DESIGN OF NODE LOCATIONS FOR INDOOR WIRELESS MESH NETWORKS

Sukunya Sauram*, Peerapong Uthansakul and Monthippa Uthansakul

Received: May 21, 2010; Revised: Sept 12, 2010; Accepted: Sept 13, 2010

Abstract

In the literature, the performance of a Wireless Mesh Network (WMN) has been analyzed by assuming the same quality on each hop. However, this assumption is hardly true in practice due to the physical obstructions in the wireless link, especially for an indoor environment. Therefore, this study revisits the analysis of a WMN performance by taking the effect of physical obstructions into account instead of assuming an equally deterministic property for each hop. These obstructions cause the degradation of signal strength which relatively decrease the success rate of transmission between each hop. This study examines these physical concerns through measured results in an indoor environment and then a design of node locations is discussed.

Keywords : Delay, throughput, wireless mesh networks

Introduction

A Wireless Mesh Network (WMN) is a network technology without wires which will be happening in the near future. It has the same basic structure as a Wireless Local Area Network (WLAN). The difference between a WMN and a WLAN is in the meaning given to parts of the equipment. The important thing is that a WMN has no router while a WLAN does. This is because a WMN includes an access point together with a router which is called a mesh router. Users in a WLAN have also been renamed as mesh clients in a WMN. Because of the combination of access point and router, it makes a WMN a better tight system than a WLAN. In addition, each access point in a WLAN is connected by cable lines which limit the coverage range of operation. In this light, new technology that can provide more flexibility in network installation and user accessibility is continuously being researched. A WMN is one of the most interesting technologies to have emerged lately because its connections are totally wireless. Hence it is easy for a WMN to extend the service range and be flexible in implementation. In a WMN, nodes are comprised of mesh routers and mesh clients. Each node operates not only as a host but also as a router forwarding packets on behalf of other nodes that may not be within direct

[1] *School of Telecommunication Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand. Tel. 044-224392, Fax 044-224603, E-mail: su_sauram@hotmail.com*

* *Corresponding author*

wireless transmission range of their destinations. A WMN is dynamically self-organized and self-configured with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves. This feature brings many advantages to a WMN such as low up-front cost, easy network maintenance, robustness, and reliable coverage (Akyildiz *et al*., 2005). A WMN is a group of wireless nodes, connecting to each other by radio waves, so in fact there are some parameters such as distance and obstruction which can degrade radio waves from sending a signal to the target point, especially when sending information inside a building. Most houses or buildings have metals as a part of their construction which definitely corrupts system performances. Hence, due to indoor obstructions, the received signal in practice has to be obtained at a lower level than expected in theory. For distance concerns, the radio wave is attenuated as a function of distance no matter which propagation models are applied. Moreover, another impact on distance is dealing with the number of transit hops used for sending packets from source node to sink node. If the number of transit hops between origin and the destination nodes increases, the performances such as throughput and delay will be changed. In Gambiroza *et al*. (2004); Jun and Sichitiu (2003); Lee *et al*. (2008) have simulation results that show that throughput and end to end delay in a WMN are significantly changed by increasing hop-count distance from the gateway. In Gupta and Kumar (2000) presented the throughput analysis in a fixed wireless network; it indicates the direct relation of throughput and the number of nodes. In Gamal *et al*. (2004) have an analytical model developed to obtain the optimal throughput-delay trade-off by varying the number of hops, the transmission range, and the degree of node mobility in an ad hoc network. In Liu and Liao (2008) show the model of statistical location-dependent throughput and delay performances in a proposed WMN. The network considered is a static ad hoc network, in which nodes are randomly distributed and the destination for each node is independently chosen. In Grossglauser and Tse (2001) show that the per-node throughput is shown to be dramatically increased by exploiting node mobility as a type of multiuser diversity. In Gamal *et al*. (2004) an analytical model is developed to obtain the optimal throughput-delay tradeoff by varying the number of hops, the transmission range, and the degree of node mobility in ad hoc networks.

From all the literature, it can be noted that the performances of a WMN relay on the number of nodes and hops as well as their locations. However, those results are simulated by assuming the same link quality on each hop without considering the effect of an obstruction. This assumption cannot be true in practice because there are different physical obstructions from one node to another. For example in an indoor environment, there are many obstructions between nodes such as walls, partitions, humans, windows, etc. These objects must be a concern when analyzing the performance of a WMN. Here we study the effect of an obstruction on the performance of a WMN by considering the relation between signal strength and the success rate of information transfer. In theory, a WMN ideally determines the successful channel-access probability with a constant value equally for each node. This constant value is always the same no matter where the node has been installed. In this study, the indoor obstructions due to node locations are considered and the successful channel-access probability resulting from indoor obstructions is measured. By using measured results, this study is able to analyze system performances and also design the optimal node locations for an indoor WMN. The throughput and delay are key parameters to evaluate the best design.

WMN Analysis

WMN Configuration

The WMN architecture is the combination of infrastructure and client meshing as shown in Figure 1. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, and sensor networks, the routing capabilities of clients provide the improved connectivity and coverage inside the WMN. The infrastructure/ backbone of a WMN is illustrated in Figure 1. As seen in this figure, the network consists of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of the WMN. They provide network access for both mesh and conventional clients.

The integration of a WMN with other networks can be accomplished through the gateway and bridging functions in the mesh routers. Mesh clients can be either stationary or mobile, and can form a client mesh network among themselves and with mesh routers.

Queuing Theorem for WMN

In this study, the model of a WMN is analyzed by using the M/M/1/K queuing theorem (Gross and Harris,1998). The throughput is defined as the number of packets which can be transmitted from source to gateway. For end to end delay, it can be defined as the time between when the first bit of this packet is sent by its source and when the packet is entirely received by the gateway. The basic block diagram of M/M/1/K is shown in Figure 2.

Each node is associated with 2 queues which are Q_r for the relayed packets and Q_s for the locally generated packets. If Q_r is empty, it hops 1 packet from Q_s (which is assumed backlogged) to send. If Q_r is not empty, it sends a packet from Q_r with a probability of $q(x_1, x_2,..., x_l)$ or a packet from Q_s with a probability of $1 - q(x_1, x_2,..., x_l)$. We study the behavior of Q_r and Q_s and analyze the throughput and delay performances of each node.

Figure 3 presents the numeric method to name each node locaion. Unlike works presented in the literature, each node is required to have a specific numeric name because each node might experience a different channel property depending on indoor obstructions. $N(x_1, x_2,...,$

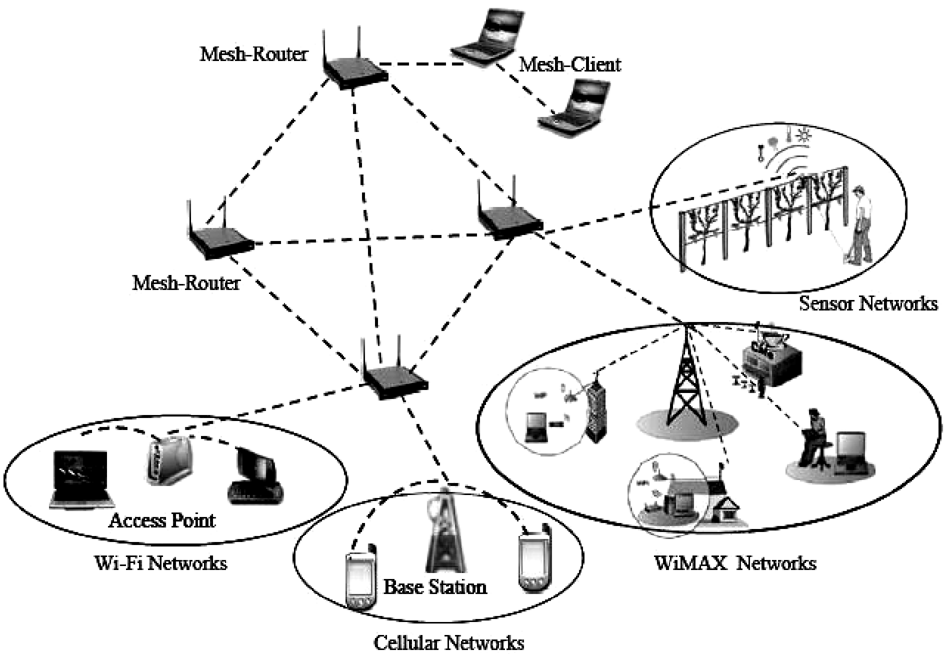

Figure 1. Infrastructure/backbone WMN.

x_l) denotes the number of nodes in ($x_1, x_2,..., x_l$)-hop. We let H denote the maximum possible hop-count distance from the gateway in the network.

From the derivation of an incoming packet presented by Liu and Liao (2008) the arrival rate of a packet can be expressed as

$$\mu(x_1, x_2, ..., x_l) \approx \frac{1}{t_c} \ln\left(\frac{1}{1 - p(x_1, x_2, ..., x_l)}\right) \quad (1)$$

where ($x_1, x_2,..., x_l$) is the hop number, t_c is the time slot of 1 packet, and $p(x_1, x_2,..., x_l)$ is the probability of successful channel access. For Q_r and Q_s at the ($x_1, x_2,..., x_l$)-hop node, the service rate of packets for either queue is equal to the product of $\mu(x_1, x_2,..., x_l)$ and the probability that the queue is selected to send. $\mu_r(x_1, x_2,..., x_l)$ is the service rate of packets for Q_r; the expression is given by

$$\mu_r(x_1, x_2, ..., x_l) = \mu(x_1, x_2, ..., x_l).q(x) \quad (2)$$

when Q_r is not empty the transmission opportunity will have a chance to come to Q_r. $Q_r(x_1, x_2,..., x_l)$ is the effective departure rate of relayed packets that are forwarded to the next hop node and can be expressed as

$$\sigma_r(x_1, x_2, ..., x_l) = \mu_r(x_1, x_2, ..., x_l).$$
$$[1 - P_0(x_1, x_2, ..., x_l)] \quad (3)$$

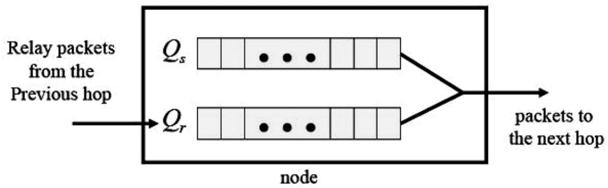

Figure 2. M/N/1K models in WMN

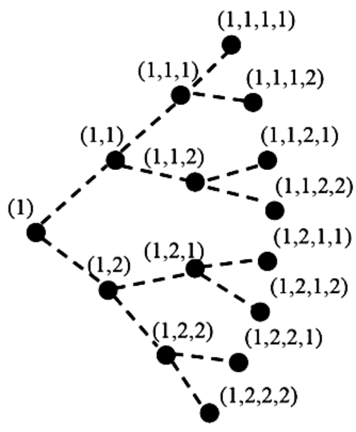

Figure 3. Example of numeric method naming node location

where $P_0(x_1, x_2,..., x_l)$ is the probability of having an empty queue in the M/M/1/K model. When Q_r is empty, the transmission opportunity is always granted to Q_s. Thus, $\mu_s(x_1, x_2,..., x_l)$ is the service rate of packets for Q_s at the $(x_1, x_2,..., x_l)$-hop node, and is calculated by

$$\mu_s(x_1,x_2,...,x_l) = \mu(x_1,x_2,...,x_l) - \sigma_r(x_1,x_2,...,x_l)$$
$$= \mu(x_1,x_2,...,x_l) - \mu(x_1,x_2,...,x_l).$$
$$q(x).\left[1 - P_0(x_1,x_2,...,x_l)\right] \quad (4)$$

Q_s for each node is assumed to be backlogged, so the output distribution of Q_s is identical to the service-time distribution of Q_s, $\sigma_s(x_1, x_2,..., x_l)$ is the effective output rate of Q_s at the $(x_1, x_2,..., x_l)$-hop node, so we have

$$\sigma_s(x_1,x_2,...,x_l) = \mu_s(x_1,x_2,...,x_l) \quad (5)$$

$\sigma(x_1, x_2,..., x_l)$ is the aggregate effective output rate for the $(x_1, x_2,..., x_l)$-hop node. From (3) and (4), it can be expressed as

$$\sigma(x_1,x_2,...,x_l)$$
$$= \sigma_s(x_1,x_2,...,x_l) + \sigma_r(x_1,x_2,...,x_l)$$
$$= \mu(x_1,x_2,...,x_l) \quad (6)$$

$\lambda_r(x_1, x_2,..., x_l)$ is the packet-arrival for Q_r at the $(x_1, x_2,..., x_l)$-hop. Note that Q_s assumed to be always backlogged. Where H is the total number of hops, it is calculated by

$$\lambda_r(x_1,x_2,...,x_l) = \begin{cases} \sum_{x_{l+1}=1}^{N(x_1,x_2,...,x_l)} \mu(x_1,x_2...,x_l,x_{l+1}) & \\ 0, & l = H \end{cases}$$

$$l = 1,2,...,H-1 \quad (7)$$

where $P_0(x_1, x_2,..., x_l)$ is the probability of Q_r being empty at the $(x_1, x_2,..., x_l)$-hop node. With the service and arrival rates of packets for Q_r at the $(x_1, x_2,..., x_l)$-hop node, we can obtain $P_0(x_1, x_2,..., x_l)$ by applying the M/M/1/K formulas (Gross and Harris, 1998), then

$$P_0(x_1,x_2,...,x_l) =$$

$$\begin{cases} \dfrac{1-\rho(x_1,x_2,...,x_l)}{1-\rho(x_1,x_2,...,x_l)^{K+1}} & ;\rho(x_1,x_2,...,x_l) \neq 1 \\ \dfrac{1}{K+1} & ;\rho(x_1,x_2,...,x_l) = 1 \end{cases} \quad (8)$$

where K is the buffer size of Q_r, $\rho(x_1, x_2,..., x_l)$ is the traffic intensity for Qr at the $(x_1, x_2,..., x_l)$-hop node, and is calculated by

$$\rho(x_1,x_2,...,x_l) =$$

$$\begin{cases} \sum_{x_{l+1}=1}^{N(x_1,x_2,...,x_l)} \dfrac{\mu(x_1,x_2,...,x_l,x_{l+1})}{\mu(x_1,x_2,...,x_l)q(x)} & l = 1,2,...,H-1 \\ 0, & l = H \end{cases} \quad (9)$$

Analysis of Throughput and Delay

Figure 4 shows the example of a physical obstruction between a node and a gateway. It is clearly seen that both links will not provide the same performance because the signal quality on each link is different. If we analyze both links using the proposed theory in the literature, both will provide the same throughput and delay. This is very misleading for the design of any gateway or node locations in practice. So far in the literature, this issue has never been considered. In this study, the parameter $p(x_1, x_2,..., x_l)$ is determined by the physical characteristic of the node location's signal strength. We now derive the end to end throughput by finding the blocking probability at each hop. $T(x_1, x_2,..., x_l)$ is the throughput of the $(x_1, x_2,..., x_l)$-hop node. $P_b(x_1, x_2,..., x_l)$ is the blocking probability for Q_r at the $(x_1, x_2,..., x_l)$-hop node. From the M/M/1/K formulas, we have

$$P_b(x_1, x_2, ..., x_l) =$$

$$\begin{cases} \dfrac{[1-\rho(x_1, x_2, ..., x_l)]\rho^K}{1-\rho(x_1, x_2, ..., x_l)^{K+1}} & ; \rho(x_1, x_2, ..., x_l) \neq 1 \\ \dfrac{1}{K+1} & ; \rho(x_1, x_2, ..., x_l) = 1 \end{cases} \quad (10)$$

where $\varrho(x_1, x_2,..., x_l)$ is given by (9). $1 - P_b(x_1, x_2,..., x_l)$ is the nonblocking probability for Q_r at the $(x_1, x_2,..., x_l)$-hop node. For a path, the end to end nonblocking probability is equal to the product of the nonblocking probabilities at all intermediate nodes. The throughput $T(x_1, x_2,..., x_l)$ is calculated by

$$T(x_1, x_2, ..., x_l) =$$

$$\begin{cases} \sigma_s(1), & l = 1 \\ \sigma_s(x_1, x_2, ..., x_l).\prod_{i=1}^{i=l-1}[1-P_b(i)], & l = 2, ..., H \end{cases} \quad (11)$$

where H is the total number of hops, $P_b(x_1, x_2,..., x_l)$ is the blocking probability of the M/M/1/K model, and $q(x_1, x_2,..., x_l)$ is the forwarding probability of the packet. We derive the end to end delay. $L_r(x_1, x_2,..., x_l)$ is the steady-state queue size of Q_r for the $(x_1, x_2,..., x_l)$-hop node. According to the M/M/1/K formulas, we have

$$L_r(x_1, x_2, ..., x_l) =$$

$$\begin{cases} \dfrac{\rho(x_1, x_2, ..., x_l)}{1-\rho(x_1, x_2, ..., x_l)} - \dfrac{\rho(x_1, x_2, ..., x_l)[K\rho(x_1, x_2, ..., x_l)]^K + 1}{1-\rho(x_1, x_2, ..., x_l)^{K+1}} \\ \qquad\qquad ; \rho(x_1, x_2, ..., x_l) \neq 1 \\ \dfrac{K(K-1)}{2(K+1)} \quad ; \rho(x_1, x_2, ..., x_l) = 1 \end{cases} \quad (12)$$

where $W_r(x_1, x_2,..., x_l)$ is the waiting time for packets in Q_r at the $(x_1, x_2,..., x_l)$-hop node. According to Little's formula (Gross and Harris, 1998), we have

$$W_r(x_1, x_2, ..., x_l) = \frac{1}{\mu(x_1, x_2, ..., x_l)q(x)} +$$

$$\frac{L_r(x_1, x_2, ..., x_l)}{N(x_1, x_2, ..., x_l)\mu(x+1)[1-P_b(x_1, x_2, ..., x_l)]} \quad (13)$$

For end to end delay, the expression is given by

$$D(x_1, x_2, ..., x_l) =$$

$$\begin{cases} t_c, & l = 1 \\ (x_1, x_2, ..., x_l).t_c + \sum_{i=1}^{i=l-1} W_r(i), & l = 2, 3, ..., H \end{cases} \quad (13)$$

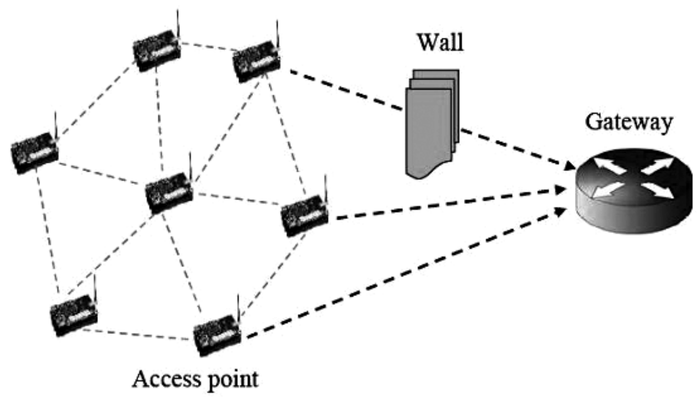

Figure 4. Example of physical obstructions between nodes to gateway

Note that t_c is the time slot for 1 packet, $L_r(x_1, x_2,..., x_l)$ is the steady state queue size of the M/M/1/K model, and $N(x_1, x_2,..., x_l)$ is the number of nodes in $(x_1, x_2,..., x_l)$-hop.

Effect of Indoor Obstructions on the Successful Channel-Access Probability

WMNs currently are standardized by the IEEE Standard 802.11s (IEEE, 1999; IEEE, 2003; IEEE, 2005; IEEE, 2008). It is comfortable to establish wireless networks with mobile wireless nodes, and infrastructure devices are used for routing. This provides higher flexibility and network coverage and decreases administration and infrastructure overheads. The IEEE Standard 802.11s can be support the IEEE Standard 802.11a/b/g/n. Most of these WMNs use the basic IEEE 802.11 (IEEE, 1999; IEEE, 2006). Therefore, in this work we used a WLAN network based on the IEEE 802.11a standard for measuring the effect of indoor obstructions. The key factor considered in measurements is the signal strength which affects the successful channel-access probability. The value of the successful channel-access probability can be captured at each node location. Figure 5 shows a layout of C-Building used for performing a signal strength measurement. The signal strength is monitored by using the freeware program named Wireless Mon. Successful channel-access probability can be indirectly measured by calculating a packet loss. If all packets can be transmitted to the destination, the successful channel-access probability is equal to 1. This study uses the freeware program named Wireshark to capture the loss of packet transmission.

In measurement scenarios, all 4 access points are tested on 3 days; in each access point there are 20 measuring spots and each spot will be repeated 3 times. Hence, the

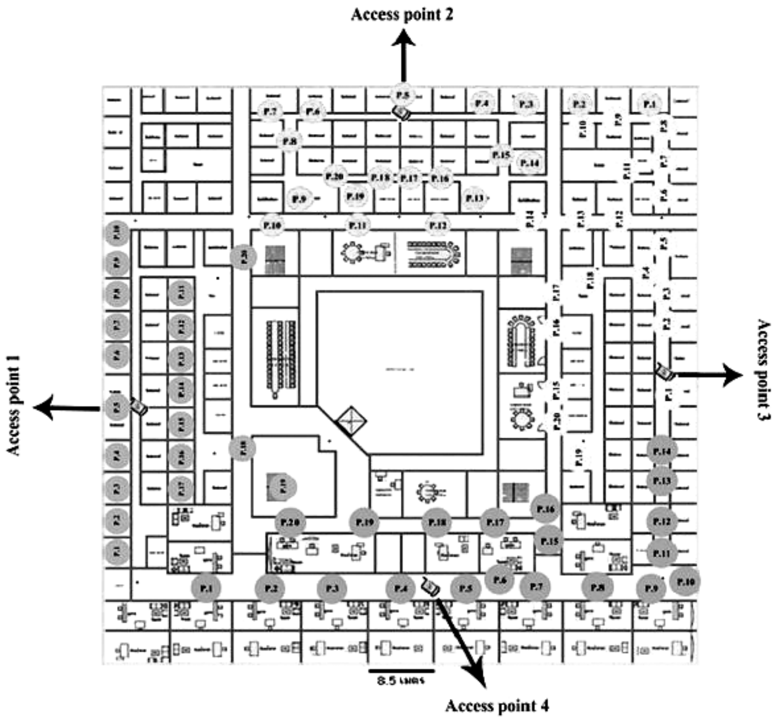

Figure 5. Map of measurement area

total number of measurements is 720. The measurement results are shown in Figure 6. It can be observed that the success of packet transmission depends on the level of the signal strength. If a high level of signal strength is received, then the chance for successful transmission is also high. The level of signal strength is influenced by both distance and obstructions. Therefore this measurement provides the direct relationship between node location and the successful channel-access probability which will be used to analyze throughput and delay in the WMN system. The successful channel-access probability $p(x_1, x_2,\ldots, x_l)$ is obtained by applying the relationship between packet loss and signal strength shown in Figure 6 along with the indoor path loss model. The level of received signal strength $P_r(x_1, x_2,\ldots, x_l)$ is expressed by

$$P_r(x_1,x_2,\ldots x_l) = P_t - 10\log\left(\frac{\lambda}{4\pi}\right) +$$

$$G_t + G_r - Loss - 20\log\left(\frac{d}{d_0}\right) \quad (15)$$

and the probability of successful channel access $p(x_1, x_2,\ldots, x_l)$ can be expressed as

$$A(x_1,x_2,..x_l) = 0.1840 * \exp$$

$$((-0.0358)(P_r(x_1,x_2,..x_l))$$

$$p(x_1,x_2,..x_l) = 1 - A(x_1,x_2,..x_l) \quad (16)$$

where P_t is the transmit signal power, P_t is set to 10 dBm, G_t is the antenna gain at the transmitter, G_r is the antenna gain at the receiver, d_0 is the distance between the transmitter and receiver, d_0 is set to 1 m, and Loss is the power attenuation due to obstructions. The authors did some measurements to realize the attenuation factors. In this work, the attenuation is determined by 6 dB per 1 wall because this value fits our experiments. For antenna gains, G_t and G_r are set to 2.2 dBi when the operating frequency is 2.45GHz.

Design of Node Locations

The site of the experimental area for designing the WMN node is C-Building the layout of which is shown in Figure 7. This building is a rectangular shape with dimensions of 76.5 x 80 mm^2. For the number of nodes it was decided to have only 4 mesh routers. This is because the existing infrastructure of the WLAN has only 4 access points. Hence, only

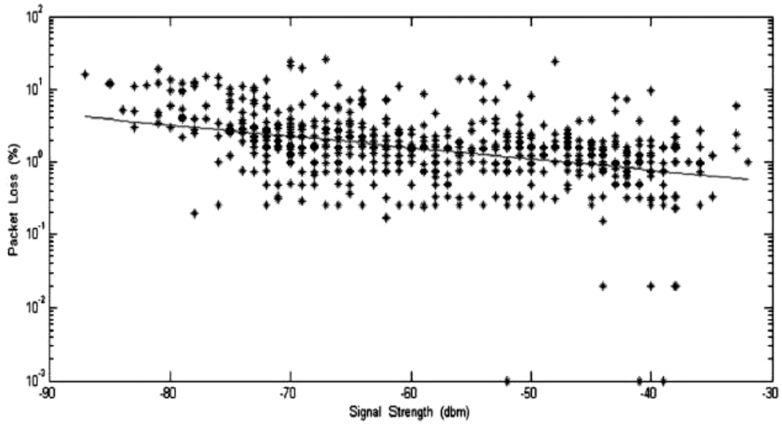

Figure 6. Relationship between packet loss and signal strength

4 nodes in the WMN are also enough for the same coverage area. The next task is to design where the nodes should be located. As seen in Figure 7, the mark points are the possible locations for either mesh routers or the gateway. In practice, it is not possible to determine the node locations for any spot of the building due to the constraint of power lines, available spaces, and construction materials. Hence, in this study, the method of designing node locations is to find the best set of node configurations from all possible installation locations. In this work, 2 groups of design are considered. The first group is based on only 1-hop nodes and the second group is based on 2-hop nodes.

For the first group, the configurations of the WMN are shown in Figure 8. There are 2 possible configurations named here as cases (a) and (b). Both cases have the gateway location at the center of the building. For the second group, there are 8 possible configurations named here as cases (c), (d), (e), (f), (g), (h), (i), and (j) which are configured as shown in

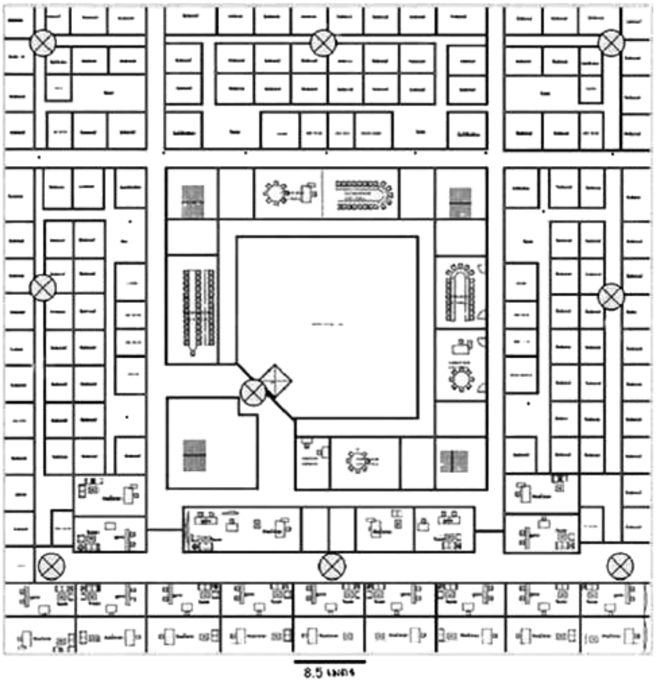

Figure 7. Layout of C-Building used for designing WMN node

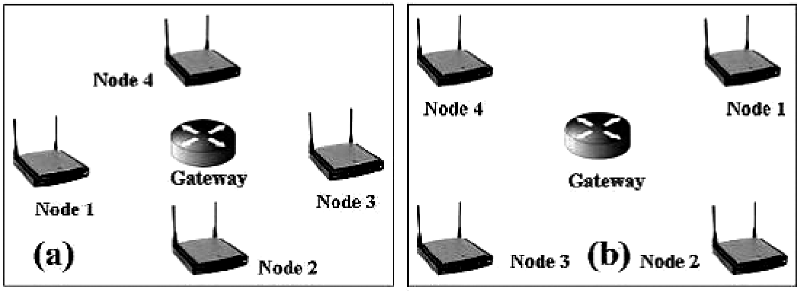

Figure 8. Configurations of WMN with 1 hop 4 nodes

Figure 9. These possible configurations are considered as possible spots as shown in Figure 7 and mesh routers can serve all the areas.

It can be noted that the throughputs and delays of cases (a) and (b) are the same if we analyze performance according to the work presented in the literature. This is because

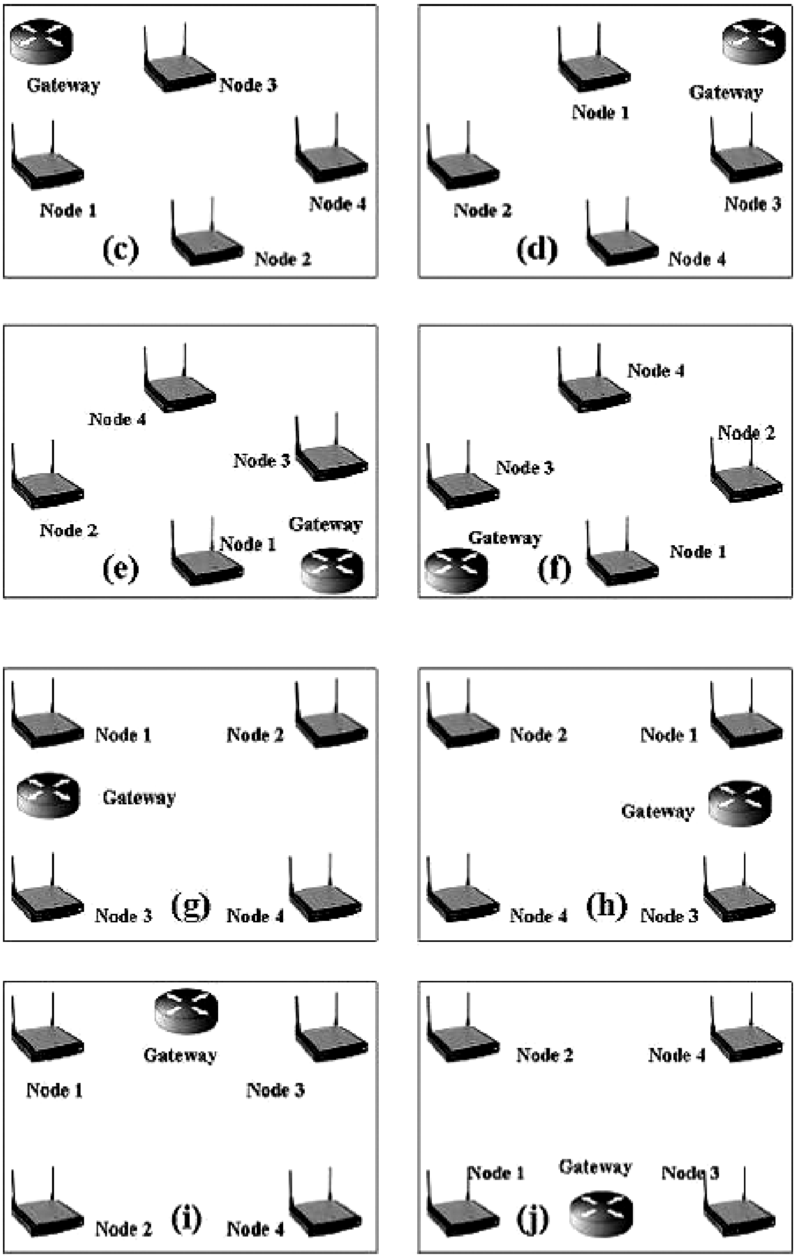

Figure 9. Configurations of WMN with 2 hops 2 nodes

they neglect the effect of indoor obstructions. Then the signal strength and $p(x_1, x_2,...,x_l)$ is assumed to be equal for each node. Also for cases (c) to (j), every configuration will theoretically provide the same throughputs and delays. In fact the performances of all cases should be different and they depend on their surroundings. The next task is to illustrate this issue and find out which case offers the best system performances.

Simulation Results

The TDMA-based system is applied in simulations in which each time slot is allocated to an $(x_1, x_2,...,x_l)$-hop node with probability $p(x_1, x_2,...,x_l)$. Thus, only 1 node is allowed to transmit within 1 time slot. All nodes operate on the same frequency channel. The data rate is 75 Mb/s with a packet size of 1500 bits. The time slot is set to the amount of airtime needed for transmitting 1 packet, i.e., 1500 B/ 75 Mb/s = 0.16 ms. The forwarding probability $q(x_1, x_2,...,x_l)$ is a setting of 0.6. The buffer size of M/M/1/K is fixed at 64 packets or K = 64.

Figures 10 and 11 show the average throughputs and delays of cases (a) and (b), respectively. We analyze the results by observing the variation of the successful channel-access probability $p(x_1, x_2,...,x_l)$ due to its physical obstruction, as illustrated in Figure 7.

The results are compared with the theoretical assumption when neglecting physical obstructions. It can be observed that the average throughputs and delays of cases (a) and (b) are totally different. This indicates the significant impact of physical obstructions on the WMN performances.

Figures 12 and 13 show the average throughputs and delays of cases (c), (d), (e), (f), (g), (h), (i), and (j), respectively. It is interesting to note that the throughputs and delays of each node are different when changing the location of the node and when considering a variation of the successful channel-access probability. The average throughputs and delays of the 10 cases are summarized in Table 1.

The first group is based on only 1 hop and it can be noted that the best WMN throughput can be achieved by the configuration of the WMN in case (a) and the best WMN delay is also obtained by case (a). For the second group based on 2 hops, it can be noted that the best WMN throughput can be achieved by the configuration of the WMN in case (f) and the best WMN delay is also obtained by case (f).

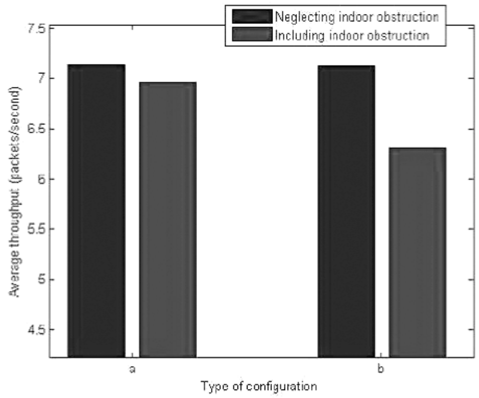

Figure 10. Average throughput per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 8.

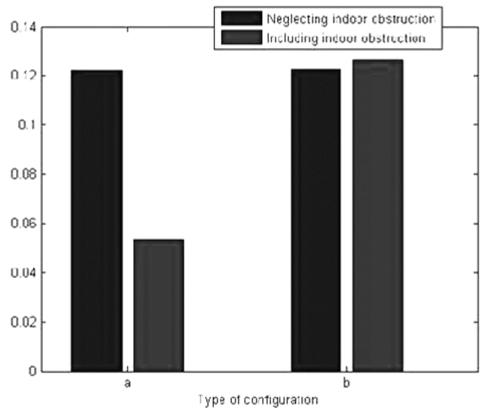

Figure 11. End-to-end delay per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 8.

These results are helpful for WMN researchers in designing the optimal locations of mesh routers and gateways by including the successful channel-access probability based on physical environments such as signal strength and distance.

Conclusions

In this study, the design of node locations for an indoor WMN is presented by including the effect of physical obstructions on performance of the WMN. From the theory of a WMN, the

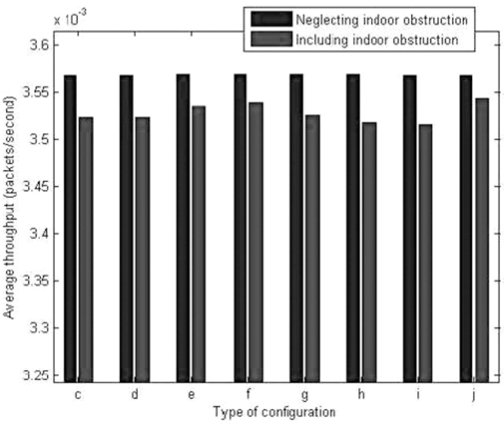

Figure 12. Average throughput per node for configuration of WMN with 2 hop 2 nodes illustrated in Figure 9.

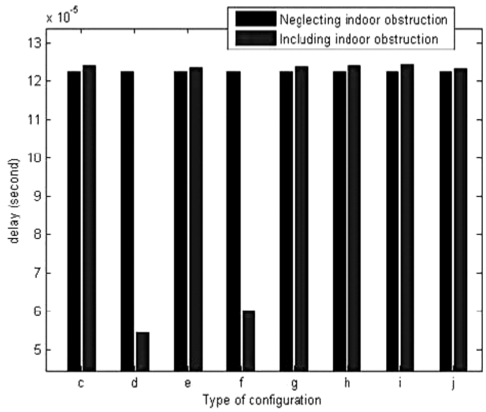

Figure 13. End-to-end delay per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 9.

Table 1. Aveage throughput and average end-to-end delay per node for WMN configured in Figure 8 and Figure 9.

Configuration	Average throughput (packet/second)	Average delay (second)
a	6.9640×10^{-3}	0.0536
b	6.0378×10^{-3}	0.1262
c	3.5227×10^{-3}	0.1240
d	3.5227×10^{-3}	0.0544
e	3.5323×10^{-3}	0.1235
f	3.5396×10^{-3}	0.0602
g	3.5252×10^{-3}	0.1239
h	3.5176×10^{-3}	0.1241
i	3.5154×10^{-3}	0.1242
j	3.5434×10^{-3}	0.1233

successful channel-access probability is invariable and equivalent. Every node location in the WMN system will have the same value of successful channel-access probability. In fact the value of successful channel-access probability is not constant when operating in a real environment. This study analyzes the WMN performances by taking the measured successful channel-access probability into account. Then the optimal node locations can be successfully designed. The results indicate that physical environments have a huge impact on the WMN performance.

Acknowledgment

This work is supported by a Research Grant from Suranaree University of Technology, Thailand.

References

Akyildiz, I.F., Wang, X., and Wang, W. (2005). Wireless mesh networks: A survey. Comput. Netw., 47(4):445-487.

Bansal, N. and Liu, Z. (2003). Capacity, delay and mobility in wireless ad-hoc networks. in Proc. IEEE INFOCOM., p. 1553–1563.

Gamal, A.E., Mammen, J., Prabhakar, B., and Shah, D. (2004). Throughput-delay trade-off in wireless networks. Proc. IEEE INFOCOM, p. 464–475.

Gambiroza, V., Sadeghi, B., and Knightly, E.W. (2004). End-to-end performance and fairness in multihop wireless backhaul networks. Proc. MOBICOM 2004, p. 287–301.

Gross, D. and Harris, C. (1998). Fundamentals of Queueing Theory. 3rd ed. Wiley, Hoboken, NJ, USA, p. 74–80.

Grossglauser, M. and Tse, D. (2001). Mobility increases the capacity of ad-hoc wireless networks. Proc. IEEE INFOCOM, p. 1360–1369.

Gupta, P. and Kumar, P.R. (2000). The capacity of wireless networks. IEEE Inform. Theory, 46(2):388–404.

IEEE. (1999). IEEE Standards. Interpretation for IEEE Standard 802.11. IEEE Standard for Local and metropolitan area networks. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

IEEE. (1999). IEEE Standards. Wireless LAN medium access control and physical layer specification, ANSI/IEEE Standard 802.11. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

IEEE. (2003). IEEE Standards. IEEE Standard for Local and Metropolitan Area Networks–Virtual Bridged Local Area Networks. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

IEEE. (2005). IEEE Standards. Task Group s. MAC Enhancement Proposal. Protocol Proposal IEEE 802.11-05/0575r3. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

IEEE. (2006). IEEE Standards. Draft amendment: ESS mesh networking. IEEE P802.11s Draft 1.00. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

IEEE. (2008). IEEE Standards. IEEE P802.11s/D2.0 – Draft STANDARD for Local and Metropolitan Area Networks–Specific Requirements–Amendment to Part 11: Mesh Networking.

Jun, J. and Sichitiu, M.L. (2003). Fairness and QoS in multihop wireless networks. Proc. IEEE VTC., p. 2936–2940. Institute of Electrical and Electronics Engineers, Inc., New York, NY, USA.

Lee, J.-F., Liao, W., and Chen, M.-C. (2008). An incentive-based fairness mechanism for multi-hop wireless backhaul networks with selfish nodes, IEEE T. Wirel. Commun., 7(2).

Liu, B., Liu, Z., and Towsley, D. (2003). On the capacity of hybrid wireless networks. Proc. IEEE INOCOM, p. 1543-1552.

Liu, T. and Liao, W. (2008). Location-dependent throughput and delay in wireless mesh networks. IEEE T. Veh. Technol., 57(2). virtual bridged lan.