Derivation of the Factors Influencing the Network Performance of Serverless Smart Exit Sign Systems based on Wireless Sensor Networks

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Abstract

This paper presents the factors that could potentially affect the reliability of a serverless smart exit sign system, namely an evacuation guidance system based on a wireless sensor network (WSN) without a central server. Serverless smart exit sign system dynamically changes the directions of signs to indicate the shortest safe evacuation paths. Thus, the reliability of these systems is critical. Nevertheless, no research has been conducted to test the reliability of serverless smart exit sign systems. As a first step, we conducted a literature review to analyze the factors that could degrade the network performance of serverless smart exit sign systems. The identified factors were grouped into three categories: physical obstacles, environmental factors, and WSN properties. We plan to develop a prototype of a serverless smart exit sign system and then to conduct experiments to validate the influence of these factors on its network performance.

Keywords –

Serverless Evacuation System; Wireless Sensor Network; Smart Exit Sign System

1 Introduction

A smart exit sign system is an evacuation guidance system that dynamically changes the directions of the signs to indicate the shortest safe evacuation paths. A serverless smart exit sign is a smart exit sign that communicates data between the exit sign nodes using a wireless sensor network (WSN) without a central server (Figure 1) [6]. When a fire breaks out, evacuees are more likely to rely on exit signs when they are in a venue they do not know well than when they are in a familiar place [23]. Traditional exit signs show fixed direction signs to the nearest exit; however, this can lead evacuees to areas of greater danger if the fire has spread.

To solve this problem, several researchers have proposed smart exit sign systems; however, most of these studies have focused on the development of algorithms to find the shortest safe path to an exit based on the assumption that a central server exists [28,32,34]. Other studies have only proposed the concept of a smart exit sign system without elaborating on details [22,26,27].

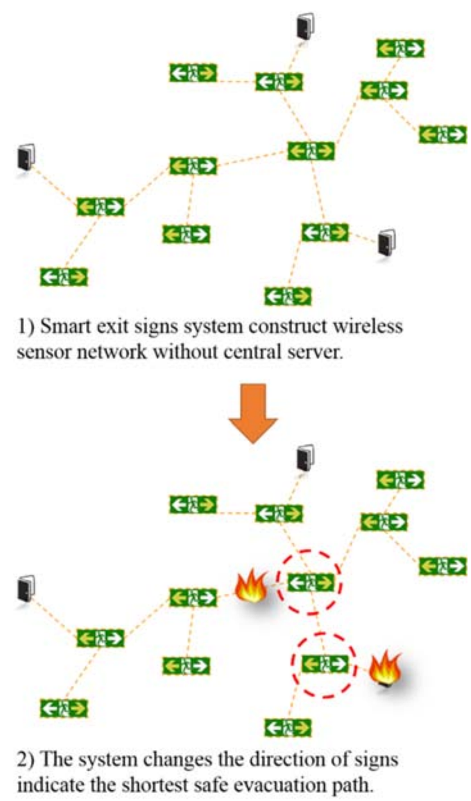

Figure 1 The concept of the serverless smart exit sign system

Serverless smart exit sign systems have several advantages over the previous server-dependent smart exit sign systems. First, serverless smart exit sign systems are more reliable than server-dependent ones because the entire server-dependent system fails if the central server fails or any line between the server and the individual exit sign nodes is disconnected due to a fire, physical damage, or other reasons. On the other hand, exit sign nodes in serverless systems are not reliant on the status of the server because they do not use a server at all and can still communicate with neighboring nodes even if some nodes are damaged. The second advantage is that a serverless smart exit sign can be installed in an existing building without complex wiring work whereas a server-dependent smart exit sign system requires complex and expensive wiring.

Thus far, two groups of researchers have independently developed serverless smart exit sign systems, one in South Korea and the other in the UK [11,12,14]. Both groups have however focused only on the development of algorithms for serverless smart exit sign systems and have not considered the hardware aspects of serverless smart exit sign systems. This paper focuses primarily on the reliability of the wireless communication of serverless smart exit sign systems.

By reliability, we mean the extent to which a system stably and consistently operates under various internal and external conditions. For example, doors and walls that can potentially deteriorate network communication are external factors, and the specifications of network modules such as network packet size are internal factors. Reliability is an important requirement of any emergency evacuation system, including serverless exit sign systems, to prevent system failure [21]. The reliability of wireless communication (networking) in particular is key to the successful operation of a serverless exit sign system because, if individual exit sign units cannot send and receive data reliably, the entire system may malfunction.

As a preliminary study, we conducted a literature review to analyze and determine the factors that should be considered during the testing of the network reliability of serverless smart exit sign systems.

2 The reliability of serverless smart exit sign systems

The reliability we describe in this paper can be explained by two aspects: network reliability and data transmission reliability.

1. Network reliability refers to the stability of a system against external physical environments and indoor environmental variations. For example, potential physical obstacles are doors and walls while indoor environmental factors include temperature variations, humidity, and smoke variations. These factors may destruct the relay connection between motes (nodes in a sensor network) in a WSN.
2. Data transmission reliability refers to the extent to which a system stably and correctly communicates data between nodes. For example, packet size is one factor that may affect data transmission reliability. Network reliability can be improved by ensuring data transmission reliability.

Based on this classification, we conducted an analysis and derived three categories of factors: physical obstacles, environmental factors, and WSN properties.

3 Research method

The literature review has conducted keywords that Wireless sensor network, WSN performance, WSN experiment. The retrieved research are categorized in three fields that network reliability related physical obstacles, environmental factors and data transmission reliability related WSN properties. Among the cases, the only empirical research based on experiments using hardware are collated in this study. Table 1 summarizes collated cases.

Table 1 Collated cases

Index	Value
Collated cases	35
Published year	2001-2014
Database	IEEE, ScienceDirect, DBpia
Keyword	Wireless Sensor Network, WSN performance, WSN experiment
Derived factors	14

The collated result shows that physical obstacles include six factors that door, wall, floor, staircase, height, and distance between motes. WSN properties have five factors that nodal processing capacity, antenna orientation, RF power, packet size, other network interference. In addition, environmental factors include temperature, humidity and smoke. To sum up, serverless smart exit sign system has to consider both aspects of hardware and software hindrance, which may occurs indoor space. Figure 2 summarizes the derived factors of physical obstacles, environmental factors and WSN properties.

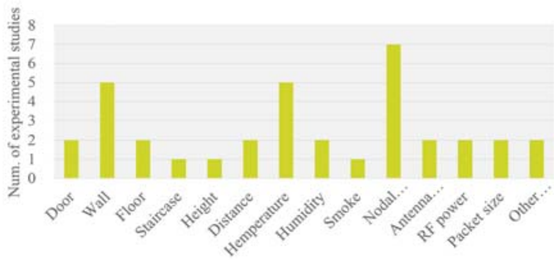

Figure 2. Derived factors influencing network performance

3.1 Physical obstacles

Many physical obstacles in a building may degrade the network performance of a WSN in an indoor environment. Jeon et al. [18] argued that signal transmission distance varies depending on building use and occupancy. For example, in office buildings, desk partition walls obstruct network communication, and in department stores, display stands and tables block signal transmission. It is however difficult to generalize the characteristics of physical obstacles by building use and occupancy. The reason is that many installations are temporary and are continuously being modified according to the occupants' changing needs. Moreover, the size of objects and their material properties may vary greatly.

Holland et al. [16] measured the degradation of WSN performance in an indoor environment. According to the study, the height difference between motes significantly affects network reliability. For instance, the packet transmission success rate between a ceiling-attached mote and a floor-embedded mote is lower than that between two ceiling-attached motes. The study showed that the vertical installation position of smart exit signs is another factor that should be taken into consideration.

Several other researchers [1,9,13,18,19,24,29] have conducted WSN performance tests while considering specific physical obstacles in indoor environments. The most commonly considered obstacle was a wall. Many studies [1,9,18,19,29] showed that the two layers of a 200 mm-thick concrete wall obstruct packet transmission. Doors, staircases, and the number of floors have also been identified as factors that degrade packet transmission [9,13].

In addition, the material type of a physical obstacle in a building is another factor that may affect network communication. For example, Di [9] and Fuhr et al. [9,13] demonstrated that motes cannot communicate with each other when they are installed over 15 m away with a steel door between them.

Although the findings of previous studies are useful in identifying the factors that generally affect network communication, the specific numbers (e.g., 200 mm concrete wall, 15 m) may change depending on the specifications of the network components and the physical obstacles. For example, Fuhr et al. [13] succeeded in reading data inside a metal food shipping container from outside the container using a radiofrequency (RF) device.

Table 2 summarizes the factors (i.e., doors, walls, floors, staircases, height, and distance between motes) that are potential physical obstacles in indoor environments.

Table 2 Derived physical obstacles

Factor	Previous research results	References	Considerations
Door	Steel doors degrade the packet success rate at a distance of 20 m between motes.	[9,13]	Door closure (half, fully) test with steel doors, glass doors, and fire shutters
Wall	Two layers of concrete walls with a total thickness of 200 mm block packet transmission.	[1,9,18,19,29]	A concrete wall test with a non-line of sight (NLOS) condition
Floor	Two stories of concrete floors block packet transmission.	[9]	Multi-story floors test with an NLOS condition
Staircase	20 m of stairs block packet transmission.	[9]	Additional mote installation test at the landing space
Height	Height differences between motes degrade the packet success rate.	[16]	Placement position test with radiofrequency (RF) power control
Distance	16 dBm over RF power is needed at a distance of 20 m between motes.	[24]	Effective distance test with RF power control

3.2 Environmental factors

In indoor spaces, a few environmental variations may influence WSN performance, for example, temperature and humidity variations. Indeed, fire causes sprayed water from sprinklers to raise the humidity level abruptly. Flames also increase the temperature of an indoor space immediately, which may affect WSN performance.

Several researchers conducted WSN performance tests in actual fired spaces to consider the temperature and humidity variations of the environment [3,5,10]. The motes read the temperature and humidity of the fired areas and continuously reported the status data using 400 MHz and 868 MHz multi-channel radio transceivers. The studies showed that WSN motes are able to communicate through penetrating flames and keep tracking the fire diffusion until they burn out. WSNs perform regardless of degradation caused by high-temperature environments.

Ruiz-Garcia et al. [31] conducted a WSN performance test in cooling environments (0−20°C). The researchers manipulated the temperatures in the cooling environments, which comprised a warehouse, a shipping container, and a vehicle for food logistics. Although the general indoor environment has a higher temperature than this range of venues, some corridors or spaces may be as cold in winter. A Zigbee-based WSN performance test showed that dynamic temperature variations have no effect on WSN performance.

Nevertheless, humid environments have a far greater effect on WSN performance than significant temperature variations. Anastasi et al. [2] and Holland et al. [16] conducted empirical research to test WSN performance in various humid environments. The studies both confirmed that rain and fog cause RF signal attenuation, which degrades WSN performance.

Hofmann et al. [15] investigated the impact of fire, smoke, and vapor on wireless communication in a tunnel. The study showed that fire and smoke do not severely affect communication performance; however, vapor significantly attenuates signal transmission.

Table 3 summarizes the environmental factors that could degrade WSN performance: temperature variations, a high humidity level, and smoke.

3.3 Wireless sensor network properties

The performance of a WSN is influenced by both its hardware and software properties. Hardware properties that could potentially affect WSN performance include the nodal processing capacity and antenna orientation. Software properties include RF power, packet size, and network interference.

Several researchers have investigated the influence of 1 to *n* connections [7,17,20,35]. When many motes transmit packets to a single mote, packet collision and channel interference occur. Kim et al. [20] found that increased data traffic and radio signal communication cause packet collision, which degrades network performance. Wilson et al. [35] argued that network expansion by multi-hop communication increases the packet error rate due to the increased number of packet collisions. Similar to maintenance work, security systems using sensor networks connect multiple nodes to a gateway node.

Choi et al. [7] determined that security system networks have an increased transmission time for inquiry and exchange packets due to the acknowledgement (ACK) responses from multiple motes. In their study, these ACK responses were used to check packet collision redundancy.

Smart exit signs also connect numerous sensor nodes in an entire building, which may cause packet collision. For instance, a hall or a lounge space may connect multiple corridors through which 1 to N connections are constructed.

Table 3 Derived environmental factor

Factor	Previous research results	References	Considerations
Temperature	1) Motes surrounded by fire can communicate with outside motes. 2) Cooling conditions (0–20°C) do not degrade the packet success rate.	[3,5,10,15,31]	This negligible factor depends on the WSN component specifications.
Humidity	1) Rain and fog attenuate radio signal. 2) Water vapor causes signal attenuation at a distance of 40 m from installed motes.	[2,15]	Humid environment test
Smoke	Smoke does not significantly attenuate the 2.4 GHz band of wireless communications.	[15]	This negligible factor depends on the WSN component specifications.

Therefore, the packet error rate at multiple connections should be considered in smart exit sign systems.

Furthermore, many other WSN properties are linked to the packet error rate. For example, the size of the packet, RF power, and other network interferences are included as well.

Bigger-sized packets can create sizable background traffic on a network, which then decreases the packet delivery ratio (%). Lee et al. [25] stated that larger-sized data payloads considerably degrade the networking performance of WSNs. When network traffic is increased, it causes packet collision due to the larger data payload. Moreover, a larger packet size also causes the battery life of the motes to shorten [30]. Therefore, packet size should be taken into account when considering network expansion and battery life.

Other networks could affect WSN performance, for instance, WiBro and satellite DMB WLAN. To avoid interference, many researchers have investigated the protocols of designated RF bands. Fuhr et al. [13] stated that an offset of 7 Mhz is required to avoid interference with other network communication. An et al. [1] conducted WiBro and satellite DMB interference tests on WSNs and suggested that an offset of 10 MHz is ideal.

Smart exit sign systems have the same network interference issues in buildings. A condensed network environment and other wireless networks may cause network interference with smart exit sign systems.

In terms of the hardware properties of WSNs, antenna orientation is important for connectivity performance [8]. In addition, the type of antenna and installation position have an influence on networking performance. Several researchers have conducted tests on antenna performance using different orientations and types of antennas [4,16].

Buckley et al. [4] pointed out that the type of antenna used influences networking performance significantly. The researchers conducted various experiments with chip internal antennas, external antennas, and planar-type, mono-type, and whip-type antennas. The results demonstrated that each antenna type performed significantly differently. The planar multilayer external antenna performed best in terms of distance and packet transmission success rate.

Holland et al. [16] conducted performance tests using different height conditions with antenna orientation. The study showed that different mote orientations with directional antennas degrade network performance.

Given the aforementioned findings, developers of smart exit sign systems should consider antenna orientation and type, particularly for floor-embedded types of smart exit signs.

RF power is another important factor influencing WSN performance. Higher RF power allows motes to communicate over longer distances; however, this does shorten battery life. Lee et al. [24] conducted a test to determine the effect of RF power over a fixed distance on packet transmission success rate. The study showed that, over a distance of 20 m, 16 dBm of RF power is needed to communicate correctly.

Table 4 Derived WSN properties

Factor	Previous research results	References	Considerations
Nodal processing capacity	The packet error rate is decreased when expanding connected motes.	[7,17,19,20, 25,29,35]	1 to *n* connection test
Antenna orientation	1) The direction of the antenna influences the packet transmission success rate by changing orientation. 2) Antenna type influences networking performance.	[4,16]	Omnidirectional antenna usage for floor-embedded smart exit signs
RF power	Higher RF power increases the packet transmission success rate.	[24,33]	RF power control test
Packet size	A larger-size packet decreases the packet delivery rate.	[24,35]	System algorithm and packet design
Other network interference	Analogue mobile communication, WiBro, Satellite DMB, and WLAN interference can be avoided if an offset of 10 MHz is used; a frequency offset of 7 MHz is demanded to avoid interference with other networks.	[1]	Other network interference tests

Sexton et al. [31] studied the physical layer protocol for use in industrial environments. The findings showed that 15 dBm may be required to achieve the desired range of 100 m NLOS to overcome physical obstacles and path loss uncertainty.

The available packet transmission distance may vary depending on the component specifications; however, these findings showed that the appropriate RF power needs to be configured to ensure optimal WSN performance in the installation environment.

Table 4 summarizes the network performance-related properties for WSNs: nodal processing capacity, antenna orientation, RF power, packet size, and other network interference.

4 Conclusion

An objective of the research is derivation of the factors considering the reliability of serverless smart exit sign systems. By conducting a literature review, we determined the factors that may influence the networking performance of serverless smart exit sign systems. The derived factors will be validated on further research using serverless smart exit sign system prototype.

So far, two groups of researchers have proposed algorithms for serverless smart exit sign systems [6,11,12,14]. No research has been done however to build a physical system while taking into consideration potential system failure. Reliability is key to the success of a serverless smart exit sign system and to prevent system failure. If individual exit signs cannot send and receive data reliably, the entire system will malfunction. We therefore defined reliability by considering two aspects of smart exit sign systems: network reliability and data transmission reliability.

Network reliability refers to the stability of a system in the presence of physical obstacles and indoor environmental variations as well as external factors. Data transmission reliability refers to the extent to which a system stably and correctly communicates data between nodes taking into account internal factors. Three categories of internal factors were derived:

1. Physical obstacles: doors, walls, floors, stairs, height differences, and distance
2. Environmental factors: temperature, humidity, and smoke
3. WSN properties: nodal processing capacity, antenna orientation, RF power, packet size, and interference from other networks

Although this paper analyzed and thus determined the factors that should be considered when testing network reliability, it has limitations. The identified factors are closely related to the installation environment and the component specifications of the WSN. Depending on the circumstances, specific numbers may change, for instance, if there is a 200 mm-thick concrete wall obstruction or a two-story floor obstruction. In addition, the importance level of the factors may vary depend on installation condition. To clarify this, we are planning to conduct experiment to validate the derived factors and its specific numbers.

Although the derived factors have the aforesaid limitations, this paper may make a meaningful contribution to future work on serverless smart exit sign systems. The identified factors should be considered when designing the network of disaster management system and testing the network reliability of a serverless smart exit sign system to fulfill the key requirements of the system. The factors can furthermore be implemented with ease in the design of a network system.

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