Modeling Environmental Mobility and its Effect on Network Protocol Stack

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***Abstract*— In this paper we address the effects of environmental mobility, that is, the ambient motion of entities like people and vehicles in the vicinity of wireless communication, on the channel characteristics and wireless network performance. We present a three step process of measurements, modeling and network simulations to quantify the significance of environmental mobility. Our field experiments show that presence of people not only cause deep fades but also distorts the fading distribution. We model the shadowing loss by three knife-edge diffraction model and propose a two-state Markov process channel fading behavior. The models are validated against measurement data and implemented in a network simulator. The models are scalable and incur execution overhead less than 15%. We also show the impact of environment mobility on protocol performance by means of two simulation case studies. We show that MAC layer data rate adaptation behavior is sensitive to environmental mobility and can result in 40% packets being delivered at lower rates. Second study on ad-hoc network performance show the throughput is decreased by 20%. We have identified that with environmental mobility the links are more sensitive to interference and the routes are less stable.**

I. Introduction

In this paper we address the effects of *environmental mobility* – that is, the ambient motion of people, vehicles etc in the vicinity of wireless communication – on the channel characteristics as well as protocol layer performance. This kind of mobility is in contrast to *nodal mobility* where the communicating nodes move. In our study of environmental mobility, the nodes themselves are static, while the non-communicating entities are moving about. We demonstrate that presence of even a single person can have significant impact on channel conditions such as signal strength and fading and these effects are propagated upwards and magnified in the protocol stack. Previously, however, this concept of environmental mobility has failed to receive it's due attention owing to dearth of thorough measurement studies, lack of suitable models and investigation on it's effect on network performance.

In order to understand and quantify the nature and significance of environmental mobility we present a three-fold approach using field measurements, modeling and network simulations. We first establish the impact of environmental mobility on signal strength by means of channel measurements. The impact of this phenomenon on wireless signal transmission is illustrated in Fig 1, where Received Signal Strength Indicator (RSSI) is measured as function of time in a corridor in a university building. The three time periods that

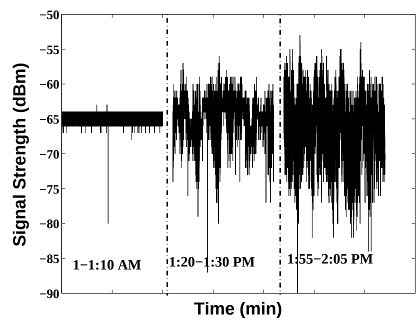

Fig. 1. Temporal plot of signal strength observed outside classrooms at different times of day. There is maximum traffic around 2 pm when students leave and enter the classes. Period around 1:30pm has moderate traffic of people and at 1am there is no human presence.

are shown correspond respectively to periods of no mobility (midnight), low mobility (classes in session) and high mobility (classroom changes). Section III presents results from controlled experiments where we draw observations showing that shadowing loss due to obstruction by people can be as high as 20dB and is subject to the relative position of people with respect to radios. We also observe that channel fading deviates from conventional Ricean distribution and is related to the number of people in the vicinity and their speed of motion. The contribution of these results is to formulate the relationship between number, speed and location of people contributing to the environmental mobility and the resulting impact on the channel fading and shadowing behavior. This study also serves a foundation for the development and validation of channel models described in section IV.

We model the phenomenon of human body shadowing loss by three knife-edge diffraction, which we utilize for our proposed two state Markov process model for channel fading. The three knife-edge diffraction model is an extension to the fresnel theory of knife-edge diffraction for the case of moving obstacles (human bodies in this paper, though it can also be employed for other obstacles like vehicles etc). We also consider the case when more than one person are blocking the LOS simultaneously. In the two-state Markov process channel model, the channel alternates between "clear channel" state and "shadowed channel" state. The model results were subsequently validated against the measurements. The model parameters are derived from Monte-Carlo based statistical simulations taking as input the density and speed of obstacles. We have implemented both models in the QualNet [1] network simulator and used in network evaluations. These models are efficient and scalable than ray-tracing or FDTD based models and the benchmarking results show that they incur an execution overhead of less than 15%.

Our final contribution from the paper is an illustration of the significance of environmental mobility in networking protocol research by means of two simulation case studies (section V). Our first evaluation study is the data rate fallback feature of the MAC protocol. We show that at density of 5 people per $100m^2$ and moving at 2m/s, as much as 40% of packets are sent at lower rate than they would have been in the absence of mobility. The second evaluation study evaluates network capacity and routing protocol behavior in an ad-hoc network. We find that the network goodput is decreased by 20%, the RTS transmissions per packet are 60% more and there can be 100% increase in routing error packets. Upon careful investigation we find that environmental mobility accentuates two aspects of ad-hoc networks: the route instability and increased sensitivity to external interference.

II. Related Work

Although it has been widely observed that a person standing next to receiver and blocking the line of sight can cause increase in packet loss and reduction in signal level (for example [2]), very little has been done to investigate or develop theory for this empirical observation. Moreover, to the best of our knowledge, no prior work has been done on modeling it in the context of network simulations and evaluating protocol stack performance.

Effect of human body on channel had gained interest in cellular and wearable radio communications, wherein FDTD techniques are used to study the impact of human body on radio reception (e.g. [3]). However, due to computationally expensive nature and ineffectiveness of model for larger separation between human body and radio, these are not applicable for 802.11 based data networks.

Wysocki et al [4] showed that motion of people in immediate vicinity of receiver cause channel fading to be Ricean distributed. This is a special case of mobility pattern that we have considered where the people are assumed to be moving at arbitrary distance from receiver. For this general case, we observe that the fading is distorted from Ricean distribution and exhibits a secondary peak.

In [5] authors noted from channel measurement traces that two state Markov model can be used for fading. However, they have not developed any theory to explain fading behavior or discussed how to derive model parameters. Alternate approaches to model channel fading in presence of humans are studied in [6] and [7], where ray tracing approach is used to derive channel profile. Not only are these models computationally intractable for use in network simulators, but they also assume constant shadowing loss for any relative separation between a person and radio, an assumption that is shown to be invalid by our results in sections **??** and III-B. Our three knife-edge diffraction and two state channel models are not only efficient and scalable, but also shown to be accurate via validations against the experimental data.

III. Field Measurement Results

A. Experiments Setup

Our measurement testbed include IBM Thinkpad T-42 laptops equipped with Orinoco Proxim WD-8470 b/g gold card operating in 802.11b mode. We have used the Airopeek SE software from Wild Packets Inc [8] to capture MAC control packets and channel characteristics. This software installs a custom driver for Aetheros chip-set based wireless cards and allows measuring Receiver Signal Strength Indicator (RSSI) for each received packet. The laptops were placed 20 meters apart at height of 1.1 m in an open stadium with no obstacles within first few fresnel zones. Broadcast traffic of 512B packets every 2 ms was transmitted at 1Mbps.

B. Shadowing Loss due to Motion of Multiple People

We further elaborate on the role of separation between person and receiver on the shadowing loss. The Case I in fig 3 shows the signal strength loss when one person is moving from transmitter (located at X-axis value 0) to receiver (located 20 meters away) while blocking the LOS (fig 2 (b)). In case II, two people next to each other were walking similarly. These two people were lined up perpendicular to LOS, thus offering twice the "width" of obstruction but same "depth" (fig 2 (c)). In both case we observe that loss is maximum at the ends and is almost a constant value in the middle.

We also consider the case when there are more than one person blocking the LOS. In Case III, two people were positioned such that both are blocking the line of sight (fig 2 (d)). In IIIa, one person was standing still 1 meter from receiver while the other was moving between transmitter and receiver. The IIIb case is same as above except the immobile person was standing 4 meters from receiver. We observe that the fading value increases in the case of two people and in general the magnitude depends on the distances of two people from the transmitter and receiver and also from each other. We summarize observations of all these cases as:

Observation 2: Shadowing loss due to blocking of line-of-sight is dependent on the relative distance of people from the receiver and transmitter and also between themselves.

C. Channel Fading in Presence of Mobile People

Our final investigation is the effect of environmental mobility on channel fading distributions. The fading distribution refers to the probability distribution of signal strength around the mean value and is known to be Ricean distributed in LOS channel. In our experiments, people were moving randomly close to the receiver and their number was varied between 1 and 3. Fig 4 shows the frequency distribution of the signal strength. The curve for "no movement" case is conventional Ricean fading distribution. For the other cases we find the fading distribution exhibits a secondary peak. The entire curve can be thought of as a sum of two distributions where mean value of second component is displaced and it's relative weight is dependent on the number of people. Similar trends are observed when the number of people is fixed but their speed is varied. This is the basis for the channel model that we present

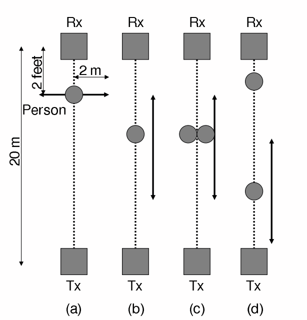

Fig. 2. Experiment design. (a) refer sec **??**; (b)-(d) refer sec III-B

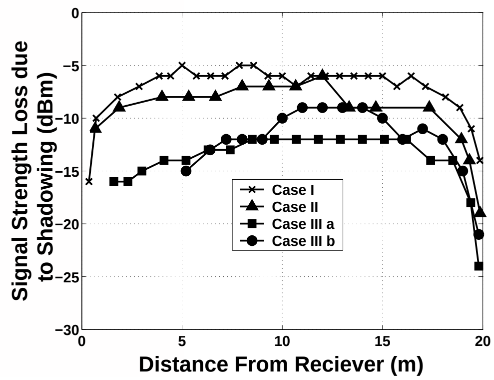

Fig. 3. Fading magnitude with two people. For the three cases refer to sec III-B.

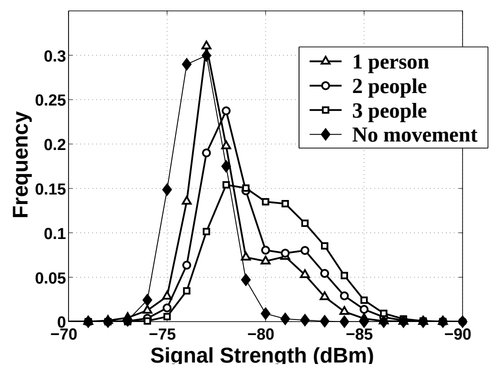

Fig. 4. Frequency distribution of signal strength with different number of people moving about.

in section IV-B, where the channel is modeled as alternating between two states corresponding to the two distributions. Again we summarize this observation as follows:

Observation 3: The fading distribution, in presence of environmental mobility, is distorted to exhibit a secondary peak. The relative magnitude of the second peak depends on the number of people and their speed.

IV. Modeling Shadowing Loss and Channel Fading

Our objective for the modeling effort is to include the impact of environmental mobility on channel fading behavior in network studies. For this reason, we have disregarded the ray-tracing based and FDTD models since the time complexity prohibits their usage in network simulations. Sec IV-A models the shadowing loss by three knife-edge which is utilized for two-state channel fading model in sec IV-B.

A. Diffraction model for fading induced by people

We explain the loss observed in signal strength due to presence of people by the process of diffraction. The classical diffraction theory suggests that if we place an absorbing screen in the path of traveling wave then the waves bend around the edge to reach the shadowed region. However, the theory require that the plane is of infinitesimal thickness (knife-edge) and infinite in width. To use this theory in the context of diffraction by people, we first observe that the human body can be considered as absorbent for frequencies greater than 2.4GHz; also the radius of curvature at edges of human body are negligible when compared with communication range and can be safely regarded as "knife-edge". To accommodate finite dimensions of human body, we propose a three knife-edge model of diffraction, wherein the rays not only diffract from the top of person but also sideways around the left and right arms.

The loss due to diffraction for a single knife edge when an obstacle of height h is placed at distance d_1 and d_2 from the transmitter and receiver respectively, is given by [9]:

$$L_{diffraction} = 20logF(h, d_1, d_2), where$$

$$F(h, d_1, d_2) = \frac{S(x) + 0.5}{\sqrt{2}sin(\Delta\phi + \pi/4)},$$

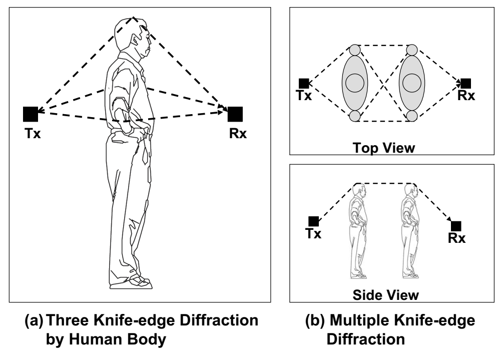

Fig. 5. Three knife diffraction model for case of single person and two people.

$$\Delta\phi = tan^{-1}\frac{S(x) + 0.5}{C(x) + 0.5} - \frac{\pi}{4}, and$$

$$x = -h\sqrt{\frac{2}{\lambda}.\frac{d_1 + d_2}{d_1 d_2}}$$

Here λ is the wavelength and $S(x)$ and $C(x)$ are fresnel sine and cosine integrals.

We have extended the model to include three knife-edge diffractions. This is shown in fig 5 (a), where the receiver receives three diffracted waves along the top, right and left sides of body. The total loss due to diffraction is

$$L = 20log_{10}(\sqrt{F(h, d_1, d_2)^2 + F(k, d_1, d_2)^2 + F(k, d_1, d_2)^2})$$

Here h and k are vertical and horizontal obstructions, respectively. Fig **??** shows the comparison between the theoretical and experimental data as previously described in fig 3. The value of h and k were obtained by measuring the dimensions of the volunteer and were found to be 60 cm and 15 cm, respectively.

For the case of fading due to multiple people, we use the peterson-epstein model of multiple knife-edge diffraction. For the case of two obstacles, the model proceeds with calculating the diffraction loss between the transmitter and tip of second obstacle, caused by first obstacle. Next, the loss is calculated between tip of first obstacle and receiver, when the second obstacle is obstructing. These two losses are added and an extra correction term is added to this sum [9].

For the three knife-edge model we have proposed, we have extended this model to account for various combinations of paths that the waves may take to reach the receiver. Fig 5 (b) shows the case for two people. There are in all five paths from transmitter to receiver, each encountering two diffraction edges. These components are added to produce the total pathloss. Comparison with the experimental data is shown in Fig 6. The curve and measurement data for Case IIIb has been shifted down by 7dBm for visual convenience. The departure of measured data from theoretical model in this case is attributed to the fact the person was not standing exactly in center of line-of-sight.

B. Two state channel fading model

It had been noted earlier in section III that in presence of mobile people the channel fading can be regarded as combination of two Ricean distributions. The distribution with higher mean value is obtained when the first fresnel zone is clear of any obstruction. The second case occurs when one or more people are impeding the line of sight. As people move, the channel alternates between these two cases. This observation is foundation of our channel model. We model the channel as a two state continuous time Markov process where the two states correspond to the two cases when line of sight is blocked and when it is not. The model, along with the parameters is shown in Fig 7.

The channel alternates between the two states and rate of transition is dependent on number of people and their speed of movement, as we have noted in observation 3. If there is a large number of people or if the people are moving fast, then the model will move to second state more frequently. The fading distribution in each state is Ricean but with different K values [1]. The Ricean value for the first state can be obtained by field measurement without any person moving near the transmitter or receiver. The signal strength in this case is:

$$\begin{aligned} RSSI_{State1} &= Tx\_Power - L_{pathloss} \\ &\quad -ricean\_fast\_fading(K) \end{aligned}$$

[1]The readers will recall that Ricean K value is the ratio of power received by line of component and power by all other specular components arriving via multipaths.

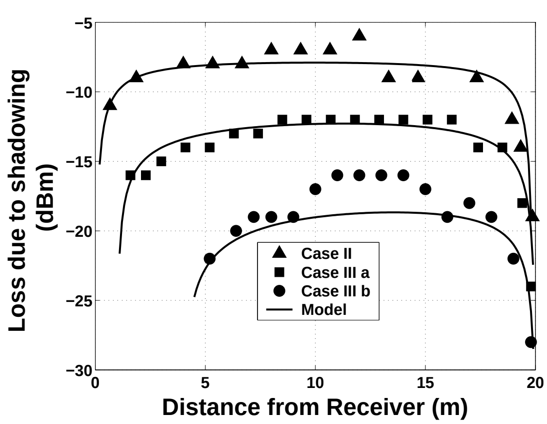

Fig. 6. Validation of model for shadowing loss due to multiple people.

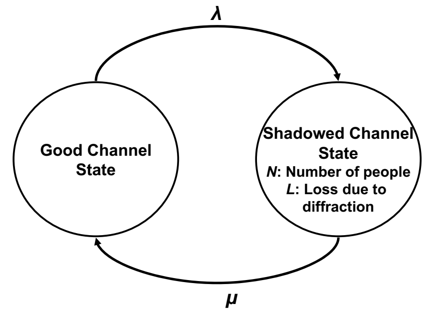

Fig. 7. Two state Markov process channel model.

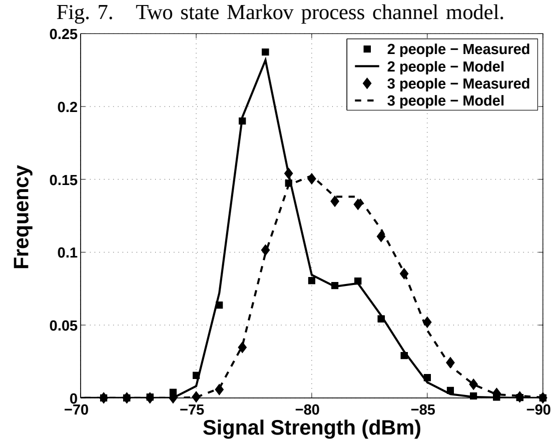

Fig. 8. Validation of two state channel model.

Before we describe how the fading K value is obtained for the second state, we first look into the “excess pathloss” parameter, L. When the channel goes to the second state, there is an additional loss due to obstruction by people. The magnitude of this value depends on number of people, their location from the radios and distances between themselves, as we have seen previously. We make use of the diffraction pathloss model here to obtain the pathloss value. First the number of people that cross simultaneously (N) is taken at random, based on some statistical, analytical or trace based distribution. For the simulations described in next section, we have obtained this probability distribution by Monte-Carlo simulations. Once the number of people that cross the link simultaneously is selected, their locations are selected by uniform distribution, and the diffraction model is used to calculate pathloss as described in previous subsection. The signal strength envelope in this state is:

$$\begin{aligned} RSSI_{State2} &= Tx\_Power - L_{pathloss} \\ &\quad -L_{diffraction} - ricean\_fast\_fading(K') \end{aligned}$$

Now we come back to problem of obtaining value of K', which the Ricean value for the second state.

$$\begin{aligned} K' &= 10log_{10}(\frac{power\ of\ LOS\ path\ after\ obstruction}{power\ of\ other\ components}) \\ &= 10log_{10}(\frac{power\ of\ LOS\ path\ before\ obstruction}{power\ of\ other\ components}) \\ &\quad -L_{diffraction} \\ &= K - L_{diffraction} \end{aligned}$$

Validation: Fig 8 shows the validation of this model with the measured channel fading results (shown in Fig 4). The fraction of time that channel was in "good" state was taken as 0.75 and 0.65 respectively. The case of single person is omitted for clarity of the graph.

V. Protocol Performance Case Studies

This section attempts to investigate the effects of environmental mobility models on network performance. We address the significance at multiple layers of protocol stack – on a MAC data-rate adaptation protocol in wireless LAN, and routing protocol and network performance in ad-hoc networks. Before venturing into the simulation case studies we describe the Monte-Carlo statistical method of determining the model parameters.

A. Case Study I: MAC Layer Data-Rate Adaptation

The wireless medium access control (MAC) protocol make provision for varying channel conditions by adapting the transmission data rate. The rationale being that traffic at lower data rates are less sensitive to noise and interference than higher rates and are more likely to be received in poor channel conditions. For this reason almost all wireless cards and drivers implements this feature. By nature, the rate adaptation algorithm is sensitive to channel behavior and therefore, we consider it as prime candidate to study for our two-state channel model.

Our simulation framework incorporate single 802.11b wireless link, with the source transmitting 512B packets at transmit power of 10dBm. Backlogged CBR traffic load is applied and static routes are set up between the pair of nodes. QualNet's default radio sensitivity values are used: -93dbm (1Mbps), -89dBm (2Mbps), -87dBm (5.5Mbps) and -83dBm (11Mbps). The link distance, and model parameters (derived from density of people and speed of movement) is varied and we note the fraction of packets sent at different data rate.

Fig 9 shows the fraction of packets transmitted at the four different data rates for the cases when there is no environmental mobility and when there is with densities 0.02 through 0.05 and speed of people 2 m/s. The results are shown for communicating link range of 100m and 200m for each case. We observe that in absence of mobility of people, almost all packets are sent at highest rate for both 100m and 200m links. However, the fraction of packets at highest rate decreases as the density of people increases and also for case of longer link. This behavior can be explained by considering the fact that during the shadowed channel state, there is higher probability that the MAC protocol will reduce the data rate and it will take some time before it can increase it when the channel moves to *good* state.

Observation 4: Environmental mobility results in degradation of link throughput by increasing the fraction of packets that are transmitter at lower rates. This phenomenon is dependent not only on density and speed of people but also the link range.

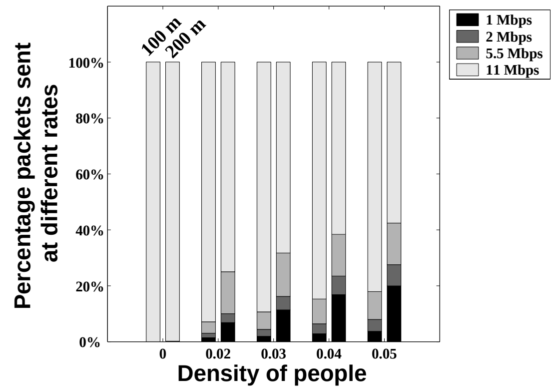

Fig. 9. MAC data-rate adaptation: fraction of packets sent at different data rates with varying mobility of people and link range.

B. Case Study II: Routing in Ad-hoc Networks

While the previous study considered a single link and MAC layer of protocol stack, our next study focusses on the network layer in an ad-hoc network. A network of 50 static nodes is configured in terrain of 1000m X 1000m. CBR sessions of 512B packets every 100ms are initiated; the number of sessions was varied between 5 and 10. As before, the density of people was varied to obtain model parameters and the network and application layer performance is observed.

Fig 10 gives the packet delivery ratio (PDR) for different density, traffic sessions and routing protocol (AODV and DSR were used in simulation). An analysis of this difference in performance proffered two key factors: (1) unstable links, which is shown in fig 11 which gives the number of RTS transmissions per data packet; and (2) unstable routing, which is presented in fig 12 which shows the number of Route Error (RERR) packets sent by the sources.

We undertake a more detailed study of the two factors noted earlier. The first case of instability of link with higher mobility of people is attributed to the increased sensitivity to interference. We designed a simulation experiment with two communicating pairs of nodes. Initially, the two links are far from each other and cannot interfere each other. One link is then moved closer to the other one, until they both are in strong interference region of each other. The throughput obtained as a function of distance between pair of links is shown in fig 13. First consider the no (environmental) mobility case, when the links are very far away from each other there is no interference and the throughput obtained for each link should be equal to the link capacity. In the other extreme case when they are quite close to each other and hear each other, the MAC protocol ensures fairness and each link gets roughly half the share of the link capacity. It is the middle region where the throughput transitions between these two values, which is of interest to us. For no mobility case we find that the two links are independent of each other upto a distance of about 600 meters. However, in case of environmental mobility, we find that with increasing density of people and their speed, the throughout starts to fall even earlier. We summarize this observation as:

Observation 5: The sensitivity of link capacity to external interference increases as the magnitude of the mobility of

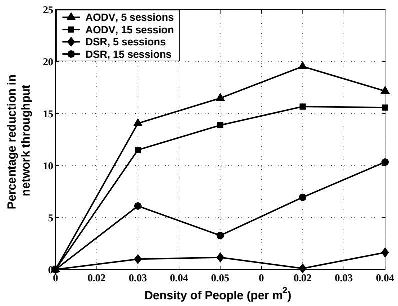

Fig. 10. Packet delivery ratio.

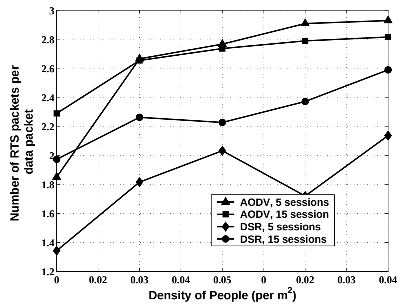

Fig. 11. Number of RTS packets per data packet.

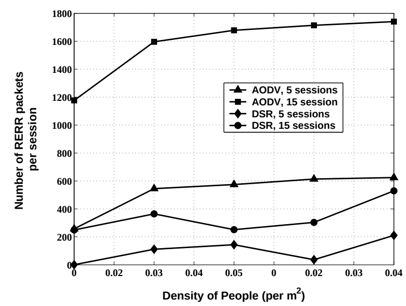

Fig. 12. Total number of route error (RERR) messages sent.

Density ($/100m^2$)	Link Range (m)	Avg. Route lifetime (AODV)	Avg. Route Lifetime (DSR)
0.02	100	4.83	2.45
0.02	200	3.33	1.69
0.05	100	4.47	1.12
0.05	200	2.44	1.12

TABLE I

AVERAGE ROUTE LIFETIME

people increases.

Our second factor was the instability of routes, that is the routes have a short lifetime. To demonstrate this, we simulated a four node "square" topology with a node sending traffic to it "diagonally opposite" node. There are two routes available between this pair of source and destination, each going through one of the other nodes. We measure the average lifetime of routes, as the density of people is increased. This is shown in table II, for both AODV and DSR routing protocols. It can be observed that the expected lifetime of route decreases with increased mobility and the routing protocol switches back and forth between two routes more frequently.

Observation 6: In ad-hoc networks, with increasing environmental mobility the routes become less stable and their expected lifetime is lower.

VI. CONCLUSIONS AND FUTURE WORK

We have investigated and quantified the impact of environmental mobility on channel conditions and protocol performance. Through the measurement studies we observed the shadowing loss due to presence of people is dependent on number and location of people. The channel fading also deviates from standard Ricean distribution. These effects are modeled and validated by our proposed three knife-edge diffraction model and two-state Markov process channel fading model, respectively. We have implemented these models in QualNet network simulator and studied the impact on MAC and network layer of protocol stack. The MAC data rate adaptation results show that for density of 5 people per 100 m^2 moving at 2 m/s as many as 40% packets are delivered at lower rate. For the ad-hoc networks we find that in presence of environmental mobility the links are more sensitive to interference and the routes are less stable.

For future work, we would like extend measurements in other scenarios such as streets, freeways, conference halls etc. Other dimension of measurement and modeling is for non line-of-sight (NLOS) channel. Although we have not presented data for NLOS channel, we had observed that signal strength can actually improve due to blockage of destructive components. Finally, we also plan to relate the environmental mobility with nodal mobility, that is, when the nodes themselves are moving and can shadow other communications.

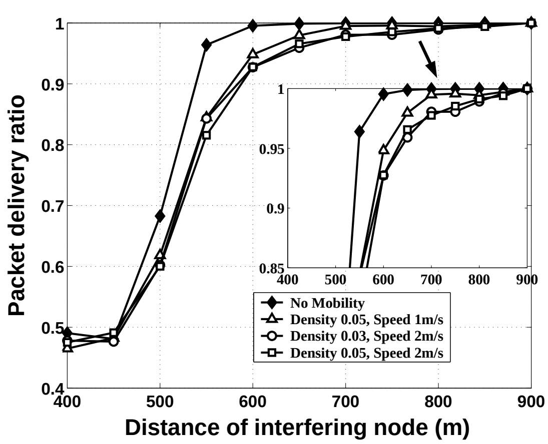

Fig. 13. Effect of interference.

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