A Group of People Acts like a Black Body in a Wireless Mesh Network[1]

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***Abstract*—A Wireless Mesh Network (WMN) is being considered for commercial use in spite of several unaddressed issues. In this paper we focus on one of the most critical issues: the impact of ambient motion of entities like people on the channel characteristics and on the WMN performance. A human body in an Electro-Magnetic (EM) field acts as an scatterer that absorbs 60% of incident EM energy, thereby shadowing the receiver. This human body model along with the human mobility behavior gives rise to a black body (a group movement) effect that traps the incident EM wave with repetitive internal reflections. The black body theory is verified by simulating the WiSEMesh testbed in picoKAIST, a tool based on deterministic ray tube method. Experimental results show each link exhibiting a unique channel variation pattern in presence of the black body. Based on the pattern we provide several insights in WMN deployment and protocol design.**

***Index Terms*—Wireless mesh network, human mobility, interference, performance.**

I. Introduction

Wireless Mesh Networks (WMNs) have emerged as a key technology for next-generation wireless access network. Because of their advantages over other wireless networks, WMNs are undergoing rapid progress and inspiring numerous applications. However, many technical issues still exist in this field. A comprehensive WMN survey [1] addresses channel characteristics as a key factor in determining the performance of the WMNs. A WMN is a multi-hop wireless infrastructure where channels between Wireless Routers (WRs) dictate overall performance of the network. These links between WRs are the backbone of the WMN and are crucial to optimum performance.

Few interest has been given to the WMN channel performance till now. A performance measurement of the MIT RoofNet [2] characterizes outdoor channel conditions. But a WMN is not limited to an outdoor broadband wireless network solution. Due to its economic benefits and deployment ease, the WMN is becoming an alternative networking solution to Ethernet and WLAN in big complexes such as malls and business houses. This paper characterizes indoor channel conditions as a function of human shadowing, human movement and WR placement inside the building. Our work has major contributions in the field of WMN planning and organization, and routing management issues.

We modeled a human body whose height and size are based on an average Korean male [12]. The theoretical Electro-Magnetic (EM) interaction model between the human body and EM waves showed 60% of the EM wave incident on the human body is absorbed. We further couple the model with human mobility behavior seen in typical high population density locations such as shopping centers, railway stations, large offices etc. Human mobility behavior shows a tendency of pedestrians walking in a group or individually based on time of the day. A group of pedestrians absorbs EM waves to an extent that a negligible or no wave escapes the cluster of people. We term such a group as a *black body*; as in physics, a black body is an object that absorbs all electromagnetic radiation that falls onto it. The black body can be characterized by the size of the group and nature of the walk that are dependent on human factors such as cultural aspects, office time table etc.

The network performance degradation due to the black body effect is a function of physical location of the source and the destination WRs. The performance of the link connecting WRs that are separated by multiple floors with no Line of Sight (LOS) but less human body movement in between the WRs shows 50% higher average throughput than those links with more human movement. The signal power received by a receiver from a transmitter located in the same floor shows attenuation due to human movement in no LOS cases.

Human body interaction with an EM wave is a well known field of research in Bio-electronics, Dosimetry. In the last decade, human body shadowing caught interest for wireless solutions such as 802.11a/b/g. Since then there have been a couple of remarkable studies that focused on pico cells in an LOS area. Recently Kara et al. in their paper [3] have shown human body effect on links within a room filled with office furniture. They measured fading as a function of polarization and obscurity of the LOS within a room. In [4], they modeled a body-shadow that exhibit scattering, diffraction, reflection and penetration losses. The body-shadow model is integrated with

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a ray-determination method. The results obtained are based on LOS path loss in presence of human body. The body shadow model used in [5] is similar to [4] with results focused on fading profiles in a LOS environment. In [6], a three knife-edge diffracted body shadow model is used. The results obtained are based on Access Point (AP) and client architecture in an LOS environment.

In this paper, we combine human behavior with human body model to represent a black body. We use a ray-tracing simulator called picoKAIST that is based on uniform geometrical theory of diffraction (UTD) [7] to model our office building in material level and human movements. The results obtained from the simulation show power degradation when a black body crosses the direct line of connection between two WRs. Our testbed, Wireless Scalable and Efficient Mesh network (WiSEMesh) at KAIST campus is deployed in outdoor (undergraduate buildings) as well as indoor office environments. The experimental results obtained from the office environment also verify the lowered received power with degraded throughput. The observations of link characteristics made in this paper assist in deployment planning of WRs considering the building layout and possible cultural impacts (human factors). They also help in drawing outlines for adaptive routing algorithms to counteract loss in the performance due to black body effect.

In the section to follow, we present our human body model along with human mobility behavior and define a black body. Section III provides a brief testbed implementation detail. picoKAIST background, and simulation setting and results are given in Section IV. Section V shows experimental results obtained from WiSEMesh testbed. The paper concludes in Section VI.

II. Human Body Shadowing & Human Behavior

A. Human Body Shadowing

An EM Wave (EMW) experiences diffraction, reflection, and penetration (transmission) at the skin. The interaction between human body and EMW is governed by Maxwell's equations and is determined by the electrical permittivity and magnetic permeability of the body. We consider the operating frequency of WMN in microwave range.

The incident EMW can be diffracted. In [8], Ryckaert et al. modeled the wireless channel around a human body. Their model of path loss for the diffracted EMW exhibits an exponential decay of the power and shows more attenuation of these diffracted EMW around the human body at higher frequencies. At breakpoint angle, they found that the path loss for 2.45 GHz is around -100dB. Therefore, we cautiously neglect any wave reaching to the receiver by the means of diffraction.

The incident EMW gets reflected from the body surface and a part is absorbed. The percentage of reflected wave is given by the medium's reflection coefficient. A reflection coefficient describes either the amplitude or the intensity of a reflected wave relative to an incident wave.

$$\Gamma = \frac{E^r}{E^i} \tag{1}$$

For biological matters, $\mu_1 = \mu_2 = \mu_0$, so,

$$\Gamma = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} = re^{j\phi} \tag{2}$$

where ε_1 is the complex permittivity of medium 1 that carries the EMW whereas ε_2 is the complex permittivity of medium 2 at which the EMW is incident. Values of r at an ISM Band frequency range are tabulated in Table I.

TABLE I
PROPERTIES OF EMW IN BIOLOGICAL MEDIA

Frequency (MHz)	High Water Content				Low Water Content			
	ε^r	σ	d	r	ε^r	σ	d	r
2450	47	2.21	1.70	0.75	5.5	96.4-213	11.2	0.406
3000	46	2.26	1.61	0.75	5.5	110-234	9.74	0.406
5000	44	3.92	0.79	0.75	5.5	162-309	6.67	0.393

At a frequency of 2.45GHz, around 40 to 75% of the incident wave is reflected back to the air medium depending on the interface. The penetration depth of the EMW is higher than the combined thickness (2-3 mm) of top two layers of skin ; the reflection at air-skin interface can be neglected. Therefore, the EMW wave reflects from the third layer (air-fat interface). Hence, referring to Table I, 40% of the incident wave is reflected while remaining is either diffracted or penetrates the body.

Now, we study penetrated wave behavior inside a human body. Because of the presence of charged particles and magnetic dipoles, the EM field within a human body is extremely complex. For simplicity, we consider the human body as a homogeneous, linear and source free medium. The Maxwell's equations for human body can be solved as:

$$E = E_0 e^{-\alpha z} e^{-jwt-\beta z} \tag{3}$$

$$H = H_0 e^{-\alpha z} e^{-jwt-\beta z} \tag{4}$$

$$\alpha = \frac{w}{c}\sqrt{\frac{\varepsilon_r^{'}}{2}}[\sqrt{1 + (\frac{\varepsilon_r^{''}}{\varepsilon_r^{'}})^2} - 1]^{1/2} \tag{5}$$

$$\beta = \frac{w}{c}\sqrt{\frac{\varepsilon_r^{'}}{2}}[\sqrt{1 + (\frac{\varepsilon_r^{''}}{\varepsilon_r^{'}})^2} + 1]^{1/2} \tag{6}$$

where $w = 2\pi f$ is the angular frequency and c is the velocity of light. The relative permittivity $\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$ where $\varepsilon_r^{''} = \frac{\sigma}{w\varepsilon_0}$ is related to the conductivity of the material, σ. $\varepsilon_r^{'}$ is the measure of the ability to store electric field energy.

Further simplifying (5) and using standard values for σ and $\varepsilon^{'}$ at 2.45 GHz frequency and $\varepsilon_0 \backsimeq 8.85 \times 10^{12} F/m$, we obtain the value of $\alpha \backsimeq 2767$. Theoretically, the penetrated wave is absorbed within few centimeters of propagation through human body.

But a human body is heterogenous in nature contrary to the assumption made above. The result obtained with homogenous human body assumption can be verified by identifying different types and layers of tissues in human body as well

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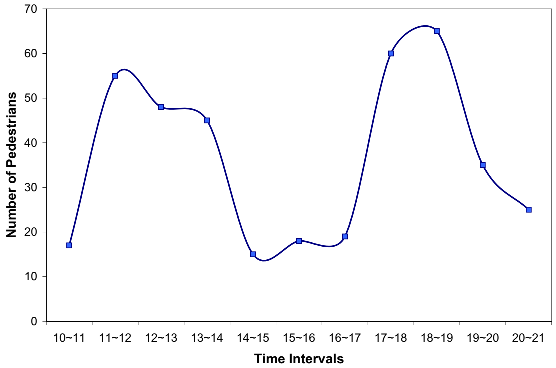

Fig. 1. Pedestrian movement in a day inside the building.

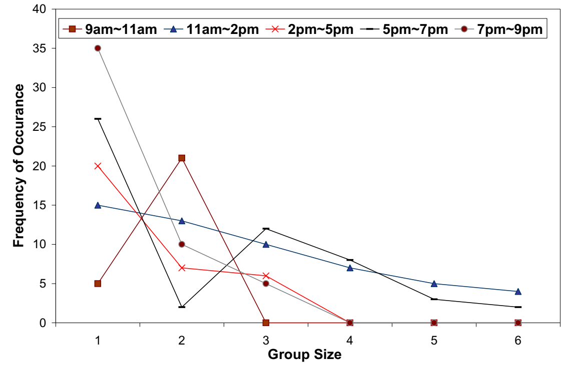

Fig. 2. Group Size Distribution.

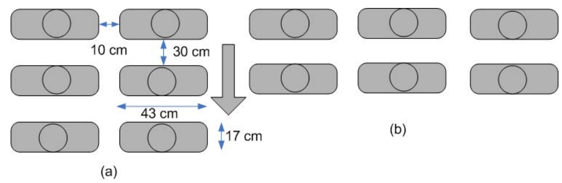

Fig. 3. Group Orientation Pattern.

as the interfaces between them [9], [10]. The absorption of microwave power will result in a progressive reduction of wave power density as the wave propagates into the tissues. We can quantify this by defining penetration depth $d = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$ or a distance that the propagating wave will travel before the power density decreases by a factor of e^{-2}. Therefore, the penetration depth at air-skin interface is around 1.7 cm. If the EM wave propagates beyond skin layer, it experiences two major phenomena: reflection and absorption. Once the EM wave penetrates beyond air-skin interface, it is totally absorbed due to repetitive internal reflections owing to the heterogeneity of human body and high water content tissues. Therefore, it is safe to assume that the penetrated wave doesn't contribute to a received signal at the receiver end.

B. Human Behavior

The testbed explained in Section III fits well with a modern building that houses many business offices. There are 7 laboratories and 2 venture business offices located in the building. Around 140 researchers and students work in the building. All the labs and offices located in the building start at 9am and finish at different times ranging from 6pm to 11pm. Therefore, pedestrian rush hours are seen in the morning and the evening. Normally, from 9am till 10pm people move within the building for number of reasons. A large number of pedestrians take a walk in staircase, hallways and corridors during lunch and dinner hours from 11am till 2pm and from 5pm till 7pm respectively. Fig. 1 depicts the rush hours. The pedestrian rush hour seen in our office building is a common phenomenon observed in large buildings, malls and public places such as train and bus terminals with different rush hour times.

Fig. 2 shows the distribution of pedestrian group size at different time observed in the building free spaces such as corridors, staircase and hallways. At lunch and dinner hours the group formation usually has 3 to 5 people most of the time. At office start and end hours, the groups usually contain a person or two. Again, this result is consistent with large complexes with many offices and workers.

Another important human behavior in a group is the positioning of people in it. Our survey showed 90% of the time, groups walk in Fig. 3 (a) pattern while 10% walk in (b) pattern. The reason behind such shape is due to the fact that the corridors and staircases are wide enough to facilitate 2 persons side by side with 10 cm gap between them. The proximity between people in two consecutive rows is around 30 cm apart.

The motive behind conducting human behavioral experiments is to find out the effect on the performance of a WMN when a group of people moves in its EM field. As discussed in Section II-A, 40% of the incident EMW is reflected back into the air. Considering a group of people moving together in an EM field, the probability of an EM wave reflected back to another person is very high. The probability depends on the number of people in the group. Therefore, larger the group size higher will be the chances that the reflected wave is trapped inside the group by successive reflections, a ping pong effect. As a reflected wave ricochets from a person just to hit another, the EMW energy decreases exponentially. Table II shows exponential power reduction of EMW inside a group of people, which is also termed as black body.

TABLE II
PERCENTAGE POWER DROP IN A PING PONG EFFECT

Number of Hits	Reflected Power
1	40
2	16
3	6.4
4	2.5
5	1
6	0.4

WRs deployed in an indoor environment do not usually have an LOS communication channel between them. The corridors and halls are filled with EM waves after multiple reflections and penetrations through walls and floors. Thus

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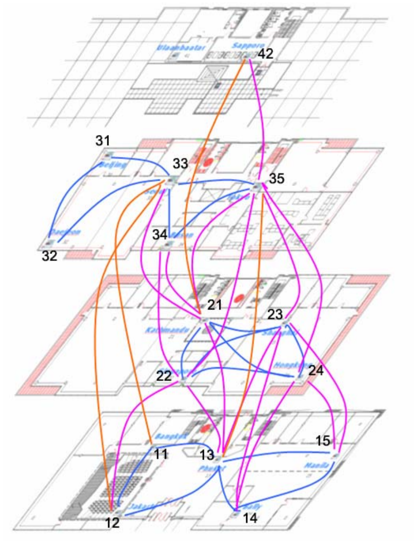

Fig. 4. Single hop connections in WiSEMesh.

the field strength is lower than an LOS signal strength. In such channel environment, when a group of people moves a significant amount of field energy is absorbed. In fact, the signal absorption is so intense that the throughput of the network decreases significantly. Our theory of black body effect is verified with experimental results in Section V.

III. Testbed Setup

WiSEMesh testbed [11] developed by our group covers one four-storey office building where labs and offices are located. We have implemented 16 WRs in the office building. Each WR is a mini computing device equipped with Intel Celeron M 360 processor with clock speed of 1.4 GHz. Ubuntu v5.10 with kernel v2.6.14 is used as an operating system. Each WR has three USB Linksys wireless network adaptors of 802.11b/g standard with an omnidirectional antenna.

One-hop links between WRs are shown in Fig. 4. During the experiment, the source-destination WR pair is allowed to communicate while rest of the WRs in the collision domain is silent. Human movement is the only interfering agent during testing. We used UDP traffic from one WR to another at a rate of 600kbps, testing at most 1 link at a time for 11 hours a day from 9am till 8pm.

The WRs are deployed near the ceiling of the rooms in the office. However, very few WRs have an LOS with each other since they are either separated by steel reinforced concrete floors or walls. Most of the walls are 4 inch thick wooden ply that partitions a floor into smaller rooms. Usually in halls where cubicles are located, the WRs maintain an LOS. We have placed most of the WRs at the corners of the corridors and halls/rooms.

IV. Simulation Results

We used a deterministic ray tube method, which is based on UTD. It is developed for quasi three-dimensional environments. This tool finds all propagation paths from a transmitter to a receiver extensively. We modeled our office building considering all the small details such as cubicles, etc. We did not model furniture as they can be moved randomly. We tested the propagation field keeping the transmission power at 0dB and obtained path loss and root mean square delay spread. In this paper we only present the path loss parameter. We model a group of people (a black body) with height 171 cm and the rest of the parameters as given in Fig. 3 ([12]). To emulate the movement or the motion, the black body is placed in several locations near the receiver and in between the transmitter and receiver path. We vary the size of the black body. As shown in Fig. 5 a direct ray from WR 13 passes through the floor and reaches the receiver WR 23 in no human presence. In presence of a black body, the previously available direct ray is no more possible and is shown with broken link on the left image. Simulation results presented below are observed when a black body is placed in the direct ray path between transmitters and receivers.

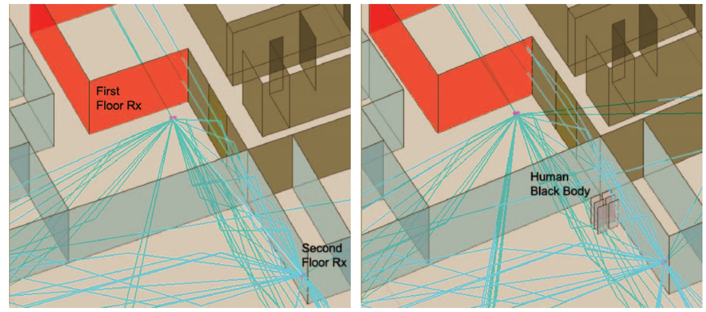

Fig. 5. A snapshot of propagation field between WRs 13-23.

Fig. 6 shows differences in received signal power. The received power is the maximum among multiple paths. In case of WRs separated by a floor, the strongest signal strength is carried by the direct path that traverses through the floor and reaches to the receiver. When a black body is placed in this path, the second highest power (alternate signal) signal is noted and is given in the Fig. 6. The power difference ranges from 5 to 10 dB. The alternate signal reached the receiver by reflections. Since the reflected ray can undergo attenuation due to another black body, the power difference of 10dB is a minimum. Some links like 35-42 and 33-11 have direct ray paths which can not be intercepted by any movement of black body. Due to this reason, there is no power difference. The links that show power difference in presence of a black body the received power degradation is so severe that the received power is lower than the sensitivity threshold and thus the signal is discarded. This leads to a drop in received data rate, which will be quantified in Section V.

Fig. 7 shows channel condition degrading while group size reaches 3 or 4. Beyond group size 4, the ray can not penetrate the black body. Links 13-23 and 21-35 perform better than the rest since these links are only 1 floor apart. During lunch and dinner time, the group size is 3 or higher and, therefore, in Section V we observe that a one-hop link throughput decreases during lunch and dinner time.

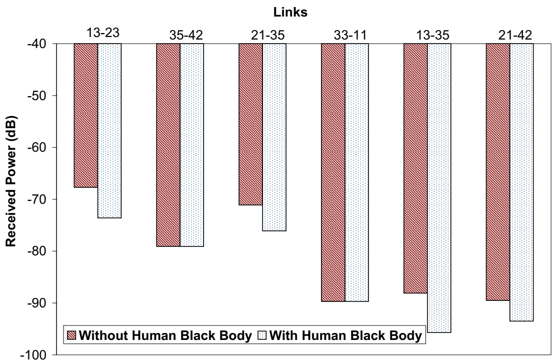

Fig. 6. Received power for WR pairs.

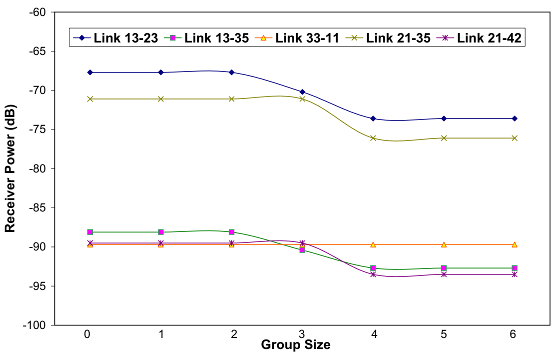

Fig. 7. Received power variation with group size.

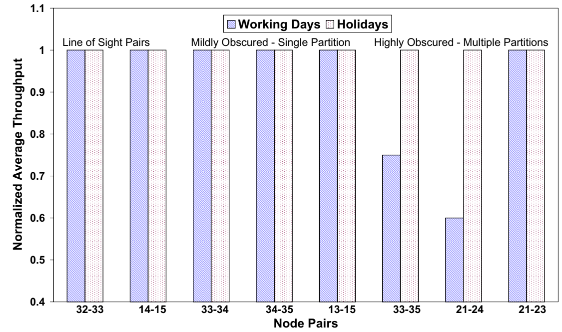

Fig. 8. Normalized throughput variation of WR pairs in same floor.

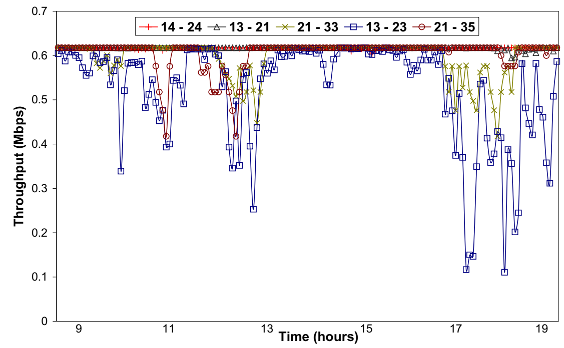

Fig. 9. Throughput variation in a typical working day between WRs separated by a floor.

V. Testbed Results

Fig. 8 shows normalized throughput between WRs whose locations are depicted in Fig. 4. The links in the Fig. 8 are further grouped by the degree of obscurity between them. Links 32-33 and 14-15 have LOS all the time. Therefore, the throughput is maximum and independent of any human movement. Mildly obscured pairs (33-34, 34-35 and 13-15) have better performance independent of human interference. These links are separated by single partition. Interesting results are seen for links that are separated by multiple partitions. The normalized average throughput of link 33-35 and 21-24 are 25% and 40% lower in working days where human movement is maximum compared to holidays where human movement is minimum. Pair 21-23 has similar degree of obscurity but has optimum throughput throughout the workdays and holidays.

Observation 1. WMN performance is less affected by environment mobility and distance between WRs when an LOS is available.

Observation 2. Lightly obscured links suffer minimal signal power loss due to partitions and, therefore, are not affected by human movement.

Observation 3. For links that are separated by multiple partitions the distance between source and destination is crucial. Ambient motion in such channels dramatically decreases the throughput.

Fig. 9 shows 11 hour observations of several links crossing a floor. These links are unique based on their WR node locations. Links 21-33, 13-23 and 21-35 show degraded throughput at early office hours and closing hours. These degradations coincide with lunch and dinner hours of the offices. But some links (14-24 and 13-21) show good throughput performance as the WR pair of each link resides in the same vertical axis along the building walls.

Fig. 10 shows 11 hour observations of several pairs whose WRs are located 2 floors apart. Links 12-33 and 11-33 maintain maximum throughout while links 21-24 and 13-35 show throughput degradation at morning and evening hours. These hours coincide with lunch, dinner and an office end time. Remarkably, the link 13-35 shows better performance in any holiday compared to a workday. This phenomenon shows

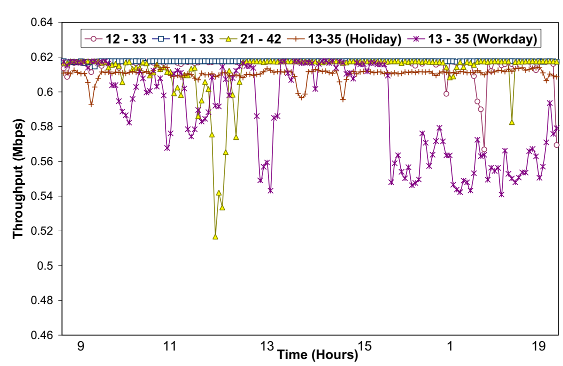

Fig. 10. Throughput variation in a typical working day between WRs separated by two floors.

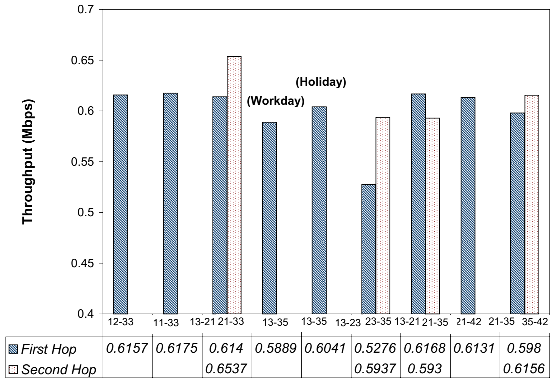

Fig. 11. Average throughput of one hop links.

the impact of the black body on WMN link performance. During early hours and middle of the day the throughput is not significantly affected even though people move around the building. The reason is simple: the group size or the black body size is 1 or at most 2.

Observation 4. A multistory building can have significant traffic bandwidth between WRs located in different floors provided that they are vertically aligned preferably on a perpendicular line.

Observation 5. Large number of people moving together in a close proximity (a black body) at certain time in a day due to various human reasons cause link quality to degrade significantly compared to a single or two persons movement.

Observation 6. WRs that are not vertically aligned and separated by the office floor/s, the black body effects are more if the "black body pathway" is near a source or a destination WR. Considering 13-23 link, a usual human walk in the second floor is right below WR 23.

Traffic from the first floor to the third floor of the office building can traverse through 3 one-hop vertical links (11-33, 12-33, and 13-35) and 3 two-hop vertical links (13-21 & 21-33, 13-23 & 23-35 and 13-21 & 21-35). The average link throughput is measured for workdays except for the link 13-35 which has both workday and holiday throughput measurement presented in Fig. (11). Considering similar propagation conditions (fixed environment entities), we observe 3 links (12-33, 11-33 and 13-21 & 21-33). Links 12-33 and 11-33 have slightly lower performance than the two-hop link. Considering another propagation pathway between the first and third floor, we notice 1 one-hop (13-35) and 2 two-hop (13-23 & 23-35, 13-21 & 21-35) links. In workdays, link 13-21 & 21-35 perform better than the rest while in holidays the one-hop link outperforms the 2 two-hop links.

Observation 7. In large complexes such as Taipei 101 and the Empire State Building, the density of people in each floor. varies in time and space. A WMN deployed in such places usually has multiple vertical pathways between number of floors. These vertical data pipelines can not always be placed in a human free zone due to space constraints. In such cases, routing algorithms can be developed to take advantage of time and space diversity induced by black bodies. A WMN routing algorithm for indoor environment needs to consider physical location of the WRs, and fixed and variable attributes of the channels.

VI. Conclusions

The performance of a WMN can significantly be improved with a proper deployment of WRs such that the human body shadowing is minimum. In some buildings, the WR deployment may result in links with less body shadowing. Our experimental results have confirmed that routing algorithms can make use of the multiple path channel diversity. In a typical WMN the human body interference is a critical performance issue for links without an LOS. These links suffer more channel degradation due to human behavior triggered by time scheduled events, such as office rush hours, and social events that promulgates in group formations. We determine that a large group of people moving together causes a black body effect where waves incident are completely absorbed.

We are now focusing on routing algorithms that uses temporal variation in channel condition due to the human body movement in WMN communication links. We are currently analyzing performance issues of the outdoor WMN deployment of our test bed considering ambient motions of entities like vehicles.

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