}^{-1}\left(\frac{1}{\tau\times Y_1(d,SF)},\tau,SF\right) \quad (5.2)$$

$$Demand(d)=\rho\times\pi\times d^2 \quad (5.3)$$

$\rho$ is the demand density. In the range of radius r, when the equation $Capacity(r)=Demand(r)$ is satisfied, the communication range can be decided. In this range, the load capacity and the bike demand are balanced. Then, in the rest part of this section, we will measure $Y_1$ and $Y_2$.

## 5.2 $Y_1$: PDR and SNR

In the experiment, we move one bike node with a fixed SF to different places with different SNRs. One bike node sends continuously 50-100 packets in one place and then PDR is calculated as the ratio of the accepted number to the total sum. We change SF from 7 to 12 and repeat the experiment. The result is shown as Figure 8. We can estimate $PDR(SNR,SF)$ as a step function:

$$PDR(SNR,SF)=\begin{cases}1, SNR\geq\gamma_{SF}\\ 0, SNR<\gamma_{SF}\end{cases} \quad (5.4)$$

Different $\gamma_{SF}$ are the PDR thresholds of SNR on different SFs, shown as Table 3. Based on LDPL model in Section 2, we collect the data to model the function relationship between SNR and packet communication distance d, using linear regression:

$$\overline{SNR}(d)=31.5-13.7lgd,\sigma_{SNR}=4.4 \quad (5.5)$$

**Table 3. The PDR threshold of SNR on different SFs**

| SF | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| $\gamma(dB)$ | -6.1 | -8.9 | -9.8 | -13.2 | -14.5 | -18.4 |

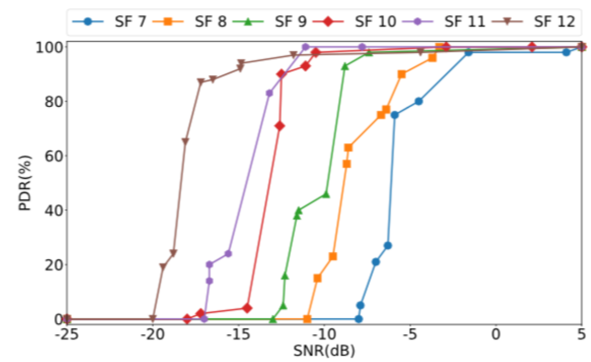


**Figure 8. PDR-SNR relationships on different SFs**

Combining the approximate step function and linear relationship, we can finally conclude $Y_1$ with equation 2.12, shown in the Figure 9. The bigger SF is, the higher PDR is.

$$Y_1(d,SF)=Q\left(\frac{13.7lgd-31.5-\gamma_{SF}}{4.4}\right) \quad (5.6)$$

## 5.3 $Y_2$: PDR and Signal Contention

LoRaWAN does not specifies the signal avoidance mechanism in the protocol. Nodes can deliver their packets at any time. In this section, we focus theoretically on signal contention[3] in the same channel with the same SF. Then we use simulation experiment to validate $Y_2(n,\tau,SF)$, the packet delivery rate considering signal contention.

For a LoRa signal $A$, we assume $A$ can be decoded only if it is not overlapped with any other signal of the same channel in one transmission period. As shown in Figure 10, $T_A$ is the transmission of signal A and $T_{A'}$ is the one of another signal A' that may lead to contention. T is the length of transmission period and du is the duty cycle. As a result, the probability that A and A' have no conflicts is:

$$P_{Not\ Interfered\ by\ A'}=1-\frac{T_A+T_{A'}}{T}=1-2du \quad (5.7)$$

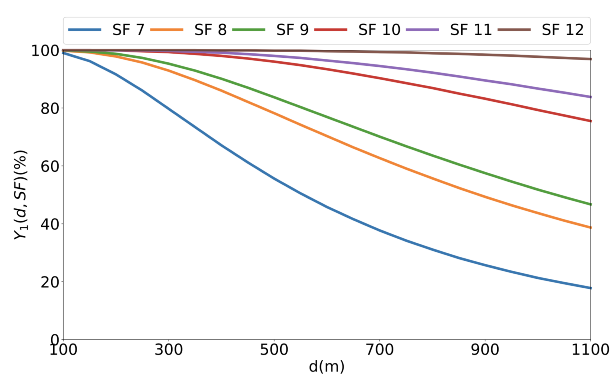


**Figure 9.** $Y_1(d,SF)$ **curving**

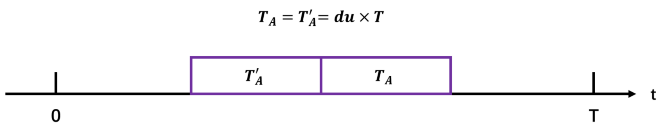


**Figure 10. Signals in One Transmission Period**

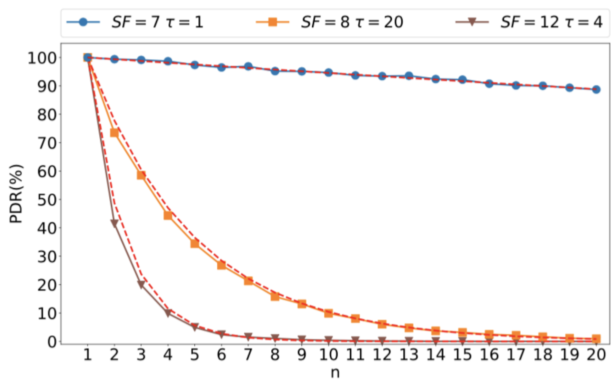


**Figure 11. Signal conflict simulation vs. theoretical results of relationship between node counts and PDR(%)**

If there are n nodes transmitting packets independently, the probability that A is not interfered is:

$$P_{Not\ Interfered} = (1 - 2du)^{n-1} \tag{5.8}$$

Since

$$du = \frac{T_{tx}(SF)}{T_\tau} = \frac{\tau \times T_{tx}(SF)}{18.35} \tag{5.9}$$

and there are eight channels that can be configured in the gateway, we can get $Y_2$ finally:

$$Y_2(n, \tau, SF) = [1 - \frac{\tau \times T_{tx}(SF)}{9.175}]^{\frac{n}{8}-1} \tag{5.10}$$

We simulate n nodes sending packets independently and randomly. In Figure 11, the comparison between theoretical results and simulation results is shown, reflecting that $Y_2$ in the equation 5.10 is valid under our asumption.

## 5.4 LoSee Range and Capacity

Combining Equation 5.2, 5.6 and 5.10 altogether, Capacity(d) can be concluded. Comparison between Capacity(d) and Demand(d) along the communication range d is shown as Figure 12. Ensuring the system capacity is larger than the number of share bikes within the coverage area, LoSee communication radius is about 1031 meters and its capacity is 423 bike nodes. To cover the whole area of Tsinghua University, only two gateways are needed, as locations in the Figure 13 show. Compared with numerous expensive 2G/3G/4G stations and devices deployed, LoRa is a efficient solution for offhand communication systems. In this application, LoRaWAN utilizes free ISM bands and LoRa Nodes are as low-power as 60mW in active mode. It is one sixth of 2G power consumption, which is up to about 400mW.

## 6 Conclusion and Future Work

In this paper, we present a LoRaWAN based share bike system LoSee, implemented as a network for communicating and tracking shared bikes in the campus. We evaluate its communication range with experimental results and simulation analysis. We prove the long-range cover and the efficient capacity of LoSee, with advantages of low power and low deployment expense over traditional mobile network systems. In the future, a more accurate estimate toward signal strength instead of LDPL needs to be studied[4]. Moreover, a LoRa-chip related interference measurement[3] can improve the contention estimate of LoSee. Correspondingly, deployed with avoidance strategy of signal contention, the coverage area of LoSee will be enlarged.

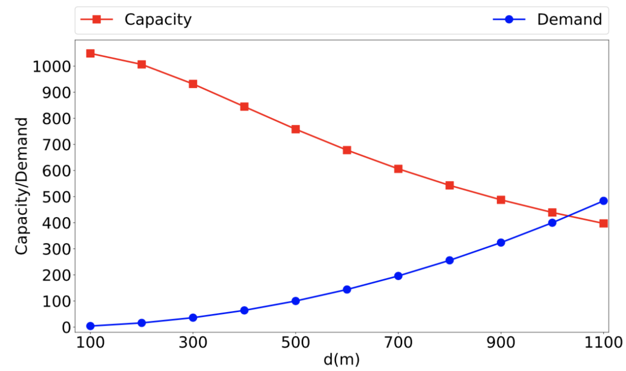


**Figure 12. Comparison between Capacity(d) and Demand(d) along the distance**

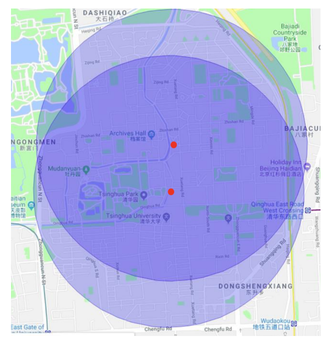

**Figure 13. LoRa Gateway Locations in Tsinghua University**

## 7 References

[1] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley. A study of lora: Long range & low power networks for the internet of things. *Sensors*, 16(9):1466, 2016.

[2] G. Boeing. Osmnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, 65:126–139, 2017.

[3] J. Haxhibeqiri, F. Van den Abeele, I. Moerman, and J. Hoebeke. Lora scalability: A simulation model based on interference measurements. *Sensors*, 17(6):1193, 2017.

[4] T. Liu and A. E. Cerpa. Foresee (4c): Wireless link prediction using link features. In *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on*, pages 294–305. IEEE, 2011.

[5] T. S. Rappaport et al. *Wireless communications: principles and practice*, volume 2. prentice hall PTR New Jersey, 1996.

[6] A. Springer, W. Gugler, M. Huemer, L. Reindl, C. Ruppel, and R. Weigel. Spread spectrum communications using chirp signals. In *EUROCOMM 2000. Information Systems for Enhanced Public Safety and Security. IEEE/AFCEA*, pages 166–170. IEEE, 2000.