Implementation and evaluation of a 2.4 GHz multi-hop WSN: LoS, NLoS, different floors, and outdoor-to-indoor communications

Vasin Chaoboworn[1], Yoschanin Sasiwat[2], Dujdow Buranapanichkit[3], Hiroshi Saito[4], Apidet Booranawong[5]
[1,2,3,5]Department of Electrical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand
[4]Division of Computer Engineering, University of Aizu, Japan

Article Info

Article history:

Received Mar 28, 2021
Revised May 24, 2021
Accepted Jun 11, 2021

Keywords:

2.4 GHz
Different floors
Multi-hop
NLoS
Outdoor to indoor
WSN

ABSTRACT

In this paper, the communication reliability of a 2.4 GHz multi-hop wireless sensor network (WSN) in various test scenarios is evaluated through experiments. First, we implement an autonomous communication procedure for a multi-hop WSN on Tmote sky sensor nodes; 2.4 GHz, an IEEE 802.15.4 standard. Here, all nodes including a transmitter node (Tx), forwarder nodes (Fw), and a base station node (BS) can automatically work for transmitting and receiving data. The experiments have been tested in different scenarios including: i) in a room, ii) line-of-sight (LoS) communications on the 2nd floor of a building, iii) LoS and non-line-of-sight (NLoS) communications on the 1st floor to the 2nd floor, iv) LoS and NLoS communications from outdoor to the 1st and the 2nd floors of the building. The experimental results demonstrate that the communication reliability indicated by the packet delivery ratio (PDR) can vary from 99.89% in the case of i) to 14.40% in the case of iv), respectively. Here, the experiments reveal that multi-hop wireless commutations for outdoor to indoor with different floors and NLoS largely affect the PDR results, where the PDR more decreases from the best case (i.e., the case of a) by 85.49%. Our research methodology and findings can be useful for users and researchers to carefully consider and deploy an efficient 2.4 GHz multi-hop WSN in their works, since different WSN applications require different communication reliability level.

Corresponding Author:

Apidet Booranawong
Department of Electrical Engineering
Faculty of Engineering, Prince of Songkla University
15 Karnjanavanich Road, Hat Yai, Songkhla 90110, Thailand
Email: apidet.boo@gmail.com, apidet.b@psu.ac.th

1. INTRODUCTION

Wireless sensor networks (WSNs) have been considered as one of the interesting research areas in recent years because of vital role in numerous applications [1]-[3]. WSNs refer to a group of distributed sensor nodes linked by wireless communications. The sensor node as the source node collects information from physical environments such as temperature, pressure, vibration, motion, and smoke, then send its sensory data to the base station or the sink node for monitoring and using [3]. Since network coverage area is larger than the radio range of single nodes, relay nodes or forwarder nodes (i.e., other nodes in the network with forwarding functions) are used to transfer the data to the destination. Here, a multi-hop communication as a type of communications in radio networks is required [4], [5]. Due to this characteristic of WSNs, WSNs with internet of thing (IoT) technology then can be deployed in numerous fields such as environmental and disaster monitoring, animal tracking, vehicle and human tracking, structure health monitoring, precision agriculture, security and surveillance, smart buildings and cities, transportation, industrial works, health care and medical services, and so on [1]-[3].

A review of related works is discussed here, and the summary is also provided in Table 1. In [6], a multi-hop wireless sensor network for an outdoor environment was developed for wildfire monitoring. Such a system was used to report results including temperature, relative humidity, and barometric pressure from field testing during prescribed test burns near San Francisco, California. The Crossbow Mica2 motes with Chipcon 1000 radio module (433 MHz frequency) and GPS were programed using TinyOS and employed for this application. The results showed that the sensor response with sampling interval of 2.5 second was excellent with low data packet. The authors also suggested to deploy the sensor nodes above (0.5 m) the top of the fuel to avoid transmission packet loss. In [7], the investigation of the mobile multi-hop wireless network for an indoor environment was tested by the experiment using an IEEE802.11b/g standard. The authors concluded that wireless link quality was dynamic in nature, especially in mobile scenarios, and the packet delivery ratio indicating the communication reliability was changed from high to low levels through the period of time. [8] stated that when the range of single-hop wireless communication was limited by distance or harsh radio propagation conditions (such as in large buildings made of heavy construction and underground structures), relay nodes could be used to extend the communication range through multi-hop relaying. Thus, in [8], MICA2 motes operating at 868-916 MHz with a relay deployment and link assessment strategy was presented and tested in an office building environment. The authors claimed that to select appropriate relay nodes could significantly improve the communication performance. In [9], performance evaluation of video streaming in multi-hop wireless networks based on IEEE 802.11 WLANs had been tested. The authors concluded that the unreliable nature and shared media of multi-hop communications made the deployment of multimedia applications a difficult task. Here, radio signals interference adversely degraded video performance. Both inter and intra-flow interference had a great impact on video quality. Therefore, the well design and deployment of multi-hop wireless network for quality of service (QoS) provisioning to support multimedia applications should be considered.

John *et al.* [10] presented the design and implementation of a WSN for agricultural monitoring using a multi-hop based architecture. Each sensor node as TelosB node was equipped with different sensors such as soil moisture, atmospheric temperature, and humidity sensors. The authors showed the contribution that each node could report its sensor data to the base station node following a sleep wake-up schedule. In [11], a WSN system to monitor the health state of heritage-buildings in real-time was presented. The multi-hop WSN with temperature sensors, humidity sensors, masonry crack sensors, rain gauge sensors, and light sensors were developed. The sensor nodes with Chipcon CC2420, 2.4 GHz/ an IEEE802.15.4 standard had been deployed and tested on the Rognosa tower in the medieval village of San Gimignano, Tuscany, Italy. The authors suggested that, from the communication network viewpoint, an appropriate battery saving policy with low power mode setting and wake-up strategy could help to improve the network lifetime.

Lee *et al.* [12], authors established a realistic indoor environment for the performance evaluation of a ZigBee wireless network. Several sets of practical experiments using ITRI ZBnode with Chipcon CC2420 had been conducted, including node connectivity, packet loss rate, and transmission throughput. The results showed that their developed ZigBee platforms could work well under multi-hop transmission. The authors also concluded that the more hops between the transmitter and the receiver, the higher packet loss rate would be. Also, packet loss rate could be significantly decreased by using a more efficient communication mechanism. Finally, performance evaluation of indoor multi-hop wireless networks using an IEEE 802.11 standard was studied in [13]. The authors suggested that the shorted path was not the best choice for data transmission, since, in general the links in the network exhibited a wide range of delivery rates. Here, minimum-hop-count route often chosen routes that had less capacity than the best paths that existed in the network. Such observations suggested that more attention be paid to link quality when choosing routes.

According to the research literature as discussed above, we can summarize that, in multi-hop WSN communications, sensor node and relay node deployment [6], [8], wireless link quality and radio signal interference [7], [9], power consumption and network lifetime [10], [11], more hops communication with packet loss rate [12], and optimal paths for data transmission [13] are the important issues which should be considered in order to achieve more efficient communications.

In this paper, a 2.4 GHz IEEE802.15.4 multi-hop WSN with its communication procedure is implemented, and a communication reliability of the multi-hop communication is evaluated. The experiments using Tmote sky sensor nodes have been tested in different five scenarios, where LoS, NLoS, different floors, and outdoor to indoor communications are focused. The results show that the multi-hop communication reliability indicated by the PDR results can vary from 99.89% to 14.40% (high to low levels), respectively. Here, the PDR reaches nearly 100% for the case of LoS communications, while the PDR is low for the case in outdoor to indoor environments with different floors and the NLoS communications.

The structure of this paper is as follows. Section 2 introduces the implemented 2.4 GHz IEEE 802.15.4 multi-hop WSN with its communication functions. Section 3 provides details of experiments, test scenarios, and performance metrics. Section 4 provides experimental results and discussion. We finally conclude the paper in section 5.

Table 1. A summary comparison between related works and this work

Ref.	– Objectives – Wireless technology	Results and major findings
[6]	– A multi-hop network for an outdoor environment was developed for wildfire monitoring. – Crossbow Mica2 motes with Chipcon 1000, 433 MHz	The sensor nodes should be deployed above (0.5 m) the top of the fuel to avoid transmission packet loss.
[7]	– A mobile multi-hop wireless network for an indoor was tested. – IEEE802.11b/g standard	– Wireless link quality was dynamic in nature, especially in mobile scenarios. – The PDR was changed from high to low levels through the period of time.
[8]	– A multi-hop network with a relay deployment and link assessment strategy was presented and tested in an office building. – MICA2 motes, 868-916 MHz	Selecting of appropriate relay nodes could significantly improve the communication performance.
[9]	– Video streaming in multi-hop wireless networks was evaluated. – IEEE 802.11 WLANs	– Radio signal interferences (i.e., both inter and intra-flow interferences) degraded video performance. – The well deployment of multi-hop wireless network for QoS provisioning to support multimedia applications should be considered.
[10]	– A multi-hop WSN for agricultural monitoring was implemented and tested. – TelosB node	Each node could report its sensor data to the base station node following a sleep wake-up schedule to prolong the network lifetime.
[11]	– A WSN system to monitor the health state of heritage-buildings in real-time was presented – Sensor nodes with CC2420, 2.4 GHz/ IEEE802.15.4 standard.	An appropriate battery saving policy with low power mode setting and wake-up strategy could help to improve the network lifetime.
[12]	– A realistic indoor environment for the performance evaluation of a node ZigBee wireless network was presented. – ITRI ZBnode with Chipcon CC2420, IEEE802.15.4	– The more hops between the transmitter and the receiver, the higher packet loss rate would be. – Packet loss rate could be decreased by using a more efficient communication mechanism.
[13]	– Indoor multi-hop wireless networks were evaluated. – IEEE 802.11 standard	– The shorted path was not the best choice for data transmission. – Minimum-hop-count route often chosen routes that had less capacity than the best paths that existed in the network.
This work	– A 2.4 GHz multi-hop WSN has been developed, and the experiments have been tested in different scenarios including a) in the room, b) LoS communications on the 2nd floor of the building, c) LoS and NLoS communications on the 1st floor to the 2nd floor, d) LoS and NLoS communications from outdoor to the 1st and the 2nd floors. – Tmote sky sensor nodes; 2.4 GHz, IEEE 802.15.4 standard.	– - The PDR can vary from 99.89% (i.e., in the room) to 14.40% (i.e., LoS and NLoS communications from outdoor to indoor). – Multi-hop commutations from outdoor to indoor with different floors and NLoS largely affect the communication reliability. – Research methodology and findings can be useful for users and researchers to carefully consider and deploy 2.4 GHz multi-hop WSNs in their works.

2. IMPLEMENTATION OF A MULTI-HOP WIRELESS SENSOR NETWORK

The system to be tested in this work is shown in Figure 1. There are four wireless sensor nodes including a transmitter node (Tx node with ID 0), the forwarder node (Fw node with ID 1), the forwarder node (Fw node with ID 2), and the base station node (BS node with ID 3) connected with the computer as the processing center via the wire connection. Tmote sky sensor nodes for low-power wireless applications [14], [15] are used, as shown in Figure 2. Tmote sky sensor node is equipped with TI MSP430F1611 microcontroller and a CC2420 RF chip [16], [17]. It is based on ZigBee, an IEEE 802.15.4 standard [18], [19], which operates at 2.4 GHz with a data rate of 250 Kbps. In our system, all nodes use the channel 15 with the transmission power of 0 dBm [20] for their communications, and the packet transmission rate is set to 100 ms. We guarantee that there is no signal interference from all Wi-Fi channels, since we first monitor all available Wi-Fi channels in the test field by using the Wi-Fi analyzer software [21].

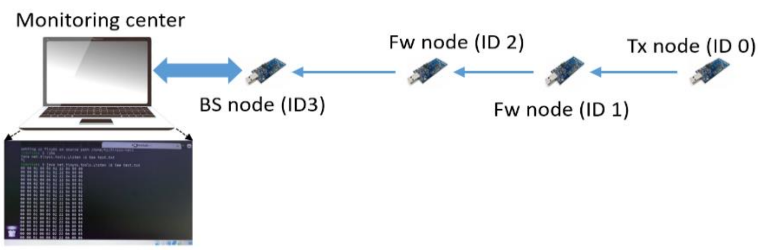


Figure 1. Multi-hop wireless sensor networks

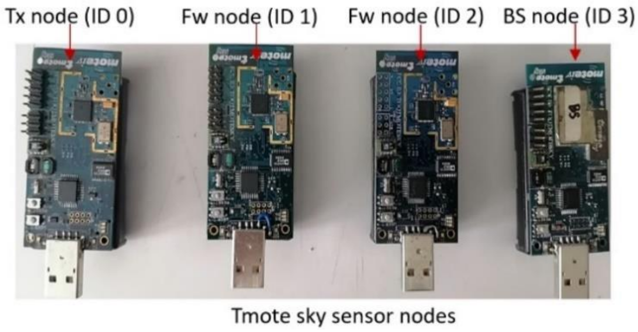


Figure 2. Tmote sky sensor nodes to be used in this work

For sensor node communications, we define that the Tx node as the source node will continuously send data packets (including the packet number) to the BS node as the sink node via the Fw node ID 1 and the Fw node ID 2, respectively. Here, to test multi-hop connection, the Tx node is only connected to the Fw node ID1, while the Fw node ID1 is connected to the Fw node ID2, and the Fw node ID2 is connected to the BS node. At the BS node, the data from the transmitter are then forwards to the personal computer (PC) or Notebook via a serial port for collecting and processing. The full process of the communication procedure is described in Algorithms 1 to 3, respectively.

Algorithm 1 Pseudo code for the Tx node
```
IF Receive the packet from other nodes in the network THEN
     Discard such a received packet
END IF
IF  Start command THEN
      Packet transmission rate configuration
      Packet number configuration
      Send all generated data packets to the Fw node ID 1 by
        unicasting
      Stop to send the packet
END IF
```

Algorithm 2 Pseudo code for Fw node ID 1
```
IF Receive the packet from the Fw node ID 2 or the BS node THEN
     Discard such a received packet
END IF
IF Receive the packet from the Tx node THEN
     Forward the packet to the Fw node ID 2 by unicasting
END IF
```

Algorithm 3 Pseudo code for Fw node ID 2
```
IF Receive the packet from the Tx node or the BS node THEN
     Discard such a received packet
END IF
IF Receive the packet from the Fw node ID 1 THEN
     Forward the packet to the BS node by unicasting
END IF
```

Algorithm 4 Pseudo code for the BS node
```
IF Receive the packet from the Tx node or the Fw node ID 1 THEN
     Discard such a received packet
END IF
IF Receive the packet from the Fw node ID 2 THEN
     Forward the packet to PC via the serial port
END IF
```

3. EXPERIMENTS AND TEST SCENARIOS

The experiments have been carried out in the indoor environment at the Department of Electrical Engineering, Prince of Songkla University, Thailand. As showed in Figure 3, this test field has two floors. There are many rooms at the second floor including staff rooms, lecture rooms, bathrooms, Master and Ph.D. student rooms, while the first floor is the electrical engineering laboratory including electric machines, tables, and cabinets. There is an exit at the first floor, as shown in Figure 3.

Figure 3. Test fields

To study the performance of the multi-hop WSN in various cases as our objective, we provide five different test scenarios, as shown in Figures 4(a) to 4(e) in appendix, respectively. Note that the summary information of the test scenarios is also provided in Table 2.

a. Test scenario #1: all nodes are placed in the room at the second floor, shown in Figure 4(a). For this scenario, we want to test and to make sure that all nodes with the communication functions can work automatically and correctly.
b. Test scenario #2: as shown in Figure 4(b), all nodes are placed at the second floor, where the Tx node, the Fw node ID 1, and the Fw node ID 2 are outside the room, and the BS node connected with the computer is in the room. Here, each hop or each communication link can be considered as the LoS communication.
c. Test scenario #3: as shown in Figure 4(c), this test scenario is look like the test scenario #2, but we move the Tx node to the different area with different surrounding environments. However, each hop can still be considered as the LoS communication.
d. Test scenario #4: as shown in Figure 4(d), the Tx node and the Fw node ID 1 are placed at the laboratory in the first floor, while the Fw node ID 2 and the BS node are on the second floor. Note that the BS node is still in the room. In this scenario, the link between the Tx node and the Fw node 1 can be considered as the NLoS communication, since there is a big cabinet and other devices as obstacles between such a link.
e. Test scenario #5: as shown in Figure 4(e), the Tx node is placed at outdoor. The Fw node ID 1 is placed on the first floor, and the Fw node ID 2 and the BS node are on the second floor. This test scenario can also be considered as NLoS communication, sine the radio link between the Tx node and the Fw node 1 is blocked by the wall.

Table 2. Summary information of the test scenarios

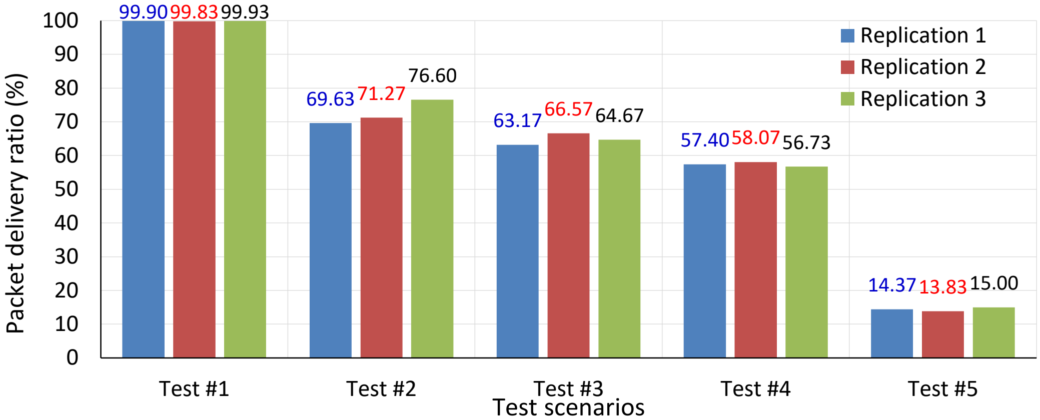
Test scenarios	Floors/Environments	LoS or NLoS
#1	1st floor/In the room	LoS
#2	2nd floor/In the room and the building	LoS
#3	2nd floor/In the room and the building	LoS
#4	1st floor to 2nd floor/In the room and the building	LoS and NLoS
#5	Outdoor to 1st floor and 2nd floor/Outdoor, in the room and the building	LoS and NLoS

To investigate and evaluate the performance of the multi-hop WSN in five test scenarios above, the packet delivery ratio (PDR) in (1) is used as the performance metric which indicates the communication reliability [22], [23]. Here, the packet delivery ratio is the ratio of the total number of packets successfully received at the BS node and the total number of packets sent by the Tx node [24]. The delivery ratio represents the level of the delivery data to the base station. For each test scenario, the experiment is repeated three times, and the average packet delivery ratio with 95% confidence interval [25] is then measured and reported.

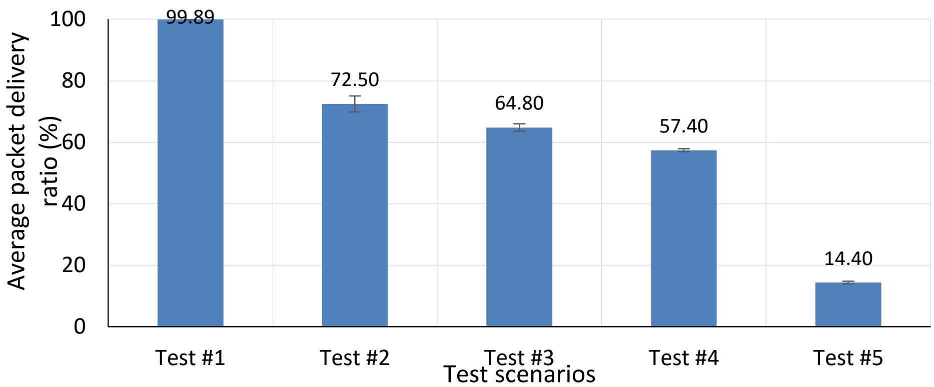
$$PDR = \frac{Total\ num.packets\ received}{Total\ num.packets\ sent} \times 100 \quad (1)$$

4. EXPERIMENTAL RESULTS AND DISCUSSION

The PDR results of three replications and the average PDR results of the test scenarios #1 to #5 are demonstrated in Figures 5(a) and 5(b), respectively. The results by our experiments reveal that the average PDRs can vary from 99.89% (for the test scenario #1) to 14.40% (for the test scenario #5); from high communication reliability to low communication reliability.



(a)



(b)

Figure 5. Average packet delivery ratio results of the test scenarios; (a) PDR results of each replication, (b) average PDR

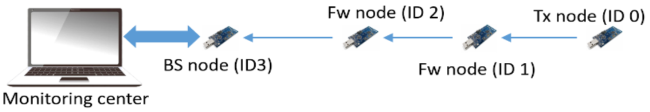
The results from the test scenario #1 confirm that our implemented multi-hop WSN with its communication functions can automatically and correctly work; where the data from the transmitter can be transferred to the destination or the base station node with the PDR close to 100%. The experimental results also reveal that, in the cases of real deployment in the second floor of the building with LoS communications, like the test scenarios #2 and #3 as in Figures 4(b) and 4(c), the PDRs reduce to 72.50% and 64.80%, respectively. Here, the PDR decreases 27.39% and 35.09% compared with the test scenario #1, and the different area and surrounding environments significantly affects the PDR results.

The experimental results from the test scenario #4 demonstrate that, for the sensor node communications from the first floor to the second floor with NLoS as in Figure 4(d), the average PDR is 57.40%. The communication reliability reduces 42.49% from the test scenario #1. The results here show that the multi-hop wireless commutations from different floors and NLoS significantly affect the PDR. Finally, the PDR results obtained from the test scenario #5 as in Figure 4(e) indicate that the multi-hop wireless commutations from the outdoor to the second floor in indoor building with NLoS have greatly effects the PDR results. The average PDR is only 14.40% which more decreases from the test scenario #1 by 85.49%. As we mentioned above, the communication reliability indicated by the PDR results obtained from five test scenarios can vary from high to low levels. These findings can be useful for users and researchers to carefully consider and deploy 2.4 GHz IEEE802.15.4 multi-hop WSNs in their works, since different WSN applications require different communication reliability level.

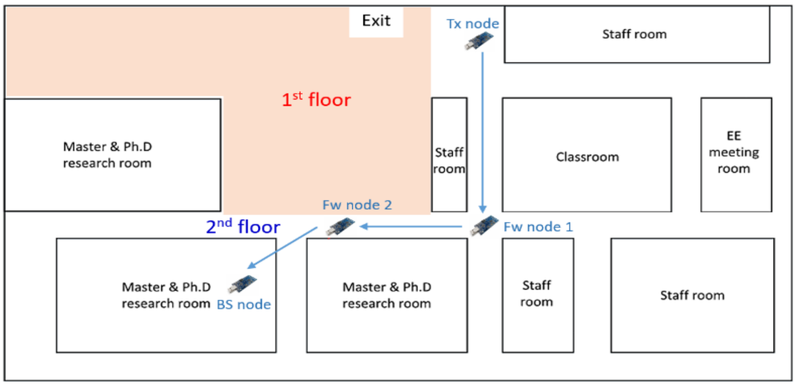
5. CONCLUSION

A communication reliability of the 2.4 GHz IEEE802.15.4 multi-hop WSN is evaluated in this paper. The experiments using Tmote sky sensor nodes have been tested in five scenarios. The experimental results indicate that the communication reliability measured by the packet delivery ratio can vary from 99.89% to 14.40%, respectively. Here, the experimental results reveal that the PDR can reach nearly 100% for the case of LoS communications. The multi-hop wireless communication among the sensor nodes from outdoor to indoor environments with different floors and the NLoS situation has greatly effects to the PDR level (with the PDR of 14.40%). In the future work, the comparison between our proposed system and other related systems, like a Wi-Fi ad-hoc network, will be considered. Also, a more efficient 2.4 GHz multi-hop WSN with IoT technology will be developed for practical use.

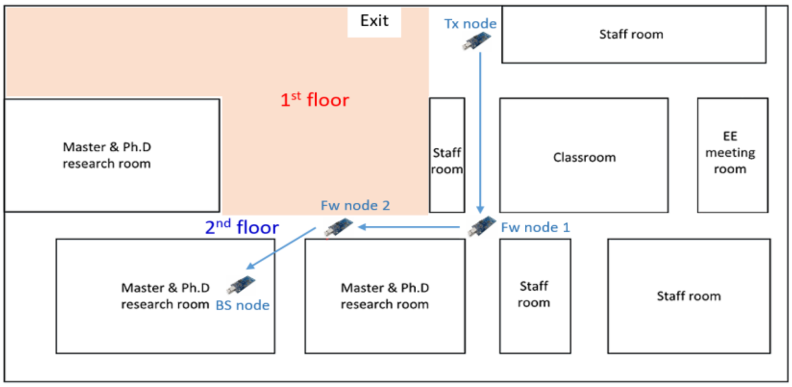
APPENDIX



(a)

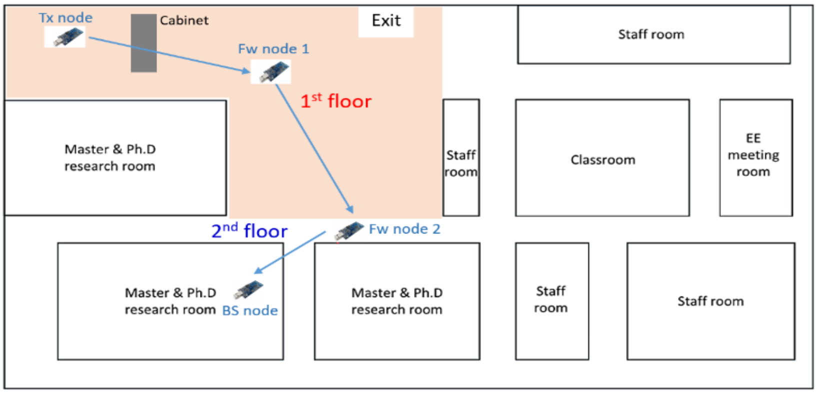


(b)

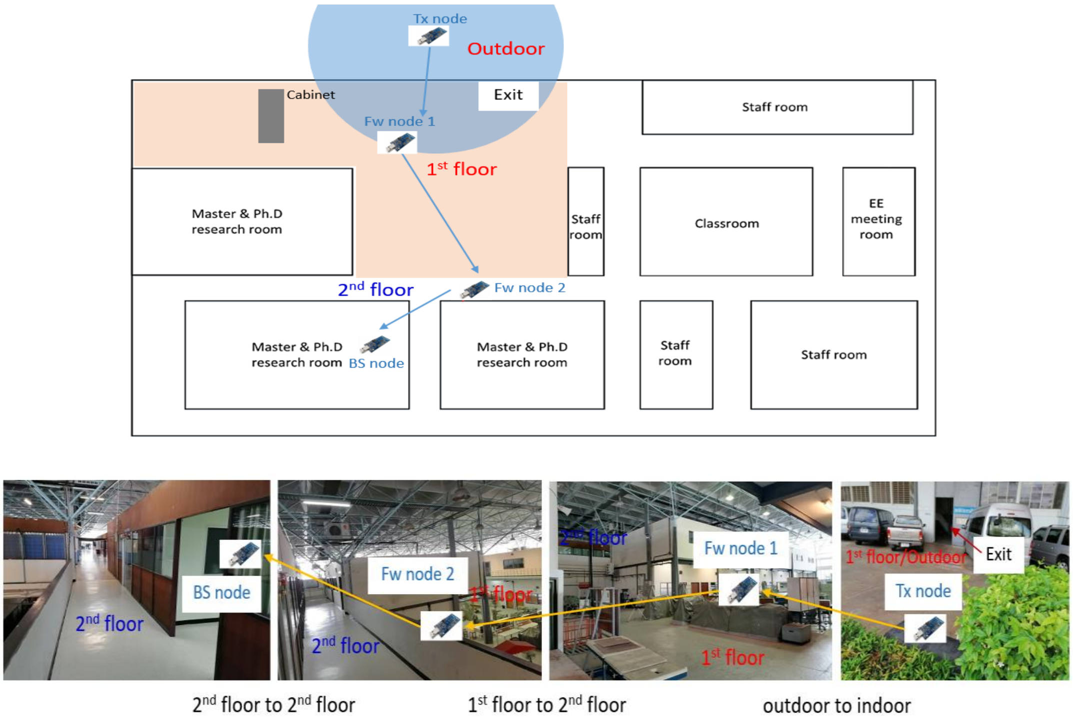


(c)

Figure 4. Test scenarios; (a) test scenario #1; all sensor nodes are in the room with the room size of 5x5 m, (b) test scenario #2; LoS communications on the 2nd floor of the building, (c) test scenario #3; LoS communications on the 2nd floor of the building (different area and surrounding environments compared with the test scenario #2), (*continue*)



(d)



(e)

Figure 4. Test scenarios; (d) test scenario #4; LoS and NLoS communications on the 2^{nd} floor to the 1^{st} floor (i.e., electrical laboratory), (e) test scenario #5; LoS and NLoS communications on the 2^{nd} floor to the 1^{st} floor and to outdoor (indoor to outdoor communications)

ACKNOWLEDGEMENTS

This work was supported by the Faculty of Engineering, Prince of Songkla University, Thailand, and The University of Aizu, Japan.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” *Computer networks*, vol. 38, no. 4, pp. 393-422, 2002, doi: 10.1016/S1389-1286(01)00302-4.

[2] D. Kandris, C. Nakas, D. Vomvas, and G. Koulouras, “Applications of wireless sensor networks: an up-to-date survey,” *Applied System Innovation*, vol. 3, no. 1, 2020, doi: 10.3390/asi3010014.

[3] M. Farsi, M. A. Elhosseini, M. Badawy, H. A. Ali, and H. Z. Eldin, “Deployment techniques in wireless sensor networks, coverage and connectivity: A survey,” *IEEE Access*, vol. 7, pp. 28940-28954, 2019, doi: 10.1109/ACCESS.2019.2902072.

[4] J. Li and G. AlRegib, “Network lifetime maximization for estimation in multihop wireless sensor networks,” *IEEE Transactions on Signal Processing*, vol. 57, no. 7, pp. 2456-2466, 2009, doi: 10.1109/TSP.2009.2016872.

[5] X. Xu, X. Y. Li, X. Mao, S. Tang, and S. Wang, “A delay-efficient algorithm for data aggregation in multihop wireless sensor networks,” *IEEE transactions on parallel and distributed systems*, vol. 22, no. 1, pp. 163-175, 2010, doi: 10.1109/TPDS.2010.80.

[6] D. M. Doolin and N. Sitar, “Wireless sensors for wildfire monitoring,” In *Smart Structures and Materials 2005: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, International Society for Optics and Photonics, vol. 5765, pp. 477-484, 2005, doi: 10.1117/12.605655.

[7] J. Zhou, M. Jacobsson, E. Onur, and I. Niemegeers, “An investigation of link quality assessment for mobile multi-hop and multi-rate wireless networks,” *Wireless Personal Communications*, vol. 65, no. 2, pp. 405-423., 2012, doi: 10.1007/s11277-011-0263-1.

[8] M. R. Souryal, J. Geissbuehler, L. E. Miller, and N. Moayeri, “Real-time deployment of multihop relays for range extension,” In *Proceedings of the 5th international conference on Mobile systems, applications and services*, 2007, pp. 85-98, doi: 10.1145/1247660.1247673

[9] X. Cheng, P. Mohapatra, S.J. Lee, and S. Banerjee, “Performance evaluation of video streaming in multihop wireless mesh networks,” In *Proceedings of the 18th International Workshop on Network and Operating Systems Support for Digital Audio and Video*, 2008, pp. 57-62, doi: 10.1145/1496046.1496060.

[10] J. John, G. S. Kasbekar, D. K. Sharma, V. Ramulu, and M.S. Baghini, “Design and Implementation of a Wireless Sensor Network for Agricultural Applications,” *arXiv preprint arXiv:1910.09818.*, pp. 1-28, 2019.

[11] A. Mecocci and A. Abrardo, “Monitoring architectural heritage by wireless sensors networks: San Gimignano-A case study,” *Sensors*, vol. 14, no. 1, pp. 770-778, 2014, doi: 10.3390/s140100770.

[12] J. S. Lee, and Y. M. Wang, “Experimental evaluation of ZigBee-based wireless networks in indoor environments,” *Journal of Engineering*, 2013, doi: 10.1155/2013/286367.

[13] D. S. De Couto, D. Aguayo, B. A. Chambers, and R. Morris, “Performance of multihop wireless networks: Shortest path is not enough,” *ACM SIGCOMM Computer Communication Review*, vol. 33, no. 1, pp. 83-88., 2003, doi: 10.1145/774763.774776.

[14] G. Werner-Allen *et al.*, “Deploying a wireless sensor network on an active volcano,” *IEEE internet computing*, vol. 10, no. 2, pp. 18-25, 2006, doi: 10.1109/MIC.2006.26.

[15] J. H. Hauer, V. Handziski, and A. Wolisz, “Experimental study of the impact of WLAN interference on IEEE 802.15. 4 body area networks,” In *European Conference on Wireless Sensor Networks*, Springer, Berlin, Heidelberg, pp. 17-32, 2009, doi: 10.1007/978-3-642-00224-3_2.

[16] *CC2420 Datasheet Chipcon Instruments from Texas Instruments*, 2012, [online] Available: http://www.ti.com/lit/ds/symlink/cc2420.pdf.

[17] M. Amirinasab, S. Shamshirband, A. T. Chronopoulos, A. Mosavi, and N. Nabipour, “Energy-efficient method for wireless sensor networks low-power radio operation in internet of things,” *Electronics*, vol. 9, no. 2, pp. 320, 2020, doi: 10.3390/electronics9020320.

[18] A. Booranawong, K. Sengchuai, D. Buranapanichkit, N. Jindapetch, and H. Saito, “RSSI-based indoor localization using multi-lateration with zone selection and virtual position-based compensation methods,” *IEEE Access*, vol. 9, pp. 46223-46239, 2021, doi: 10.1109/ACCESS.2021.3068295.

[19] S. Ishida, Y. Arakawa, S. Tagashira, and A. Fukuda, “Wireless local area network signal strength measurement for sensor localization without new anchors,” *Sensors and Materials*, vol. 32, no. 1, pp. 97-114, 2020, doi: 10.18494/SAM.2020.2592.

[20] A. Booranawong, K. Sengchuai, N. Jindapetch, and H. Saito, “Enhancement of RSSI-based localization using an extended weighted centroid method with virtual reference node information,” *Journal of Electrical Engineering and Technology*, vol. 15, pp. 1879-1897, 2020, doi: 10.1007/s42835-020-00457-y.

[21] A. Booranawong, N. Jindapetch, and H. Saito, “A system for detection and tracking of human movements using RSSI signals,” *IEEE sensors journal*, vol. 18, no. 6, pp. 2531-2544, 2018, doi: 10.1109/JSEN.2018.2795747.

[22] A. Jain, M. Khari, E. Verdú, S. Omatsu, and R.G. Crespo, “A route selection approach for variable data transmission in wireless sensor networks,” *Cluster Computing*, vol. 23, no. 3, pp. 1697-1709, 2020, doi: 10.1007/s10586-020-03115-0.

[23] M. Angurala, M. Bala, and S.S. Bamber, “Performance analysis of modified AODV routing protocol with lifetime extension of wireless sensor networks,” *IEEE Access*, vol. 8, pp. 10606-10613, 2020, doi: 10.1109/ACCESS.2020.2965329,

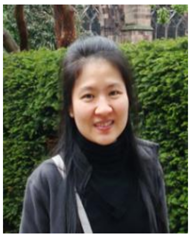
[24] A. Tsirigos, and Z.J. Haas, “Analysis of multipath routing-Part I: The effect on the packet delivery ratio,” *IEEE Transactions on wireless communications*, vol. 3, no. 1, pp. 138-146, 2004, doi: 10.1109/TWC.2003.821207.

[25] F. Deniz, H. Bagci, and I. Korpeoglu, “Energy-efficient and fault-tolerant drone-BS placement in heterogeneous wireless sensor networks,” *Wireless Networks*, vol. 27, no. 1, pp. 825-838, 2021, doi: 10.1007/s11276-020-02494-x.

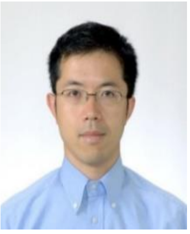
BIOGRAPHIES OF AUTHORS

Vasin Chaoboworn was born in Trang, Thailand. He now is studying the B.Eng. degree in Electrical Engineering (EE) from Prince of Songkla University (PSU), Thailand. His research interests are wireless communications and wireless sensor networks.

Yoschanin Sasiwat received the B.Eng degree in Computer Engineering from the Department of Computer Engineering, Prince of Songkla University (PSU), Thailand, and the M.Eng. Degree in Electrical Engineering (EE), PSU. He now is the Ph.D. student at EE, PSU. His research interest is computer engineering, wireless sensor networks, network protocols, and RSSI-based localization.



Dujdow Buranapanichkit received the B.Eng. degree in Electrical Engineering (EE) from Prince of Songkla University (PSU), Thailand, in 1999, the M.Sc. degree in Information Science from King Monkut's Institute of Technology Ladkrabang, Thailand, in 2003, and the Ph.D. degree in Electronic and Electrical Engineering from University College London (UK), in 2013. She is now an Assistant Professor at the Department of EE, PSU. Her research interests are in wireless sensor networks, distributed synchronization mechanisms, and protocol design.



Hiroshi Saito received his B.S. and M.S. degrees in Computer Science and Engineering from the University of Aizu in 1998 and 2000, respectively. In 2003, he received his Ph.D. degree in Electronic Engineering from the University of Tokyo. He is a Senior Associate Professor of the University of Aizu. His research interests include asynchronous circuit design, multi-core system design, and wireless sensor network system design.

Apidet Booranawong received the B.Eng. degree in Electrical Engineering (EE) from Walailak University, Thailand, in 2007, and the M.Eng. and the Ph.D. degrees in EE from Prince of Songkla University (PSU), Thailand, in 2009 and 2015, respectively. He was a visiting researcher with the University of Aizu, Aizu-Wakamatsu, Fukushima, Japan, in 2016-2017. He now is an Assistant Professor at the Department of EE, PSU. His research interests include wireless sensor networks, signal processing, and RSSI-based localization.