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Comparative Analysis of Wireless Transmission Methods for Firefighting Communication in Challenging Indoor Environments

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***Abstract*—The demand for firefighting has significantly risen in recent decades, accompanied by increased risks faced by firefighters. Tragic incidents, such as the Shanghai factory fires, have resulted in the loss of over thirty firefighter lives. One of the primary contributing factors is the abrupt breakdown in communication between firefighters inside a building and the commanding officer stationed outside, attributable to the harsh and complex indoor environment. This study aims to conduct a comparative analysis of different widely used wireless transmission methods, including Wi-Fi, Bluetooth Low Energy (BLE), and Long Range (LoRa). The experiments are conducted in a two-room setup, with two brick walls acting as a barrier. A wireless data transmitter is placed in one room, while smoke is generated. A receiver placed at varying distances collects the signal strengths. The findings indicate that LoRa exhibits the least drop in signal strength compared to the other methods. In contrast, BLE shows high signal strength variation for the same distances and is not recommended for firefighting communication purposes. This study provides valuable insights for selecting suitable wireless communication modules, particularly in the design of wearable devices for assessing safety risks faced by firefighters.**

***Index Terms*—Firefighting communication, signal strength analysis, wearable devices, wireless transmission**

I. Introduction

Firefighting is a challenging occupation that often involves operating in harsh environments filled with smoke, high temperatures, and limited visibility, posing significant safety risks. From 2005 to 2013, Chinese fire departments responded to nearly 3 million more fires, resulting in 85 firefighter fatalities, 163 injuries, and over 100 billion CNY in property damage [1]. Surprisingly, although the fire rate in the United States was 80% higher than in China, the number of firefighter fatalities was considerably higher in China, as noted in a study by [2]. The 2018 China Fire Yearbook [3] revealed that the main causes of firefighter deaths between 2012 and 2017 were explosions, suffocation, and falling debris. Young firefighters are particularly vulnerable as they often receive inadequate training before being deployed on actual firefighting missions [4]. In fireground situations, radio signals can be obstructed or unreliable due to smoke and high temperatures, leading to communication breakdowns between firefighting teams and their commanders.

Currently, the wireless communication network used in firefighting operations in China follows an isolated design, focusing primarily on establishing a connection between the on-site command center and the remote command center. However, this setup faces limitations due to the severe environmental conditions and the restricted range of front-line firefighting and rescue activities. To address these challenges, several studies have proposed the use of wearable sensor devices equipped with temperature, movement, heartbeat, and other sensors for firefighters. These sensors collect valuable data, which is then transmitted to the on-site command center [5]. Consequently, wireless communication between wearable devices and the transmission of data from sensors to the command center play a crucial role in facilitating effective fire rescue activities.

Firefighters getting lost inside unfamiliar buildings is a

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common occurrence, and it is often attributed to the limited effectiveness of wireless signal transmission in smoke-filled environments [6]. Previous studies have extensively explored the utilization of wireless sensor networks to address the challenge of indoor localization and tracking for firefighters. In Europe and the United States, commercial localization systems such as the ultrasound-based SummitSafety Pathfinder system [7] and the radio-based Draeger FRS1000 system [8] have been developed. These systems provide handheld directional tracking devices that facilitate locating missing firefighters equipped with corresponding beacons. However, it is important to note that these systems face signal degradation in environments with heavy smoke.

Considering the demanding nature of firefighters' operational environment, it is crucial to assess and determine the most effective wireless data transmission techniques to enable real-time monitoring of firefighter safety. Thus, the objective of this project is to conduct a comparative analysis of signal quality among various wireless communication protocols, such as Wi-Fi, Long Range (LoRa), and Bluetooth low energy (BLE), in both smoke-free and smoke-filled environments. This evaluation will be carried out through a series of carefully designed scenarios involving multiple rooms with concrete walls.

Hofmann *et al.* [9] conducted a study to evaluate the performance of various IEEE 802.x wireless technologies in the presence of fire, smoke, and vapor. However, their experiments were limited to a controlled laboratory environment. Similarly, [10] investigated how firefighter equipment can affect radio signals. On the other hand, [11] reported no significant impact on radio reception caused by gaseous vapor commonly encountered in rescue missions. Another study by Liu *et al.* [12] focused on creating a robust ad-hoc network for indoor localization, where nodes are automatically deployed based on signal strength measurements to ensure a minimum 90% network connectivity. However, since this system was not evaluated in an actual fireground, its performance can only be estimated. A major limitation of positioning using wireless technologies is that signal obstruction by obstacles and signal attenuation due to weather or smoke from fires in the fireground can significantly impact the accuracy of positioning.

Several studies have focused on analyzing signal strength in smoke and heat environments. Singh *et al.* [13] proposed a design for a heatmap generation tool that displays signal strength at different locations for a given transmitter. By considering losses caused by the antenna and transceiver front-end parameters, the heatmap tool provides signal strength estimates close to the actual values, with a standard deviation of approximately 2.94 dB. Rosli *et al.* [14] examined Wi-Fi signal characteristics using received signal strength indicator (RSSI) readings collected through ESP8266. Their study demonstrated that RSSI readings are significantly influenced by obstructions between the transmitter and receiver, and the variation of RSSI near the transceiver is highly affected by the presence of individuals. Mahmud *et al.* [15] investigated the impact of obstacles and walls on packet loss rate and signal strength. Their findings revealed that an increased number of obstacles and walls led to higher packet loss rates and poorer signal strength. The study also highlighted that as the distance from an object located at the corner of a building increased, the packet loss rate significantly increased with lower RSSI readings. Yoppy [16] conducted a study to evaluate the wireless coverage distance of ESP8266 Wi-Fi in an outdoor setting by measuring RSSI readings with four different types of antennas.

Regarding applications, the work of Habaebi *et al.* [17] involved the development of a WiFi-based system for small office home office (SOHO) environments. Their aim was to explore the energy-saving potential of harvesting wireless signals. In a similar vein, Wu *et al.* [18] devised a temperature sensor that incorporated a low-power Bluetooth module. This sensor was deployed within a building to monitor changes in temperature and issue a notification if high temperatures indicated the presence of a fire. On a different note, Feng *et al.* [19] proposed a packaging technique for reducing the number of transmissions in BLE devices, specifically focusing on wearables and related applications. Notably, these studies overlooked the impact of environmental factors such as smoke and heat on the characteristics of wireless signals, which are crucial considerations in firefighting activities.

II. Methods

The primary objective of this study is to examine the performance of various wireless communication methods while taking into account obstacles such as walls that may exist between the transmitter and receiver. This section focuses on the wireless communication modules utilized in the study and provides details about the design of experimental scenarios.

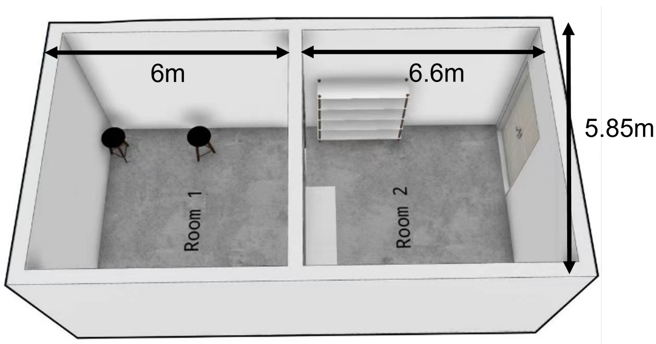
A. Hardware Specification

In order to assess and compare the performances of various wireless communication methods, this study gathers RSSI readings using four distinct wireless communication modules, as outlined in Table I. Each module is configured to function as either a transmitter or a receiver, with individual SSID and password settings. The receiver captures 100 RSSI measurements at a sampling rate of 10 Hz every five seconds, resulting in five sets of repeated measurements for analysis.

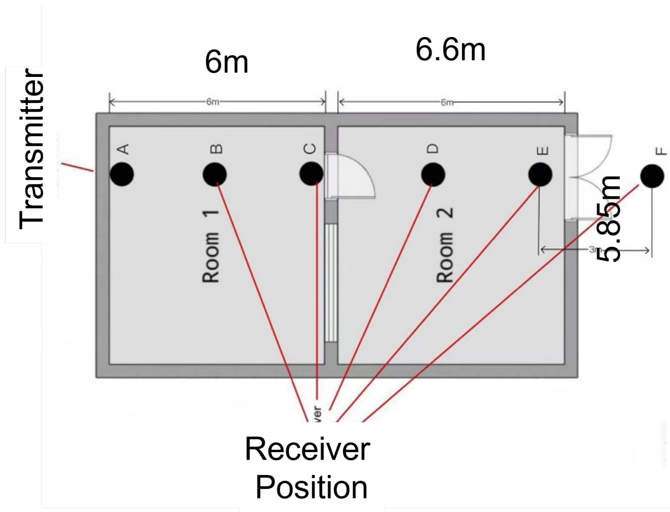
1) BLE: The HM10 module is a BLE module designed for applications that prioritize low-power consumption and the ability to operate for extended periods using a small coin-sized battery. BLE technology finds extensive application in various fields, such as indoor positioning [20] and wearable devices [19].

2) LoRa: The E22-400T22DC module is a wireless serial port module (UART) that utilizes SEMTECH's SX1262 RF chip and operates on long-range (LoRa) technology. LoRa is a popular choice for wireless network communication due to its numerous advantages, including low-power consumption, low bit rate, long range capability, and suitability for single hop wireless communication. Several studies have utilized LoRa technology in detecting forest fires by employing multiple sensors to measure parameters such as temperature, humidity, wind speed, and carbon dioxide concentration [21]–[23].

3) Wi-Fi: In this study, the ESP8266 Wi-Fi module is employed as a standalone system-on-chip (SoC) with an integrated TCP/IP stack, enabling a microcontroller (MCU) to connect to a Wi-Fi network. Previous research has utilized



(a) Rooms 3D structure



(b) Placement of transmitter and receiver

(c) Non-smoke environment

(d) Smoke environment with 1m visibility

Fig. 1: Experiment setup in a multiple rooms with designed scenarios of distinct distance between the transmitter and receiver under smoke and non-smoke environments.

TABLE I: Hardware specification of wireless communication modules

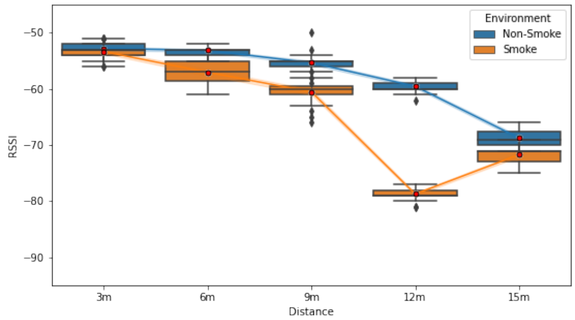
Module	Operating Frequency	Max. TX Power	Supply Voltage
HM-10 BLE	2.4 GHz	6 dBm	3.3V
EBYTE-E22-400T22DC	410.125 - 493.125 MHz	22 dBm	5V
ESP8266 Wi-Fi	2.4 - 2.5 GHz	30 dBm	3.3V
USR-WIFI232-B2	2.412 - 2.484 GHZ	19 dBm	3.3V

TABLE II: Experiment scenarios

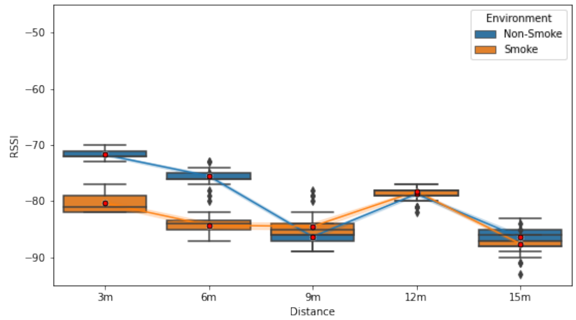
Distance (TX and RX)	Room	Position (Fig. 1)	Category
3m	1	B	I
6m	1	C	I
9m	1 and 2	D	II
12m	1 and 2	E	II
15m	1 and 2 and outer space	F	III

TABLE III: Descriptive statistics of RSSI readings for ESP8266-WiFi under non-smoke (NS) and smoke-filled (S) environments (1m visibility)

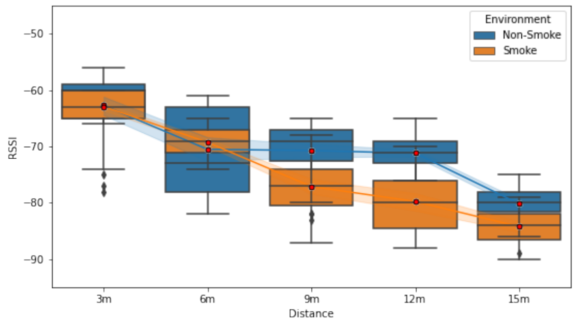
Distance	Mean (dbm)		Median (dbm)		Mode (dbm)		Std Dev (dbm)	
	NS	S	NS	S	NS	S	NS	S
3m	-52.7843	-53.3529 ↓	-46	-53	-45	-53	0.8600	1.2462
6m	-53.1372	-57.0392 ↓	-50	-57	-50	-58	1.2042	1.9795
9m	-55.3333	-60.5098 ↓	-55	-67	-55	-67	1.3216	1.8600
12m	-59.5294	-79.7254 ↓	-60	-70	-60	-70	1.1019	0.9608
15m	-68.7450	-75.5490 ↓	-69	-75	-70	-75	1.3978	2.4192



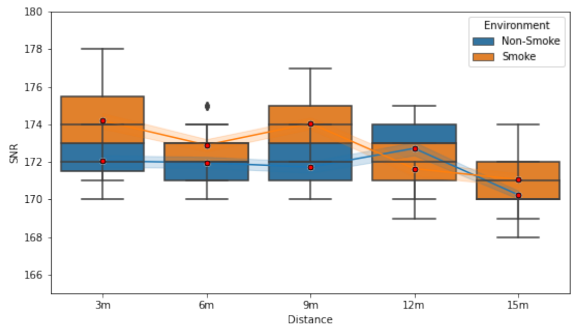
(a) ESP8266-WiFi



(b) USR-WIFI232-B2



(c) BLE



(d) LoRa

Fig. 2: Plotting of the performances of wireless signals transmission for (a) ESP8266-WiFi, (b) USR-WIFI232-B2, (b) BLE, and (c) LoRa for distances of 3m, 6m, 9m, 12m and 15m under smoke and non-smoke environments. The red dot represents the mean of the data.

TABLE IV: Descriptive statistics of RSSI readings for USR-WIFI232-B2 under non-smoke (NS) and smoke-filled (S) environments (1m visibility)

Distance	Mean (dbm)		Median (dbm)		Mode (dbm)		Std Dev (dbm)	
	NS	S	NS	S	NS	S	NS	S
3m	-71.7254	-80.3333 ↓	-72	-81	-72	-82	0.6951	1.4514
6m	-75.5098	-84.2745 ↓	-76	-84	-76	-85	1.1379	1.9398
9m	-84.4705	-86.3137 ↓	-85	-86	-85	-86	2.2481	1.2568
12m	-78.7058	-78.2352 ↑	-79	-78	-79	-78	0.9443	1.0693
15m	-86.4313	-87.5686 ↓	-86	-88	-85	-88	2.0518	1.1001

TABLE V: Descriptive statistics of RSSI readings for BLE under non-smoke (NS) and smoke-filled (S) environments (1m visibility)

Distance	Mean (dbm)		Median (dbm)		Mode (dbm)		Std Dev (dbm)	
	NS	S	NS	S	NS	S	NS	S
3m	-62.7058	-62.9019 ↓	-60	-63	-60	-65	5.8456	2.1656
6m	-70.4901	-69.2549 ↑	-73	-69	-63	-67	2.4644	7.9079
9m	-70.7058	-77.2549 ↓	-69	-77	-67	-78	4.6660	2.5756
12m	-71.1764	-80.1568 ↓	-71	-80	-71	-81	2.1043	2.8381
15m	-80.9411	-84.2156 ↓	-80	-84	-80	-82	2.1693	2.9954

TABLE VI: Descriptive statistics of SNR for LoRa under non-smoke (NS) and smoke-filled (S) environments (1m visibility)

Distance	Mean (dbm)		Median (dbm)		Mode (dbm)		Std Dev (dbm)	
	NS	S	NS	S	NS	S	NS	S
3m	172.06	174.20 ↑	172	174	172	174	1.1386	1.5364
6m	171.96	172.90 ↑	172	173	173	173	1.1128	1.0817
9m	171.72	174.06 ↑	172	174	172	175	1.1327	1.1386
12m	172.72	171.65 ↓	173	172	174	173	1.3126	1.2934
15m	170.25	171.06 ↑	170	171	170	171	0.8448	1.2395

the ESP8266 in various domains and for different purposes, such as environmental monitoring [17], coverage studies [16], and transmission of medical healthcare data [24], [25]. The ESP8266 Wi-Fi module offers a cost-effective solution for implementing lightweight Internet of Things (IoT) systems, with an average power dissipation of 80 mA @3.3v. To evaluate Wi-Fi communication quality in a wider range of industrial monitoring applications, particularly under dynamic scenarios involving automation control, this study also investigates the usage of the USR-WIFI232-B2 module. The USR-WIFI232-B2 is an embedded UART Wi-Fi module compliant with 802.11 b/g/n standards, facilitating the connection of traditional serial devices and MCU-controlled devices to a Wi-Fi network for device management.

B. Experiment Setup

The laboratory experiments were conducted in a controlled setting comprising two rooms, as depicted in Fig. 1. Room one had dimensions of 6×5.85 m^2, while room two measured 6.6×5.85 m^2. Wireless signal strength measurements were taken at five positions: 3m (B), 6m (C), 9m (D), 12m (E), and 15m (F) from the transmitter (A). The experiments aimed to explore the impact of obstructions on received signal strength indicator (RSSI) readings. An obstruction was defined as any physical wall that hindered the line-of-sight or direct free-space path between the transmitter and receiver. Consequently, wireless data collection involved transmitting over a distance of 9m (D) and 12m (E) within a single room, as well as transmitting across both rooms over a distance of 15m (F). The experiments were conducted under two conditions: non-smoke and smoke-filled environments. To simulate the presence of smoke, a commercial-grade smoke generator was utilized, positioned in the upper left corner of room one. This allowed for the replication of a realistic firefighting scenario, as smoke, consisting of micro particles and vapor, is a significant factor influencing the quality of wireless transmission [26]. The experiment scenarios are summarized in Table II. Figure 1(c) illustrates the non-smoke environment, while Fig. 1(d) represents the experiments conducted under smoke conditions, with a smoke density estimated to provide visibility within a 1 m range.

III. Results & Discussion

The wireless data transmission strength of BLE and Wi-Fi was analyzed using RSSI readings, while the signal quality of LoRa was analyzed using the signal-to-noise ratio (SNR) method. Fig. 2 illustrates the performance of wireless signals under different transmission methods and environments at various distances. The ESP8266 Wi-Fi module exhibited minimal degradation in signal strength when operating within a single room, regardless of the presence of smoke. However, as the distance between the transmitter and receiver exceeded 9 m, the measured signal strength experienced a significant decline. It is worth noting that no smoke was introduced in Categories II and III. At 12 m, the signal strength reached its lowest point, with the largest disparity observed between the smoke and non-smoke environments. This discrepancy could potentially be attributed to the uneven distribution of smoke particles in a smoke-filled room, resulting in lower RSSI values compared to the RSSI at 15 m. However, for other distances, the disparity is not significant. Table III provides a summary of the descriptive statistics for ESP8266-WiFi signal strength.

The plot in Fig. 2(b) illustrates that the USR-WiFi module exhibits the weakest signal strength among all the modules tested. The findings indicate a significant reduction in signal strength when both the transmitter and receiver are located in the same room under a smoke-filled environment. However, there are no substantial differences in signal strength between a smoke and non-smoke environment when the transmitter and receiver are not within the same room (Categories II and III). It is noteworthy that the signal strength at 12 m is higher than at 9 m. One possible explanation for this outcome could be the dynamic power dissipation arrangement of the USR-WiFi module, where the current at a distance of 12 m is greater than the current at a distance of 9 m. This result suggests that the signal strength of the USR-WiFi module is significantly affected by smoke but not by obstacles such as walls. A summary of the descriptive statistics for USR-WiFi signal strength is presented in Table IV.

Table V provides a summary of the standard deviation values for the BLE signal strength in both smoke and non-smoke environments. The results demonstrate that the BLE signal strength exhibits higher variance and greater instability in both environments, as depicted in Fig. 2(c). Additionally, it is noteworthy that the BLE RSSI readings exhibit the greatest disparities (maximum and minimum RSSI readings), particularly when the distance exceeds 12 m with two walls acting as obstacles between the transmitter and receiver.

In conclusion, the LoRa communication method exhibited superior performance compared to the other methods in both smoke and non-smoke environments, as depicted in Figure 2(d). The signal strength of LoRa remained remarkably stable within a range of 15 m even when transmitted across two walls, as indicated in Table VI.

Although our research primarily concentrates on firefighting scenarios, the knowledge acquired from our study has the potential to be extended to other environments encountering comparable challenges. Industries that operate in complex indoor spaces or hazardous environments, for example, could derive benefits by adopting robust wireless communication methods like LoRa. Such methods can facilitate effective communication among personnel in these environments. Furthermore, the insights obtained from our work can also be valuable for enhancing communication among other first responders, including police and medical personnel, who operate in complex indoor settings. Implementing effective communication solutions between indoor and outdoor environments can greatly enhance their operational capabilities. In summary, our research findings have broader applications beyond firefighting scenarios, encompassing industries facing similar challenges as well as first responders operating in complex indoor environments. By considering wireless communication methods such as LoRa, these entities can establish and maintain efficient communication channels, improving overall safety and operational effectiveness.

IV. Conclusion

This study presents a comparative analysis of three wireless communication methods: Wi-Fi, BLE, and LoRa. The findings indicate that LoRa performed exceptionally well even in a smoke-filled environment, maintaining robust signal transmission even through brick walls. On the other hand, BLE demonstrated unstable signal strength and significant variability in both smoke and non-smoke environments, making it unsuitable for firefighting communication. This research lays the foundation for the design of a wireless communication system for wearable devices intended for firefighters, with a focus on assessing safety risks. Future investigations will explore the impact of moving obstacles in a smoke environment on signal transmission, as well as examine the dynamic changes in signal strength for both moving transmitters and receivers. Additionally, further research will investigate the effect of different wall thicknesses and materials on signal attenuation.

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