Design of Node Locations for Indoor Wireless Mesh Network

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ABSTRACT

In literatures, the performance of Wireless Mesh Network (WMN) has been analyzed by assuming the same quality for each hop. However, this assumption is hardly true in practice due to the physical obstructions of wireless link, especially for an indoor environment. Therefore, this paper revisits the analysis of 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 hop to hop. This paper examines these physical concerns through the measured results and then the design of node locations can be achieved. Moreover, it is well known that the analysis of throughput in WMN has indicated the impact of near-far mesh locations. However, these examinations have neglected the quantity of user accessibility. Therefore, this paper presents the effect of user accessibility in terms of traffic intensity on WMN throughput. The simulations provide a substantial remark to realize the effect of physical obstruction and traffic intensity on designing WMN node locations.

Keywords: Wireless Mesh Network, Throughput, Traffic Intensity.

1. INTRODUCTION

Wireless Mesh Networks (WMN) is a network technology without wires which will be happening in the near future. WMN has the same basic structure as WLAN. The different between WMN and WLAN is the meaning given to each part of equipment. The important thing is WMN has no router while WLAN does. This is because WMN includes access point together with router so called as mesh router. Users in WLAN have also renamed as mesh client in WMN. Because of combining access point and router, it makes WMN be a better tight system than WLAN. In addition, each access point in WLAN is connected by cable lines which limit the coverage range of operation. In this light, a new technology that can provide more flexibility on network installation and user accessibility is continuously researched. 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 [1].

WMN is a group of wireless nodes, connecting each other by radio wave, so in fact there are some certain parameters such as distance and obstruction which can degrade radio wave from sending signal to the target point, especially sending information inside the building. Most of houses or buildings have metals as a part of construction which definitely corrupts system performances. Hence, due to indoor obstructions, the received signal in practice has to be obtained at 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 destination nodes increases, the performances such as throughput and delay will be changed. In [2], the maximum throughput in a fixed wireless network is obtained. 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 [3], the average throughput per node is shown to be dramatically increased by exploiting node mobility as a type of multiuser diversity. In [4], 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 [5-6] have been reported for the throughput and delay performances in mul-

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tihop wireless networks. In [7-9], 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 [10], 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 without considering an effect of obstruction. 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. This paper studies effect of obstruction to performance of WMN by considering the relation between signal strength and success rate of information transfer. In theory, 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 node has been installed. In this paper, the indoor obstructions due to node locations are concerned and the successful channel-access probability resulting from indoor obstructions is measured. By using measured results, this paper is able to analyze system performances and also design the optimal node locations for indoor WMN. The throughput is key parameters to evaluate the best design and these works are undertaken by neglecting the influence from mesh clients. However, it is the fact that the greater the number of clients accessing to the same mesh routers, the greater the probability of congestions in transmission from or to other mesh routers. Hence, this paper studies the effect of user accessibility in term of traffic intensity on throughput of WMN. The formulations are revisited by including the new parameter of traffic intensity in each mesh router. Then the simulations reveal the impact of traffic intensity on dependency property of mesh locations.

The remainder of this paper is organized as follows. Section 2 grounds all basic knowledge to analyze WMN performances. The queuing theorem is implemented to evaluate the per-node throughput as functions of the hop count distance from the gateway. The static network consisting of N mesh nodes and one gateway is considered here. In Section 3, the effect of indoor obstructions on the successful channel-access probability is described in details. The measured results indicate the certain relation between signal strength and its probability. From theory of WMN the successful channel access probability is invariable and equivalent. Every node location in the WMN system will be assumed with the same value of successful channel-access probability. The results confirm that successful channel-access probability in theory of WMN system does not exist in what obtained in measurements. After that, the designs of node locations using measured results are discussed in Section 4 and their simulation results are given in Section 5. Finally, the main points of this work are concluded in Section 6.

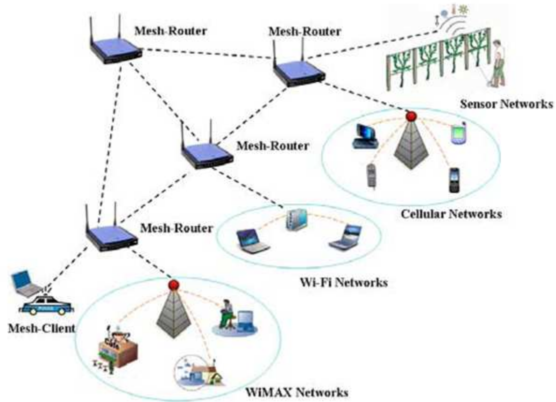

Fig.1: *Infrastructure/backbone WMN.*

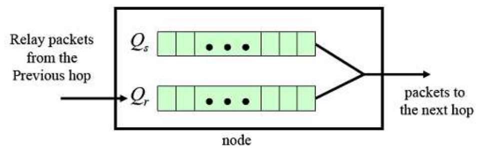

Fig.2: *M/M/1/K models in WMN.*

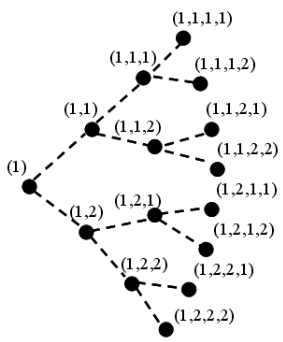

Fig.3: *Example of numeric method naming node location.*

2. WMN ANALYSIS

2.1 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 infrastruction/backbone WMN is illustrated in Figure 1. As seen in this 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 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.

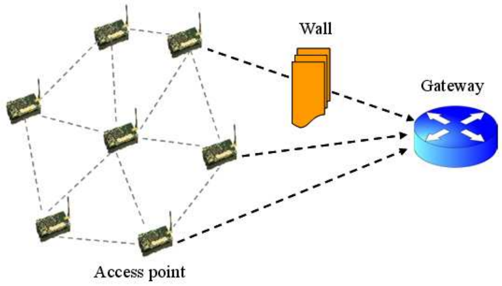

Fig.4: *Example of physical obstructions between nodes to gateway.*

2.2 Queuing theorem for WMN

Paragraph In this paper, the model of WMN networks is analyzed by using M/M/1/K queuing theorem [11]. The throughput is defined as the number of packets which can be transmitted from source to gateway. Figure 2. Each node is associated with two queues which are Q_r for the relayed packets and Q_s for the locally generated packets. If Q_r is empty, it pops one 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 $q(x_1, x_2, \ldots, x_l)$ or a packet from Q_s with a probability of $1 - q(x_1, x_2, \ldots, x_l)$.We study the behavior of Q_r and Q_s and analyze the throughput performances of each node.

Figure 3 presents the numeric method to name each node location. Unlike works presented in literatures, each node is required a specific numeric name because each node might experience a different channel property depending on indoor obstructions. $N(x_1, x_2, \ldots, x_l)$ denotes number of nodes in $(x_1, x_2, \ldots, x_l)$-hop. We let H denote the maximum possible hop-count distance from the gateway in the network.

From the derivation of incoming packet presented in [10], the arrival rate of packet can be expressed as

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

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

$$\begin{aligned} \mu_r(x_1, x_2, \ldots, x_l) &= \mu(x_1, x_2, \ldots, x_l).q(x_1, x_2, \ldots, x_l) \\ \mu_s(x_1, x_2, \ldots, x_l) &= \mu(x_1, x_2, \ldots, x_l).(1 - q(x_1, x_2, \ldots, x_l)) \end{aligned} \tag{2}$$

when Q_r is nonempty will the transmission opportunity have a chance to come to Q_r and $\sigma_r(x_1, x_2, \ldots, x_l)$ is the effective departure rate of relayed packets that are forwarded to the next hop node and the output distribution (i.e., the distribution of the time interval between two successive departures) of Q_s is identical to the service-time distribution of Q_s. In other words, the effective output rate of Q_s at the $(x_1, x_2, \ldots, x_l)$-hop node, which is denoted by $\sigma_s(x_1, x_2, \ldots, x_l)$ is equal to its service rate and can be expressed as

$$\begin{aligned} \sigma_r(x_1, x_2, \ldots, x_l) &= \mu_r(x_1, x_2, \ldots, x_l).[1 - P_{0r}(x_1, x_2, \ldots, x_l)] \\ \sigma_s(x_1, x_2, \ldots, x_l) &= \mu_s(x_1, x_2, \ldots, x_l).[1 - P_{0s}(x_1, x_2, \ldots, x_l)] \end{aligned} \tag{3}$$

where $P_{0r}(x_1, x_2, \ldots, x_l)$ and $P_{0s}(x_1, x_2, \ldots, x_l)$ is the probability of having empty queue in M/M/1/K model. $\lambda_r(x_1, x_2, \ldots, x_l)$ is the packet-arrival for Q_r and Q_s at the $(x_1, x_2, \ldots, x_l)$-hop ,where H is the total number of hops and ρ_s is the traffic intensity for Q_s and is calculated by

$$\begin{aligned} \lambda_r(x_1, x_2, \ldots, x_l) &= N_r(x_1, x_2, \ldots, x_l).\mu(x_1, x_2, \ldots, x_l).[1 - P_{0sum}(x+1)] \\ \lambda_s(x_1, x_2, \ldots, x_l) &= \rho_s(x_1, x_2, \ldots, x_l).\mu(x_1, x_2, \ldots, x_l).(1 - q(x_1, x_2, \ldots, x_l)) \end{aligned} \tag{4}$$

where $N_r(x_1, x_2, \ldots, x_l)$ is the expected number of $(x_1, x_2, \ldots, x_l)$-hop nodes for which each x-hop node has to relay when a is $(x_1, x_2, \ldots, x_l)$ and $P_{0sum}(x_1, x_2, \ldots, x_l)$ is the probability of Q_r and Q_s being empty at the $(x_1, x_2, \ldots, x_l)$-hop node. With the service and arrival rates of packets for Q_r and Q_s at the $(x_1, x_2, \ldots, x_l)$-hop node, which can be expressed as

$$P_{0sum}(a+1) = \begin{cases} \dfrac{1 - \rho_{sum}(a+1)}{1 - \rho_{sum}(a+1)^{K+1}} & ; \rho_{sum}(a+1) \neq 1 \\ \dfrac{1}{K+1} & ; \rho_{sum}(a+1) = 1 \end{cases} \tag{5}$$

where K is the buffer size of Q_r, ρ_{sum} $(x_1, x_2, \ldots, x_l)$ is the traffic intensity for Qr and Qs at the $(x_1, x_2, \ldots, x_l)$-hop node and is calculated by

$$\rho_{sum}(a+1) = \frac{[N_r(a+1).\mu(a+2)].[1-\rho_{0sum}(a+2)]+[\rho_s.\mu(a+1).(1-q(a+1))]}{\mu(a+1)} \qquad (6)$$

2.3 Analysis of Throughput

Figure 4 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. 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 $p(x_1, x_2, \ldots, x_l)$ is determined by the physical characteristic of node location is signal strength. We now derive the end-to-end throughput by finding the blocking probability at each hop. $T(x_1, x_2, \ldots, x_l)$ is the throughput of the $(x_1, x_2, \ldots, x_l)$-hop node. $P_{br}(x_1, x_2, \ldots, x_l)$ is the blocking probability for Q_r at the x-hop node. From the $M/M/1/K$ formulas, we have

$$P_{br}(x_1, x_2, \ldots, x_l) = \begin{cases} \dfrac{[1-\rho_r(x_1, x_2, \ldots, x_l)]\rho_r{}^K}{1-\rho_r(x_1, x_2, \ldots, x_l)^{K+1}} & ; \rho_r(x_1, x_2, \ldots, x_l) \neq 1 \\ \dfrac{1}{K+1} & ; \rho_r(x_1, x_2, \ldots, x_l) = 1 \end{cases} \qquad (7)$$

where $\rho_r(x_1, x_2, \ldots, x_l)$ is given by

$$\rho_r(x_1, x_2, \ldots, x_l) = \frac{\lambda_r(x_1, x_2, \ldots, x_l)}{\mu_r(x_1, x_2, \ldots, x_l)} = \frac{N_r(x_1, x_2, \ldots, x_l).\mu(a+1).[1-P_{0sum}(a+1)]}{\mu(x_1, x_2, \ldots, x_l).q(x_1, x_2, \ldots, x_l)} \qquad (8)$$

where $1 - P_{br}(x_1, x_2, \ldots, x_l)$ is the nonblocking probability for Q_r at the $(x_1, x_2, \ldots, x_l)$-hop node . For a path, the end-to-end nonblocking probability is equal to the product of the nonblocking probabilities at all intermediate nodes and the throughput $T(x_1, x_2, \ldots, x_l)$ is calculated by

$$T(x_1, x_2, \ldots, x_l) = \begin{cases} \sigma_s(1), & l = 1 \\ \sigma_s(x_1, x_2, \ldots, x_l).\prod_{i=1}^{i=l-1}[1-P_{br}(i)], & l = 2, \ldots, H \end{cases} \qquad (9)$$

where H is the total number of hops, $P_{br}(x_1, x_2, \ldots, x_l)$ is the blocking probabilityofM/M/1/K model.

3. EFFECT OF INDOOR OBSTRUTIONS ON THE SUCCESSFUL CHANNEL-ACCESS PROBABILITY

WMN currently are standardized by the IEEE 802.11s [12-15]. It is comfortable to establish wireless networks with mobile wireless nodes and infrastructure devices are used for routing. This provides

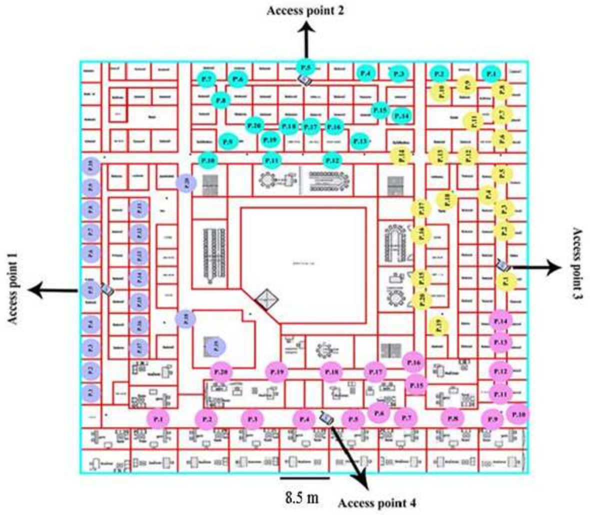

Fig.5: *Map of measurement area.*

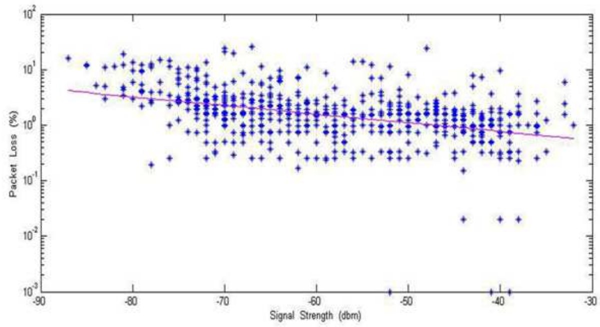

Fig.6: *: Show relationship between packet loss and signal strength.*

higher flexibility and network coverage and decreases administration and infrastructure overhead.

IEEE 802.11- based WMN and IEEE 802.11s a standard to support IEEE 802.11a/b/g/n. Most of these WMN use the basic IEEE 802.11[16-17] .Therefore, in this work we used WLAN network based on the IEEE 802.11a standard for measuring the effect of indoor obstructions. The key factor considered in measurements is a signal strength which affects the successful channel-access probability. The value of 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 freeware program named as WirelessMon. For successful channel-access probability, it 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 paper uses freeware program named Wireshark to capture the loss of packet transmission. In measurement scenarios, all 4 access points are tested in 3 days, in each access point the measuring points are 20 spots and each spot will be repeated 3 times. Hence, the total number of measurements is 720 times. The measurement results are shown in Figure 6. It can be observed that the successful of packet transmission depends on a level of signal strength. If the high level of signal strength is received, then the chance for successful transmission is also high. For level of signal strength, it 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 in 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 indoor path loss model. The expression of received signal strength $P_r(x_1, x_2, \ldots, x_l)$ is expressed by

$$P_r(x_1, x_2, \ldots, x_l) = P_t - 10\log\left(\frac{\lambda}{4\pi}\right) + G_t + G_r - Loss - 20\log\left(\frac{d}{d_0}\right) \tag{10}$$

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

$$\begin{aligned} \mathbf{A}(x_1, x_2, \ldots, x_l) &= 0.1840 * \exp((-0.0358)(P_r(x_1, x_2, \ldots, x_l)) \\ p(x_1, x_2, \ldots, x_l) &= 1 - A(x_1, x_2, \ldots, x_l) \end{aligned} \tag{11}$$

where P_t is the transmit signal power , P_t is set to 10 dBm, 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 [18] because this value is fit to our experiments. For antenna gains, G_t and G_r is set to 2.2 dBi [19] when the operating frequency is 2.4 GHz.

4. DESIGN OF NODE LOCATIONS

The site of experimental area for designing WMN node is C-Building which its layout is shown in Figure 7. This building is a rectangular shape with dimension of 76.5×80 m^2. The number of nodes is decided to be only four mesh routers. This is because the existing infrastructure WLAN has only four access points. Hence, only four nodes in WMN are also enough for keeping the same coverage area. The next task is to design where nodes should be located. As seen in Figure 7, the mark points are the possible locations for either mesh routers or gateway. In practice, it is not possible to determine node locations on any spot of buildings due to constraint of power lines, available spaces and construction materials. Hence, in this paper, the method to design node locations is to find the best set of node configurations from all possibly installable locations. In this work, two groups of design are considered. The first group is based on only one-hop nodes and the second group is based on two-hop nodes.

For the first group, the configurations of WMN are shown in Figure 8. There are two possible configurations as named here by case (a) and (b). Both cases have the gateway location at the center of building. For the second group, there are eight possible configurations as named here by case (c), (d), (e), (f), (g), (h), (i) and (j) which are configured as shown in Figure 9. These possible configurations are considered by possible spots shown in Figure 7 and mesh routers can serve all service areas.

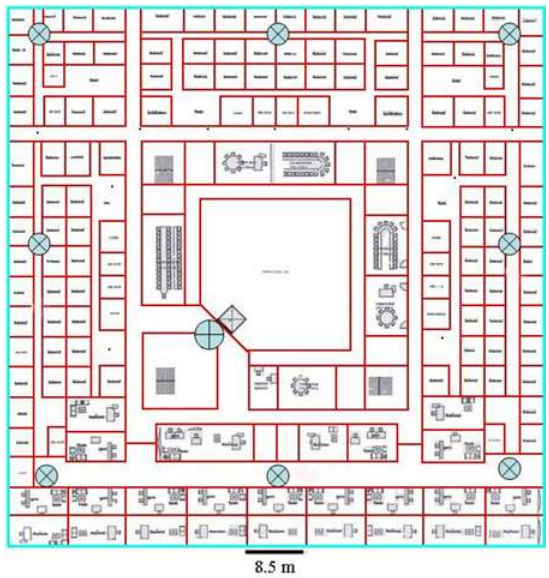

Fig.7: *Layout of C-Building used for designing WMN node.*

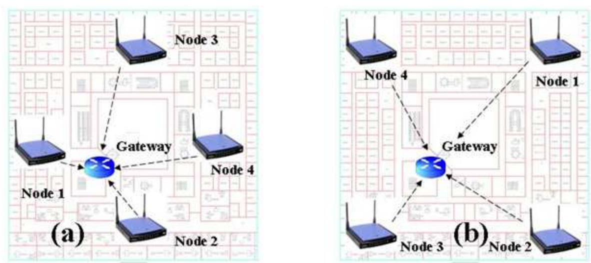

Fig.8: *Configurations of WMN with 1 hop 4 nodes.*

It can be noted that the throughputs of case (a) and (b) are the same if we analyze performance according to works presented in literatures. This is because they neglect the effect of indoor obstructions. Then the signal strength and $p(x_1, x_2, \ldots, x_l)$ is assumed to be equal for each node. Also for case (c) to (j), every configuration will theoretically provide the same throughputs. In fact the performances of all cases should be different and they depend on their surroundings. Next task is to illustrate this issue and find out which case offers the best system performances.

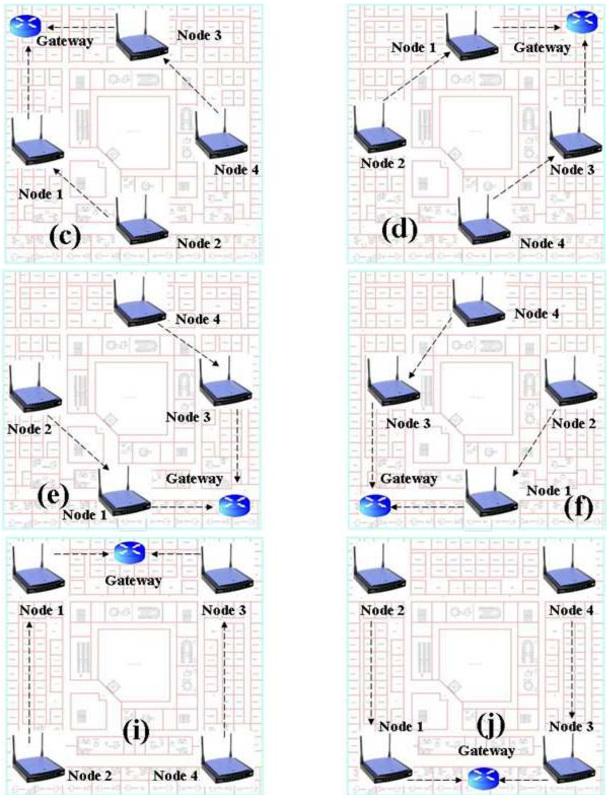

Fig.9: *Configurations of WMN with 2 hops 2 nodes.*

5. SIMULATION RESULTS

The TDMA-based system is applied in simulations in which each time slot is allocated to an $(x_1, x_2, \ldots, x_l)$-hop node with probability $p(x_1, x_2, \ldots, x_l)$. 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 B/75 Mb/s = 0.16 ms. The forwarding probability $q(x_1, x_2, \ldots, x_l)$is setting of 0.7 .The buffer size of M/M/1/K is fixed at 64 packets or K = 64.

Figure 10 show the average throughputs of case (a) and (b), respectively. We analyze results by observing variation of the successful channel-access probability $p(x_1, x_2, \ldots, x_l)$ due to its physical obstruction illustrated in Figure 7. The results are compared with theoretical assumption when neglecting physical obstructions. It can be observed that the average throughputs of case (a) and (b) are totally different. This indicates the significant impact of physical obstructions and the effect of traffic intensity on throughput on WMN performances.

Figure 11 show the average throughputs of case (c), (d), (e), (f), (g), (h), (i) and (j), respectively. It is interesting to notice that the throughputs of each node are different when changing the location of node and traffic intensity ρ_s at 0.25 and 0.95 and when considering a variation of successful channel-access probability. The first group is based on only one hop it can be noticed that the best WMN throughput can be achieved by the configuration of WMN in case (b). For the second group based on two hops, it can be noticed that the best WMN throughput can be achieved by the configuration of WMN in case (g). These results are helpful for WMN researchers to design the optimal locations of mesh routers and gateway by including the successful channel-access probability based on physical environments such as signal strength and distance etc.

In figure 10 and figure 11, it can be observed that low traffic intensity provides a similar throughput for any hops while high traffic intensity degrades throughput as a function of distance. For high traffic

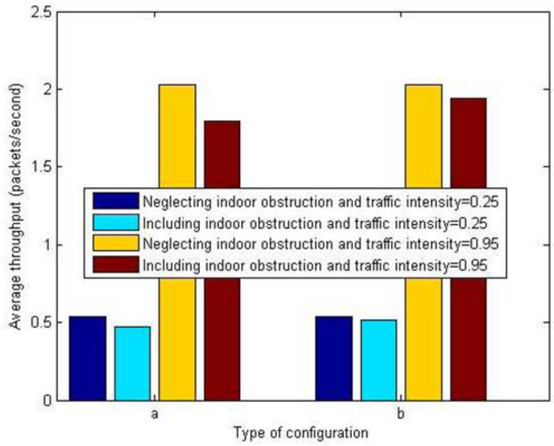

Fig.10: *Average throughput per node for configuration of WMN with 1 hop 4 nodes illustrated in Figure 8 when traffic intensity ρs at 0.25 and 0.95.*

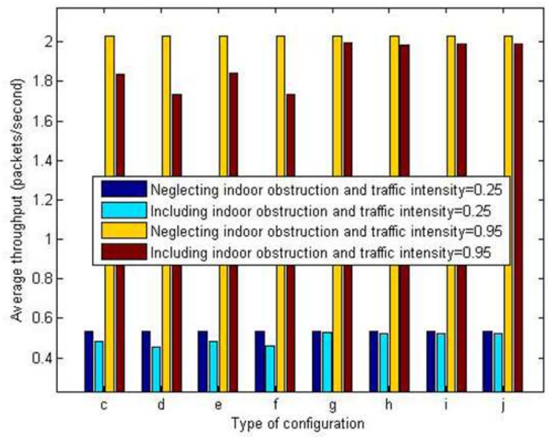

Fig.11: *Average throughput per node for configuration of WMN with 2 hops 2 nodes illustrated in Figure 9 when traffic intensity ρ_s at 0.25 and 0.95.*

intensity, this conclusion is the same as described in literature [10] but for low traffic intensity there is no impact of location dependency on throughput. This is important to aware the effect of user capacity on network planning purpose.

6. CONCLUSION

In this paper, the design of node locations for indoor WMN is presented by including the effect of physical obstruction on performance of WMN. From theory of WMN, the 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 as operating in a real environment. This paper analyzes WMN performances by taking a 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 WMN performance. Furthermore, it can be concluded that low traffic intensity provides a location-independent throughput while high traffic intensity degrades throughput as a function of distance.

7. ACKNOWLEDGMENT

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