

บรรณานุกรม

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ภาคผนวก

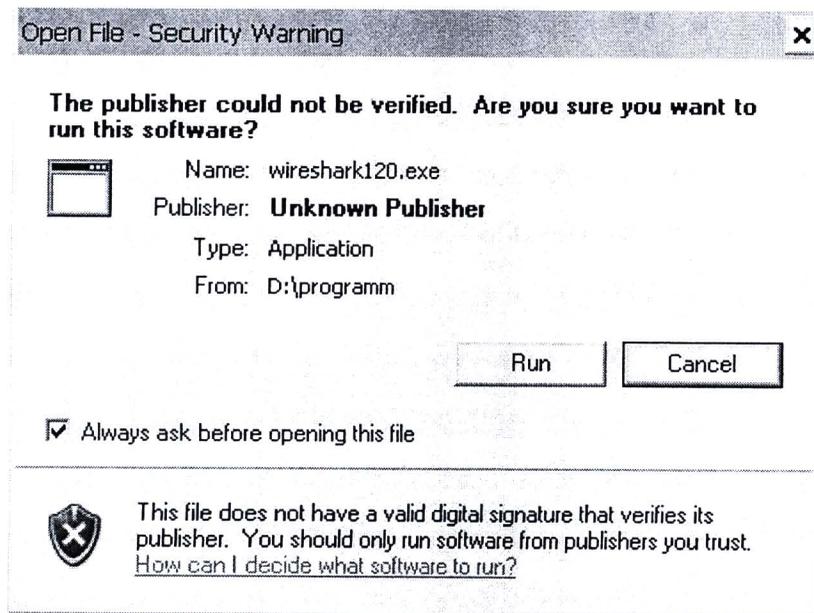
ภาคผนวก ก

การติดตั้งและใช้งานโปรแกรม Wireshark

ก.1 การติดตั้งโปรแกรม Wireshark

1. Double Click ที่ไอคอน  wireshark120.exe

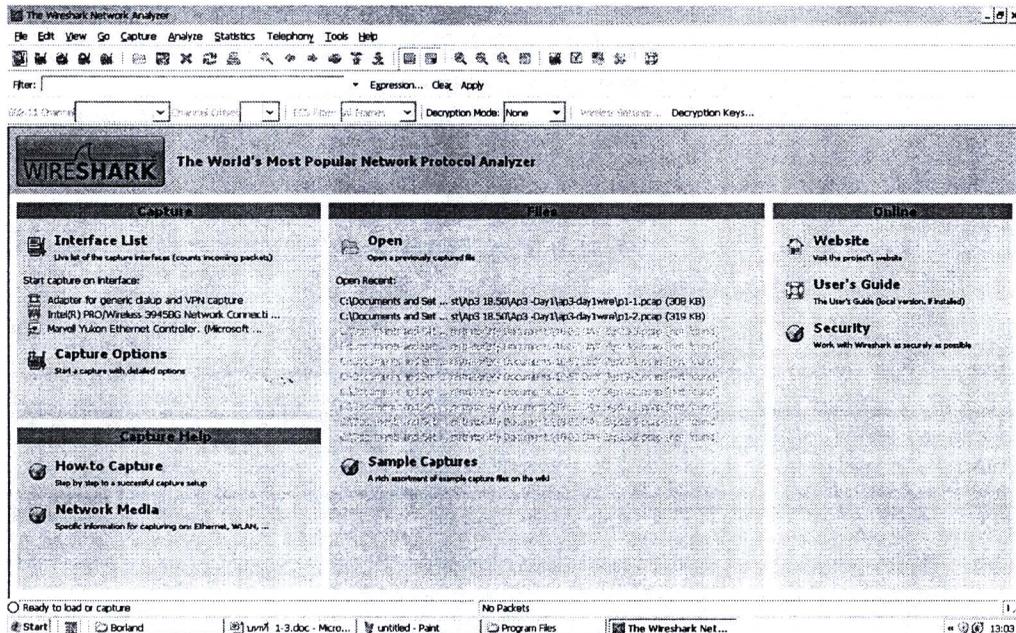
2. ปรากฏหน้าต่าง Setup – Wireshark ให้ Click ปุ่ม Run (ดังรูปที่ ก-1)
แล้วรอนกว่าจะติดตั้งโปรแกรมจนสำเร็จ



รูปที่ ก-1 หน้าต่าง Setup – Wireshark

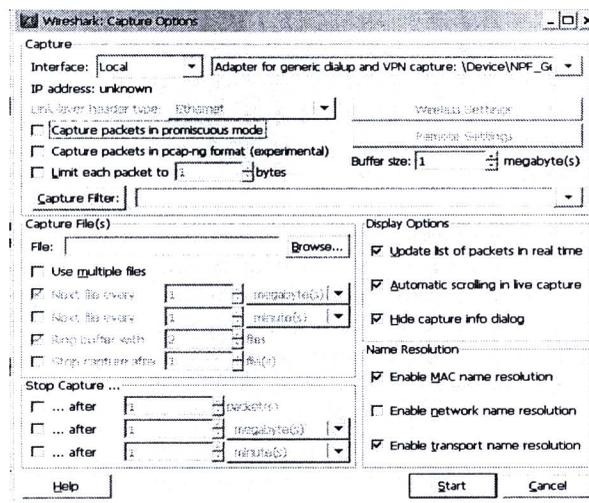
ก.2 ใช้งานและการทดสอบการจับ Packet ของ โปรแกรม Wireshark

1. Double Click ที่ไอคอน  จะปรากฏหน้าต่างของโปรแกรม



รูปที่ ก-2 หน้าต่างแรกของการใช้งาน Wireshark

- เลือก Capture => Option จะปรากฏหน้าต่างดังกล่าว แล้วทำการเลือก Click ที่บัตืกด Capture packet in promiscuous mode ออก ในส่วนของ Interface ให้เลือก การ์ดแลน ให้ตรงกับเครือข่าย จากนั้น Click Start



รูปที่ ก-3 หน้าต่างเลือกช่องทางในการดักจับข้อมูล



3. เมื่อ Click Start แล้ว จะปรากฏหน้าต่างแสดงการ Capture Packet ต่างๆ โดยในส่วนช่อง Filter ให้เลือกโปรโตคอลที่ต้องการจับ จากนั้น Click Apply ในที่นี้ทำการ Capture TCP Protocol

The screenshot shows the Wireshark interface with the following details:

- Filter:** tcp
- Packet List:**

No.	Time	Source	Destination	Protocol	Info
124	2009-08-13 13:22:10.713691	40.0.4.242	40.0.13.98	TCP	50161 > icslap [ACK] Seq=269 Ack=3824 win=17520 Len=0
125	2009-08-13 13:22:11.719443	40.0.4.242	40.0.13.98	TCP	50161 > icslap [ACK] Seq=269 Ack=3824 win=17520 Len=0
141	2009-08-13 13:22:11.474921	40.0.13.98	202.142.204.1	TCP	atc-lm > http-alt [ACK] Seq=1 Ack=1 win=3760 Len=0
143	2009-08-13 13:22:11.479517	202.142.204.1	40.0.13.98	HTTP	Continuation of non-HTTP traffic
144	2009-08-13 13:22:11.479896	202.142.204.1	40.0.13.98	HTTP	Continuation of non-HTTP traffic
145	2009-08-13 13:22:11.479938	40.0.13.98	202.142.204.1	TCP	atc-lm > http-alt [ACK] Seq=1 Ack=2921 win=17520 Len=0
146	2009-08-13 13:22:11.480124	202.142.204.1	40.0.13.98	HTTP	Continuation of non-HTTP traffic
- Packet Details (Frame 127):**
 - Ethernet II, Src: IntelCor_5c:4a:be (00:1b:77:5c:4a:be), Dst: IntelCor_97:9b:26 (00:13:02:97:9b:26)
 - Internet Protocol, Src: 40.0.4.242 (40.0.4.242), Dst: 40.0.13.98 (40.0.13.98)
 - Transmission Control Protocol, Src Port: 50161 (50161), Dst Port: icslap (2869), Seq: 269, Ack: 3824, Len: 0
- Packet Bytes:**

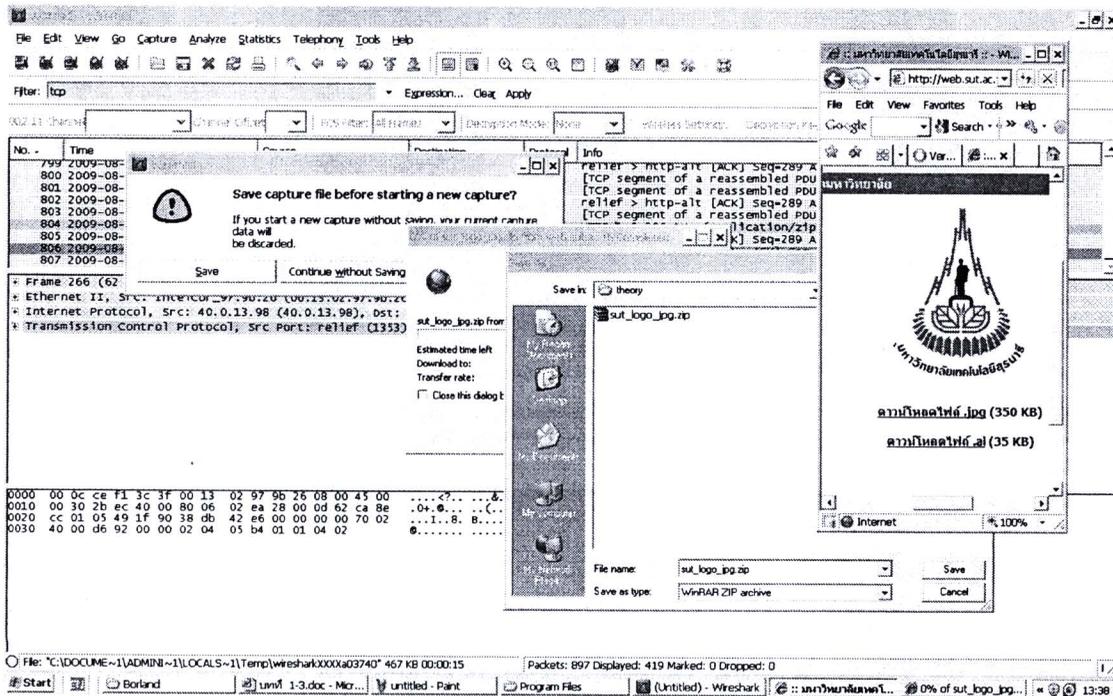
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0000 00 13 02 97 9b 26 00 1b 77 5c 4a be 08 00 45 00  ....&..wJ...E.
0010 00 28 28 0c 40 00 80 06 70 70 28 00 04 f2 28 00  .((.@...pp((...
0020 0d 62 c3 f1 0b 35 11 67 ae 0d 37 3c 0d 77 50 14  .b...5.g..7<.wp.
0030 00 00 7a 2e 00 00 00 00 00 00 00 00          .2.....

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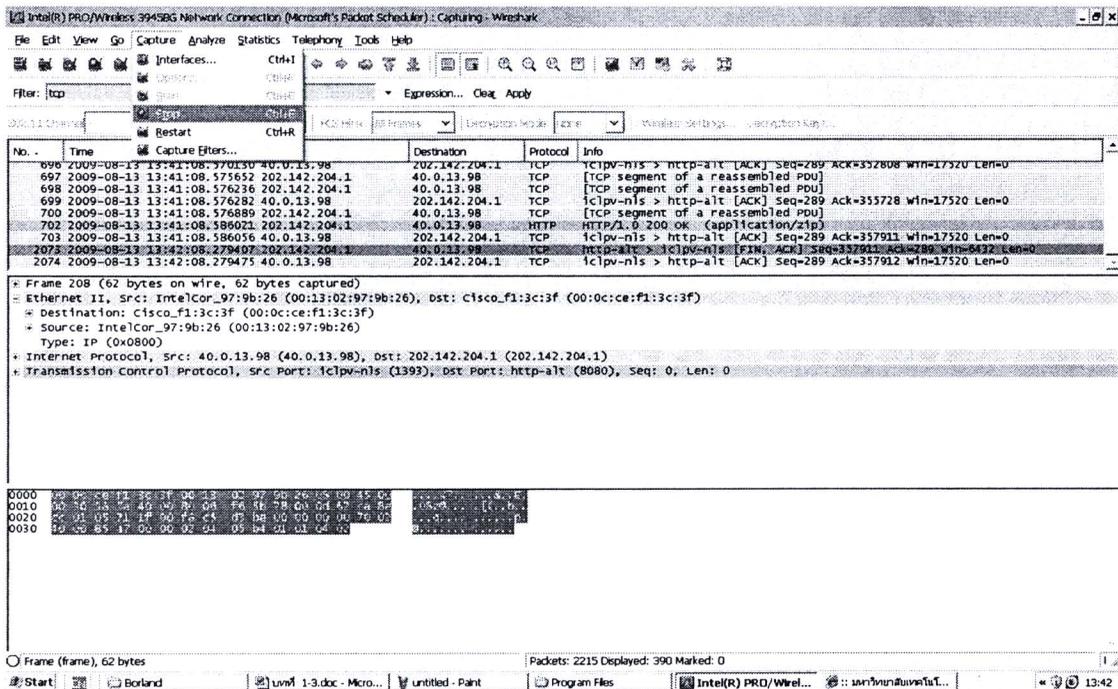
รูปที่ ก-4 หน้าต่างแสดงการสรุปข้อมูลที่ดักจับได้

4. ทำการดาวน์โหลดไฟล์ ที่ทำการจับ Packet ในขณะเดียวกัน ก็ทำการ capture packet พร้อมกันไป ด้วย Click Capture=> start จากนั้น click Continue without saving จะเริ่มทำการ Capture Packet จากไฟล์ที่ทำการดาวน์โหลด



รูปที่ ก-5 หน้าต่างแสดงการโหลดข้อมูลจาก Wireshark

5. จะปรากฏหน้าต่างแสดงรายละเอียดการ Capture Packet เมื่อทำการดาวน์โหลดและ Capture เสร็จแล้ว Click Stop แล้วทำการ SAVE ข้อมูล



รูปที่ ก-6 หน้าต่างแสดงรายละเอียดข้อมูลที่คักจับไว้

ภาคผนวก ข

การเผยแพร่ผลงานวิจัย

บทความวิจัยที่ได้รับการตีพิมพ์เผยแพร่ในวารสารวิชาการระดับชาติ

S. Sauram, P. Uthansakul, and M. Uthansakul, (2010) “**Design of node locations for indoor wireless mesh networks,**” Suranaree Journal of Science and Technology, Vol. 17, No. 3, pp. 211-223, 2010.

บทความวิจัยที่ได้รับการตีพิมพ์เผยแพร่ในงานประชุมวิชาการนานาชาติ

Saurum S., Uthansakul, P. and Uthansakul, M. (2009) “**Design of Gateway Locations in an Indoor WMN,**” ECTI-CON 2009, Thailand, pp. 1004-1007

ภาคผนวก ค

บทความวิจัยที่ได้รับการตีพิมพ์

DESIGN OF NODE LOCATIONS FOR INDOOR WIRELESS MESH NETWORKS

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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 light 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

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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 Sichertu (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 rely 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_1 for the relayed packets and Q_2 for the locally generated packets. If Q_1 is empty, it hops 1 packet from Q_2 (which is assumed backlogged) to send. If Q_2 is not empty, it sends a packet from Q_1 with a probability of $q(x_1, x_2, \dots, x_k)$ or a packet from Q_2 with a probability of $1 - q(x_1, x_2, \dots, x_k)$. We study the behavior of Q_1 and Q_2 , and analyze the throughput and delay performances of each node.

Figure 3 presents the numeric method to name each node location. 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, $N(x_1, x_2, \dots,$

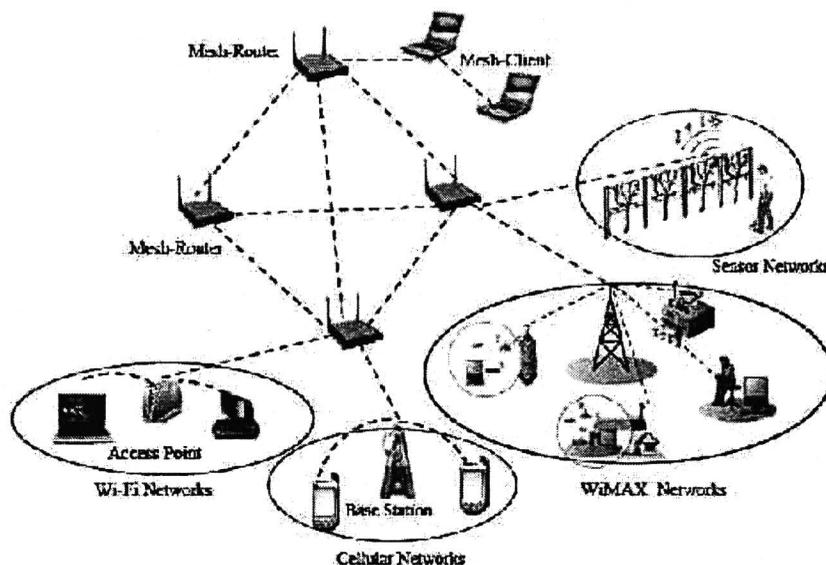


Figure 1. Infrastructure/backbone WMN.

x_i) denotes the number of nodes in (x_1, x_2, \dots, x_i) -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

$$\lambda(x_1, x_2, \dots, x_i) = \frac{1}{t_c} \ln \left(\frac{1}{1 - p(x_1, x_2, \dots, x_i)} \right) \quad (1)$$

where (x_1, x_2, \dots, x_i) is the hop number, t_c is the time slot of 1 packet, and $p(x_1, x_2, \dots, x_i)$ is the probability of successful channel access. For Q_r and Q_s at the (x_1, x_2, \dots, x_i) -hop node, the service rate of packets for either queue is equal to the product of $\mu(x_1, x_2, \dots, x_i)$ and

the probability that the queue is selected to send. $\mu(x_1, x_2, \dots, x_i)$ is the service rate of packets for Q_s ; the expression is given by

$$\mu_r(x_1, x_2, \dots, x_i) = \mu(x_1, x_2, \dots, x_i) \cdot \eta(x) \quad (2)$$

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

$$\eta_r(x_1, x_2, \dots, x_i) = \mu_r(x_1, x_2, \dots, x_i) \cdot [1 - P_0(x_1, x_2, \dots, x_i)] \quad (3)$$

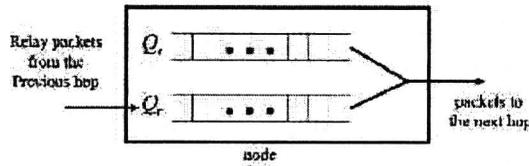


Figure 2. M/N/1K models in WMN

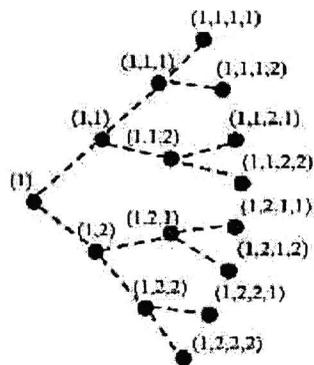


Figure 3. Example of numeric method naming node location

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

$$\begin{aligned} \mu_i(x_1, x_2, \dots, x_i) &= \mu(x_1, x_2, \dots, x_i) - \sigma_r(x_1, x_2, \dots, x_i) \\ &= \mu(x_1, x_2, \dots, x_i) - \mu(x_1, x_2, \dots, x_i) \\ & \quad \rho(x) [1 - P_0(x_1, x_2, \dots, x_i)] \end{aligned} \tag{4}$$

Q_i for each node is assumed to be backlogged, so the output distribution of Q_i is identical to the service-time distribution of Q_i . $\sigma_i(x_1, x_2, \dots, x_i)$ is the effective output rate of Q_i at the (x_1, x_2, \dots, x_i) -hop node; so we have

$$\sigma_r(x_1, x_2, \dots, x_i) = \mu_r(x_1, x_2, \dots, x_i) \tag{5}$$

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

$$\begin{aligned} & \sigma(x_1, x_2, \dots, x_i) \\ &= \sigma_r(x_1, x_2, \dots, x_i) + \sigma_r(x_1, x_2, \dots, x_i) \\ &= \mu(x_1, x_2, \dots, x_i) \end{aligned} \tag{6}$$

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

$$\lambda_i(x_1, x_2, \dots, x_i) = \begin{cases} \sum_{j=0}^{N(x_1, x_2, \dots, x_i)} \mu(x_1, x_2, \dots, x_i, x_{i+1}) \\ 0, & i = H \end{cases} \tag{7}$$

where $P_0(x_1, x_2, \dots, x_i)$ is the probability of Q_i being empty at the (x_1, x_2, \dots, x_i) -hop node.

With the service and arrival rates of packets for Q_i at the (x_1, x_2, \dots, x_i) -hop node, we can obtain $P_0(x_1, x_2, \dots, x_i)$ by applying the M/M/1/K formulas (Gross and Harris, 1998), then

$$P_0(x_1, x_2, \dots, x_i) = \begin{cases} \frac{1 - \rho(x_1, x_2, \dots, x_i)}{1 - \rho(x_1, x_2, \dots, x_i)^{K+1}} & \rho(x_1, x_2, \dots, x_i) \neq 1 \\ \frac{1}{K+1} & \rho(x_1, x_2, \dots, x_i) = 1 \end{cases} \tag{8}$$

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

$$\rho(x_1, x_2, \dots, x_i) = \begin{cases} \sum_{j=0}^{N(x_1, x_2, \dots, x_i)} \frac{\mu(x_1, x_2, \dots, x_i, x_{i+1})}{\mu(x_1, x_2, \dots, x_i)} \rho(x) & i = 1, 2, \dots, H-1 \\ 0, & i = H \end{cases} \tag{9}$$

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 $\rho(x_1, x_2, \dots, x_i)$ 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. $T(x_1, x_2, \dots, x_i)$ is the throughput of the (x_1, x_2, \dots, x_i) -hop node. $P_b(x_1, x_2, \dots, x_i)$ is the blocking probability for Q_i at the (x_1, x_2, \dots, x_i) -hop node. From the M/M/1/K formulas, we have

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

where $\rho(x_1, x_2, \dots, x_l)$ is given by (9). $1 - P_b(x_1, x_2, \dots, x_l)$ is the nonblocking probability for Q_i at the (x_1, x_2, \dots, 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 $\mathcal{N}(x_1, x_2, \dots, x_l)$ is calculated by

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

where H is the total number of hops. $P_b(x_1, x_2, \dots, x_l)$ is the blocking probability of the M/M/1/K model, and $q(x_1, x_2, \dots, x_l)$ is the forwarding probability of the packet. We derive the end to end delay, $L(x_1, x_2, \dots, x_l)$ is the steady-state queue size of Q_i for the

(x_1, x_2, \dots, x_l) -hop node. According to the M/M/1/K formulas, we have

$$L_i(x_1, x_2, \dots, x_l) = \begin{cases} \frac{\rho(x_1, x_2, \dots, x_l) \rho(x_1, x_2, \dots, x_l) [K - \rho(x_1, x_2, \dots, x_l)]^2 + 1}{1 - \rho(x_1, x_2, \dots, x_l)} & \rho(x_1, x_2, \dots, x_l) \neq 1 \\ \frac{K(K-1)}{2(K+1)} & \rho(x_1, x_2, \dots, x_l) = 1 \end{cases} \quad (12)$$

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

$$W_i(x_1, x_2, \dots, x_l) = \frac{1}{\mu(x_1, x_2, \dots, x_l) \rho(x)} + \frac{L_i(x_1, x_2, \dots, x_l)}{\mathcal{N}(x_1, x_2, \dots, x_l) \rho(x+1) [1 - P_b(x_1, x_2, \dots, x_l)]} \quad (13)$$

For end to end delay, the expression is given by:

$$D(x_1, x_2, \dots, x_l) = \begin{cases} t_s, & l=1 \\ t_s + \sum_{i=2}^{l-1} W_i(i), & l=2, 3, \dots, H \end{cases} \quad (13)$$

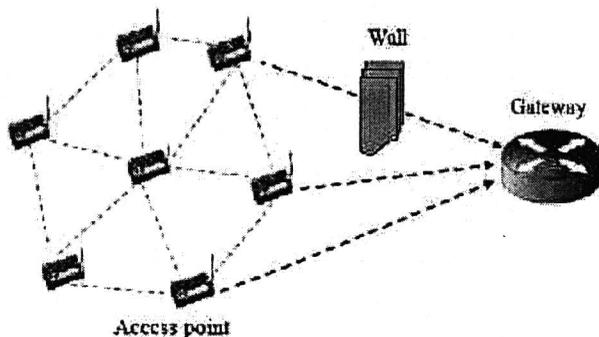


Figure 4. Example of physical obstructions between nodes to gateway

Note that t is the time slot for 1 packet, $L_s(x_1, x_2, \dots, x_i)$ is the steady state queue size of the M/M/1/K model, and $N(x_1, x_2, \dots, x_i)$ is the number of nodes in (x_1, x_2, \dots, x_i) -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 802.11n/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

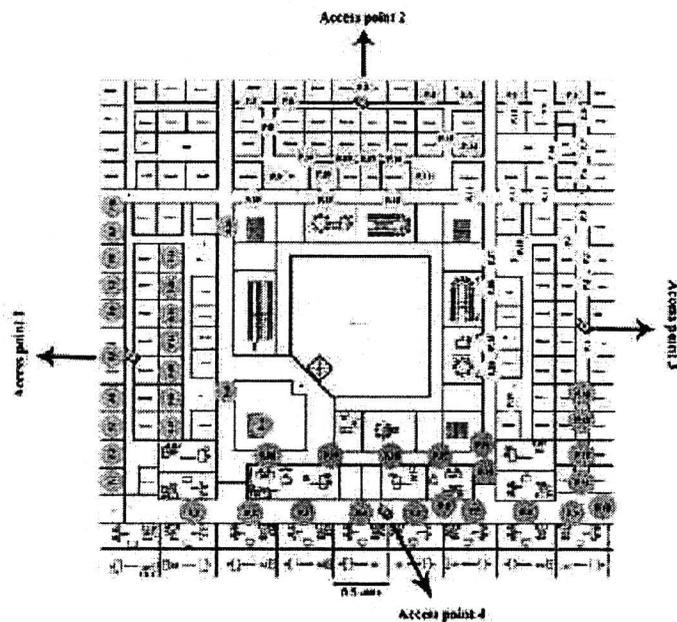


Figure 5. Map of measurement area

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 $p(x_1, x_2, \dots, x_i)$ 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 $P_r(x_1, x_2, \dots, x_i)$ is expressed by

$$P_r(x_1, x_2, \dots, x_i) = P_t - 10 \log \left(\frac{A}{4\pi} \right) + G_t + G_r - L_{obs} - 20 \log \left(\frac{d}{d_0} \right) \quad (15)$$

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

$$A(x_1, x_2, \dots, x_i) = 0.1840 * \exp((-0.0358) * P_r(x_1, x_2, \dots, x_i))$$

$$p(x_1, x_2, \dots, x_i) = 1 - A(x_1, x_2, \dots, x_i) \quad (16)$$

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 L_{obs} 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 mm². 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

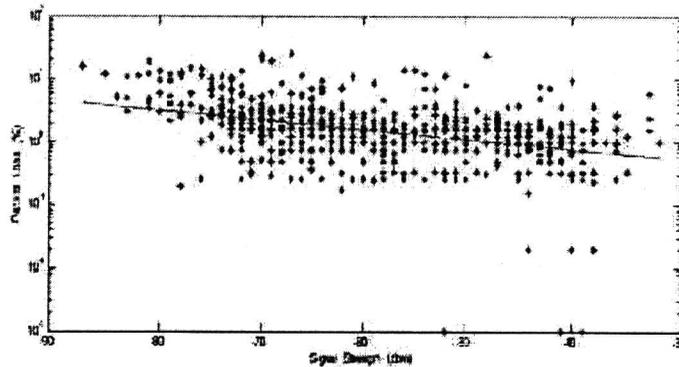


Figure 6. Relationship between packet loss and signal strength

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

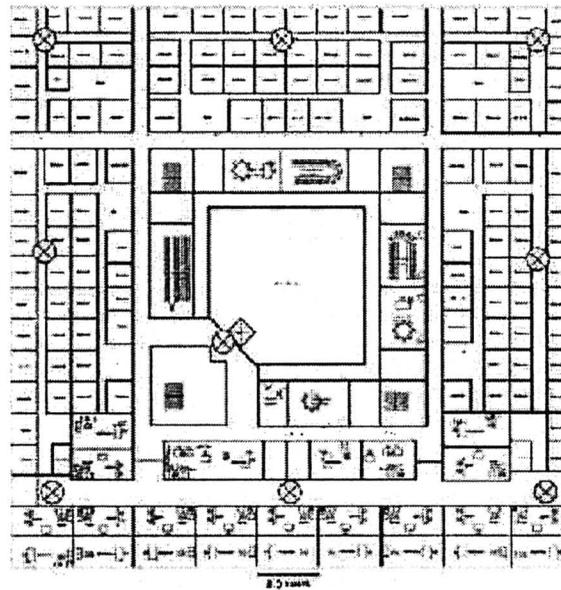


Figure 7. Layout of C-Building used for designing WMN node

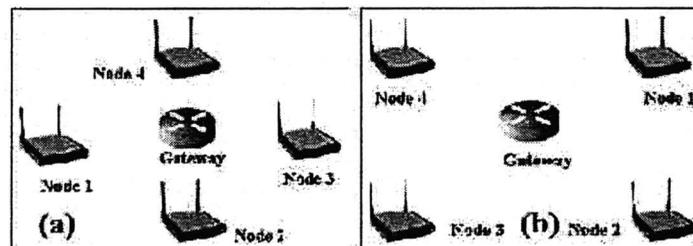


Figure 8. Configurations of WMN with 1 hop 4 nodes

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

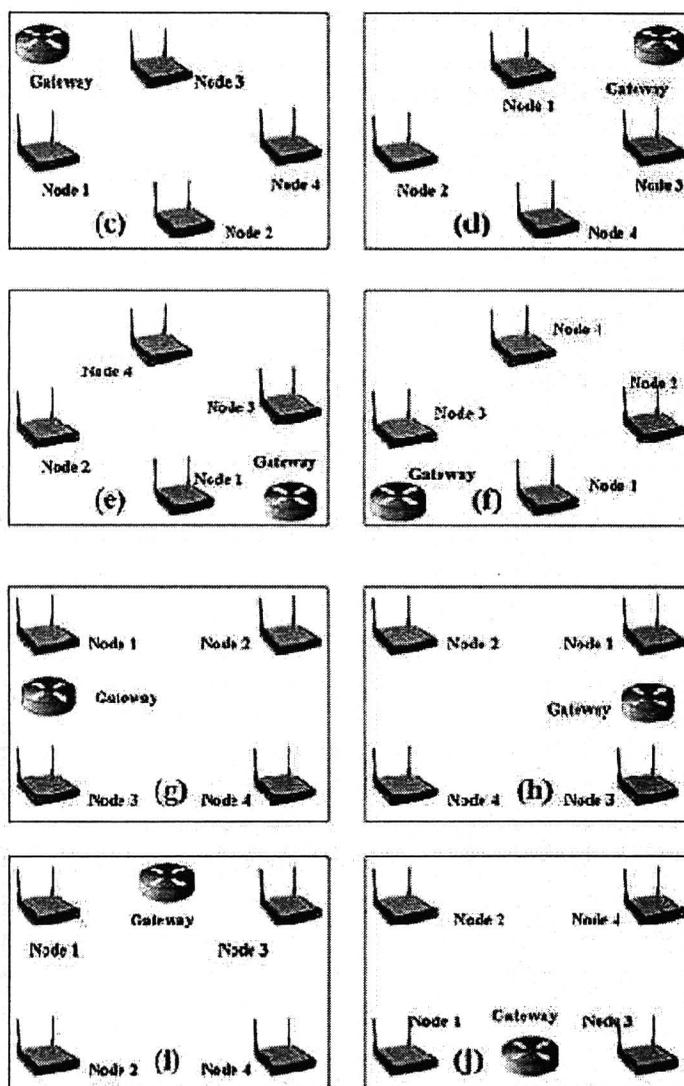


Figure 9. Configurations of WMN with 2 hops 2 nodes

they neglect the effect of indoor obstructions. Then the signal strength and $p(x_1, x_2, \dots, x_j)$ 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, \dots, x_j) -hop node with probability $p(x_1, x_2, \dots, x_j)$. 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., $1500 \text{ B} / 75 \text{ Mb/s} = 0.16 \text{ ms}$. The forwarding probability $q(x_1, x_2, \dots, x_j)$ 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 $p(x_1, x_2, \dots, x_j)$ 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).

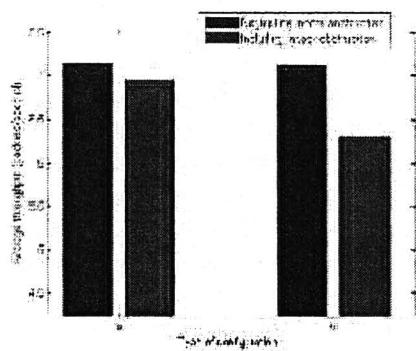


Figure 10. Average throughput per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 8.

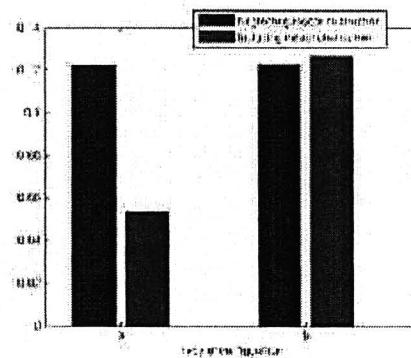


Figure 11. End-to-end delay per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 8.

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

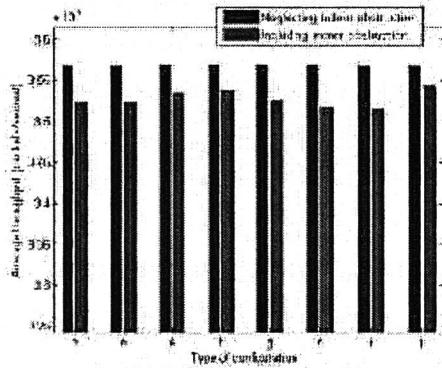


Figure 12. Average throughput per node for configuration of WMN with 2 hop 2 nodes illustrated in Figure 9.

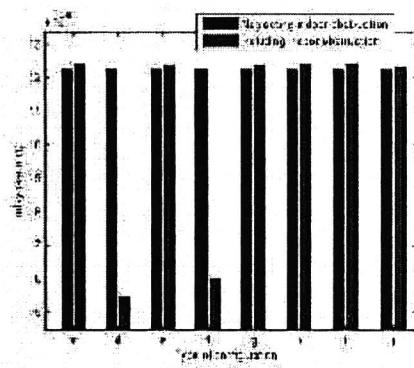


Figure 13. End-to-end delay per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 9.

Table 1. Average 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 $\cdot 10^3$	0.0536
b	6.0378 $\cdot 10^3$	0.1262
c	3.5227 $\cdot 10^3$	0.1240
d	3.5227 $\cdot 10^3$	0.0544
e	3.5323 $\cdot 10^3$	0.1235
f	3.5396 $\cdot 10^3$	0.0602
g	3.5252 $\cdot 10^3$	0.1239
h	3.5176 $\cdot 10^3$	0.1241
i	3.5154 $\cdot 10^3$	0.1242
j	3.5434 $\cdot 10^3$	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

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Design of Gateway Locations in an Indoor WMN

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Abstract—In literatures, the performance of Wireless Mesh Network (WMN) has been investigated through end to end delay and throughput by assuming the same quality on each hop. However, this assumption is hardly true in practice due to the physical obstructions in wireless link. In this paper, the design of gateway locations in an indoor scenario has been presented by taking a physical environment into account. The simulation results show that throughput and delay are significantly influenced by changing the location of gateway. This paper does not only provide a frame work for studying WMN performance but also gives an insight into the design strategy for WMN gateway.

I. INTRODUCTION

Recently, the wireless networks have evolved into many applications providing better services. In this light, a new technology that can provide more flexibility on network installation and user accessibility is continuously researched. Wireless Mesh Networks (WMN) is one of the most interesting technologies having been emerged lately because its connections are totally wireless. Hence it is easy for WMN to extend the service range and flexible to be implemented in practice. In 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 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 WMN such as low up-front cost, easy network maintenance, robustness, and reliable coverage.

In [2]-[4], the simulation results show that throughput and end-to-end delay in WMN are significantly changed by increasing hop-count distance from the gateway. In [5], the throughput analysis in a fixed wireless network is presented. It indicates the direct relation of throughput and number of nodes. In [6], the average throughput per node is shown to be dramatically increased by exploiting node mobility as a type of multiuser diversity. In [7], 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 network. In [8], the model of statistical location-dependent throughput and delay performances in WMN is proposed. From all literatures, it can be noticed that the performances of WMN are relied on number of nodes and hops as well as their locations. However, those results are simulated by assuming the same link quality on each hop. This

assumption cannot be true in practice because there is a different physical obstruction between on node to another. For example in an indoor environment, there are many obstructions between node to node such as wall, partition, human, window, etc. These objects are necessary to be concerned when analyze the performance of WMN.

In this paper, the performances of WMN in an indoor environment are investigated by taking the physical obstructions into account. Consequently, with this analysis, the proper location of gateway can be optimally designed. In addition, the simulations indicate that the gateway is not able to be located randomly otherwise the performance will be lower than theory design.

II. ANALYSIS OF WMN

A. WMN Configuration

The infrastructure/backbone WMN is illustrated in Figure 1. As seen in Figure, the network is consisted of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of WMN. They provide network access for both mesh and conventional clients. The integration of WMNs with other networks such as the Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks, etc. 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.

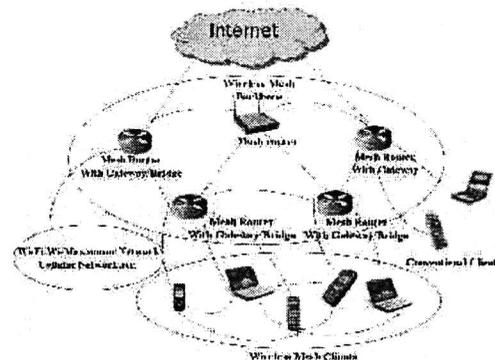


Figure 1. Infrastructure/backbone WMN.

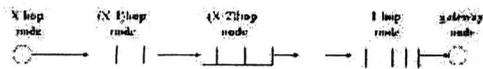


Figure 2. M/M/1/K models in WMN.

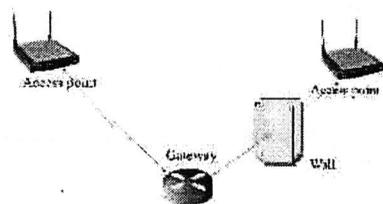


Figure 3. Example of physical obstructions between node to gateway.

B. Queuing theorem for WMN

In this paper, the model of WMN is analyzed by using M/M/1/K queuing theorem [10]. 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 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.

Form the derivation of incoming packet presented in [8]. The arrival rate of packet can be expressed as

$$\mu(x) = \frac{1}{t_c} \ln \frac{1}{1 - p(x)} \quad (1)$$

where x is the hop number, t_c is the time slot of one packet, $p(x)$ is the probability of successful channel access.

Figure 3 shows the example of physical obstruction between node to 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 proposed theory in literatures, both will provide the same throughput and delay. This is a big misleading to design any gateway or node locations in practice. So far in literatures, this issue has never been considered.

In this paper, the parameter $p(x)$ is determined by the physical characteristic of node location. The measurements in [9] provide the information of probability of successful transmission as a function of Signal to Noise Ratio (SNR). Therefore, this paper adopts the relation of $p(x)$ and SNR presented in [9] for taking the physical environments into account. After concerning $p(x)$, the throughput $T(x)$ is calculated by

$$T(x) = \begin{cases} \mu(1) - \mu(1)q(1)[1 - P_b(1)] & x=1 \\ \mu(x) - \mu(x)q(x)[1 - P_b(x)] \prod_{i=1}^{x-1} [1 - P_b(i)] & x=2, \dots, H \end{cases} \quad (2)$$

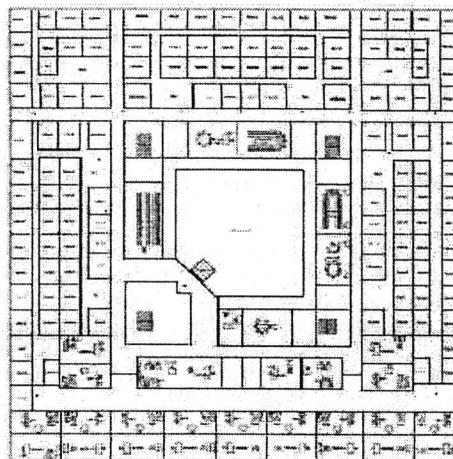


Figure 4. Layout of C-Building used for designing WMN gateway.

where H is the total number of hops, $P_b(x)$ denotes the blocking probability of M/M/1/K model, $P_e(x)$ denotes the probability of having empty queue in M/M/1/K model, $q(x)$ is the forwarding probability of packet.

For end to end delay, the expression is given by

$$D(x) = \begin{cases} \frac{1}{\mu(x)}, & x=1 \\ x t_c + \sum_{i=1}^{x-1} W_q(i), & x=2, 3, \dots, H \end{cases} \quad (3)$$

where

$$W_q(x) = \frac{1}{\mu(x)q(x)} + \frac{L_q(x)}{N_s(x)\mu(x+1)[1 - P_b(x)]}$$

Note that t_c is the time slot for one packet, $L_q(x)$ is the steady state queue size of M/M/1/K model, $N_s(x)$ is the number of nodes in x hop.

C. Indoor path loss model

To realize the parameter $p(x)$, it is necessary to know SNR. Hence, the task to get SNR can be achieved by calculating from received signal strength. The indoor path loss model has been used in this work and the expression of received signal strength P_r is expressed by

$$P_r = P_t - 10 \log \frac{\lambda}{4\pi} + G_t + G_r - Loss - 20 \log \frac{d}{d_0} \quad (4)$$

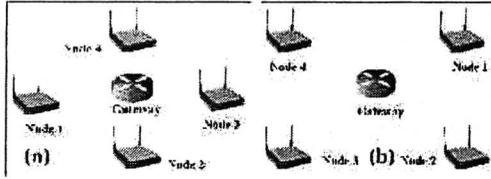


Figure 5. Configurations of WMN with 1 hop 4 nodes.

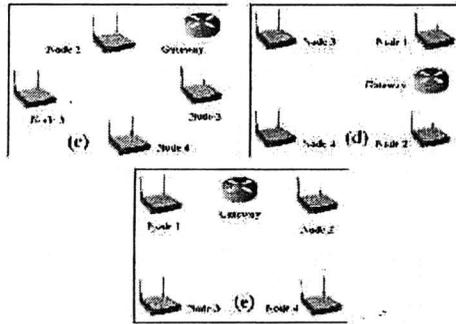


Figure 6. Configurations of WMN with 2 hops 2 nodes.

where P_t is the transmit signal power, G_t is the antenna gain at transmitter, G_r is the antenna gain at receiver, d is the distance between 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 one wall because this value is fit to our experiments. Also from our measurements, the power spectrum of noise floor in experimental area is around -70 dBm. Therefore, SNR can be calculated by $SNR = P_r + 70$. For antenna gains, G_t and G_r , is set to 2.2 dBi when the operating frequency is 2.45GHz.

III. GATEWAY DESIGN

The site of experimental area for designing WMN gateway is C-Building which its layout is shown in Figure 4. This building is a rectangular shape with dimension of 76.5x80 m^2 . The number of nodes is decided to four mesh routers. This is because the existing infrastructure WLAN has only four access point. Hence, only four nodes in WMN are also enough for keeping the same coverage area. The next task is to design where the gateway should be located. In this work, two groups of gateway design are considered. The first group is based on only one hop and the second group is based on two hops.

For the first group, the configurations of WMN are shown in Figure 5. There are two possible configurations as named here by case (a) and (b). In the second group, there are three

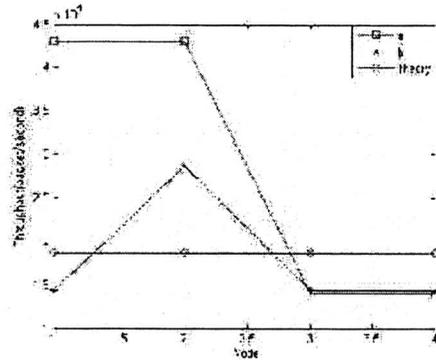


Figure 7. Throughput per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 5.

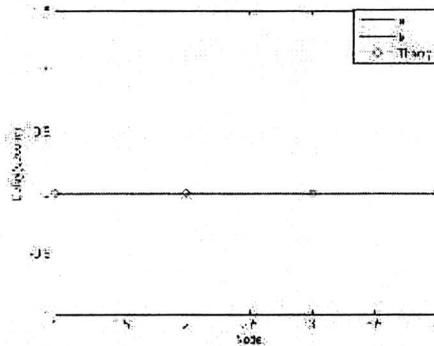


Figure 8. End to end delay per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 5.

possible configurations as named here by case (c), (d) and (e). For two hops, the first and second hops have 2 nodes which is configured as shown in Figure 6. All physical obstructions are simulated according to the wall on Figure 4.

It can be noted that the throughputs of case (a) and (b) are the same if neglecting the relation of SNR and $p(s)$. Also for case (c), (d) and (e), the same throughputs and delays are expected if following the theory in literatures.

IV. SIMULATION RESULTS

The TDMA-based system is applied in simulations in which each time slot is allocated to an x-hop node with probability $p(x)$. Thus, only one node is allowed to transmit within one time slot. All nodes operate on the same frequency channel. The data rate is 75 Mb/s with packet size of 1500 bits. The time slot is set to the amount of airtime needed for transmitting one packet, i.e., $1500 \text{ B} / 75 \text{ Mb/s} = 0.16 \text{ ms}$.

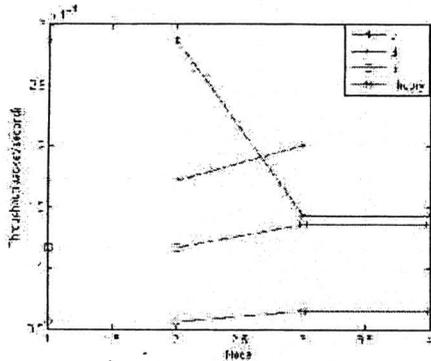


Figure 9. Throughput per node for configuration of WMN with 2 hops 2 nodes illustrated in Figure 6.

Table I. Average throughput and average end-to-end delay per node for WMN configured in Figure 5 and Figure 6.

Configuration	Average throughput (packet/second)	Average delay (second)
a	2.85×10^4	0.16×10^{-3}
b	1.79×10^4	0.16×10^{-3}
c	2.15×10^4	0.24×10^{-3}
d	1.87×10^4	1.03×10^{-3}
e	1.26×10^4	1.43×10^{-3}

The buffer size of M/M/1/K is fixed at 64 packets or $K = 64$. Figure 7 and 8 show the throughputs and delays of case (a) and (b), respectively. The results are compared with theory neglecting physical obstructions. The throughputs of case (a) and (b) are totally different from theory. This indicates the significant impact of physical obstructions on WMN performance. For delay, there is a constant delay for one hop design because every node is next to the gateway.

Figure 9 and 10 show the throughputs and delays of case (c) (d) and (e), respectively. It is interesting to notice that the throughput and delay of each node are different when changing the location of gateway. The average throughputs and delays of five cases are summarized in Table I. It can be noticed that the best WMN throughput can be achieved by the configuration of WMN in case (a) and the best WMN delay is obtained by case (c). This is because case (a) has the least hop and physical obstructions while case (c) has the most uniform pattern of $p(x)$. These results are helpful for WMN researchers to design the gateway location based on indoor environments.

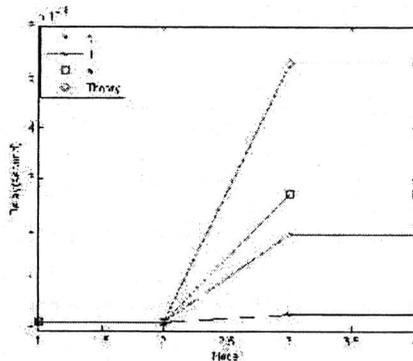


Figure 10. End-to-end delay per node for configuration of WMN with 2 hops 2 nodes illustrated in Figure 6.

V. CONCLUSION

In this paper, the design of gateway location in an indoor environment for WMN is presented. By applying the physical obstructions, the throughputs and delays of various configurations of WMN gateway locations are investigated. The results indicate that physical environments have a huge impact on WMN performance.

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ประวัติผู้วิจัย

ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล สำเร็จการศึกษาหลักสูตรวิศวกรรมศาสตรบัณฑิต และ วิศวกรรมศาสตรมหาบัณฑิตจากจุฬาลงกรณ์มหาวิทยาลัย เมื่อ พ.ศ. 2539 และ 2541 จากนั้นเข้าทำงานใน ตำแหน่งวิศวกรระบบโทรคมนาคมที่องค์การโทรศัพท์แห่งประเทศไทย จนกระทั่ง พ.ศ. 2543 จึงได้ย้ายมา เป็นอาจารย์ประจำสาขาวิชาวิศวกรรมโทรคมนาคม สำนักวิชาวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีสุรนารี และได้ลาศึกษาต่อระดับปริญญาเอกตั้งแต่ปี พ.ศ. 2546 ณ University of Queensland, Australia เมื่อ พ.ศ. 2549 จึงได้กลับเข้ามาปฏิบัติหน้าที่อาจารย์ตามเดิม ผู้วิจัยมีเชี่ยวชาญในด้านระบบ MIMO, Information Theory, Signal Processing, Radio Wave Modelling, Mobile Communication, Advance Wireless Communication ปัจจุบันมีบทความวิจัยตีพิมพ์เผยแพร่ในวารสารวิชาการ 21 บทความและในการประชุม วิชาการ 60 บทความ หนังสือวิชาการในประเทศ 1 เล่มและต่างประเทศ 1 เล่ม มีลิขสิทธิ์ 1 รายการและ สิทธิบัตร 1 รายการ

ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล ได้รับรางวัล Young Scientist Travel Grant Award จากงานประชุมวิชาการนานาชาติ International Symposium on Antenna Propagation ปี พ.ศ. 2547 ณ ประเทศญี่ปุ่น และได้รับรางวัล Best Student Presentation Award จากงานประชุมวิชาการนานาชาติ Australian Symposium on Antenna ปี พ.ศ. 2548 ณ ประเทศออสเตรเลีย ในปี พ.ศ. 2553 ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล ได้รับรางวัลพนักงานดีเด่น ด้านการวิจัย สำหรับนักวิจัยรุ่นใหม่ จากมหาวิทยาลัย เทคโนโลยีสุรนารี

