

Measurement–Based Physical Layer Modeling for Wireless Network Simulations

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Abstract—Simulation methods have become an integral part of almost all aspects of networking research and particularly in the area of wireless networks. Any new protocol or methodology that is proposed for wireless networks almost always will be demonstrated using simulations. However, there is little evidence that existing models of physical layer signal propagation and signal strength calculations produce realistic or meaningful results. Indeed, there have been a number of empirical studies that have shown little predictability in measured signal strength and packet receipt probability for deployed networks. Common assumptions used in simulation models about the behavior of the wireless signal have been shown to often be invalid. These prior works motivated us to design a *stochastic model* for wireless signal propagation in our *GTNetS* simulator. Our model is based on a detailed empirical measurement study and uses random variations to produce more realistic behavior for wireless packet transmissions and reception modeling.

I. INTRODUCTION AND RELATED WORK

Network simulations have been used extensively to evaluate the performance of wireless networks. With the advent of Wireless Ad-Hoc networks and Sensor networks, simulation has become a virtual necessity because of the scale and complexity of a given network.

There are several popular network simulators [1], [2], [3], [4], [5] used in the research community as well as the industry. Almost all of them include protocol models of the IEEE 802.11 specifications in considerable detail. However, most of these have fairly theoretical models of wireless PHY layer. In fact, many simulators provide a simple free space model in which the signal loss is a function of the inverse square of the distance ($1/r^2$). The two such models which are most prevalent are the *Friis free-space* model and the *Two-ray ground reflection* model. The *Friis free space* model assumes a flat ideal terrain without any obstacles. It ignores fading and shadowing effects. The *Two-ray ground reflection model*, on the other hand, considers both the direct and the ground-reflected propagation paths between the transmitter and the receiver. The latter has been shown to be reasonably accurate in the case of predicting signal-strengths over distances of several kilometers when the transmitter power is large and the transmitter is mounted

at a large elevation. In contrast, wireless links in WLANs use low power transmitters and the distances involved are hardly more than a couple of hundred meters. Recently, shadowing models [6] have also been incorporated into some simulators [1]. These models account for obstructions in indoor scenarios and outdoor shadowing via a statistical component. However, this shadowing model does not take into consideration any correlations that exist because of the proximity of the communicating nodes. Explicit models for the cross correlation function of the shadowing components affecting the links between communicating nodes should include both the autocorrelation mode for single components [7] and the cross-correlation for multiple components [8]. Ideally, RF (Radio Frequency) propagation models should be based on exact mechanics of RF propagation. They should account for factors that affect the connectivity of a radio link. It is worth noting that even though all the details of RF propagation are not essential for realistic wireless network simulations, the models used should offer realism in connectivity and the changes in connectivity as the topology and environment changes spatially and temporally.

Kotz et al. [9] addressed many of the common ideal assumptions made in modeling wireless links. They conducted experimental studies to evaluate several assumptions made in prevalent simulation models. They surveyed a set of research publications over a period of 7 years and concluded that most of the works had either very ideal PHY models or very simple radio propagation models. Based on their survey they listed six axioms upon which most MANET simulation studies and results explicitly and implicitly relied. These axioms, not all of which are orthogonal, affect how higher layer protocol models behave.

- 1) The world is flat. i.e, simulations consider mostly two dimensional terrain characteristics.
- 2) A radio's transmission area is circular. i.e, A transmitting node's radio reception area is essentially a circle, whose radius is the radio range.
- 3) All radios have equal range.

- 4) If I can hear you, you can hear me. i.e, all radio links are symmetrical in nature. This property is often referred to as link symmetry.
- 5) If I can hear you at all, I can hear you perfectly. i.e, the error rates are fairly constant over a given radio distance.
- 6) Received Signal Strength at the receiving nodes is a simple function of distance.

They proceed to examine these axioms and compare it with the data they gather from their outdoor routing experiment. All the above listed axioms are shown to be strongly contradicting to what was observed in reality. Thus they suggest that their results cast doubt on published simulation results that implicitly rely on these assumptions.

Measurement studies carried out at the Roofnet Project [10], [11], [12] indicate that theoretical models do not accurately reflect the characteristics of a wireless local area network. This work starts with the understanding that real wireless links differ from their abstracted models in a number of ways. They question the very principles on which the widely prevalent 802.11 MAC protocols are based. They observe that many routing and link-layer protocols assume the validity of a “neighbor” abstraction that partitions all the pairs of nodes into pairs that can communicate directly, and pairs that cannot. This leads to the design of MAC protocols such as 802.11 which assume that a pair of nodes either hear each other’s control packets (RTS/CTS) or will not interfere each other’s communication. Neighbor abstraction is supported by assumptions about the relationship between signal-to-noise ratio and bit error rate. Empirical measurements have not conclusively proved whether neighbor abstraction holds or not. There have been measurements that indicate both models. It further tries to provide an insight into which differences are important enough to worry about, and to draw conclusions relevant to the design of MAC and routing protocols. To illustrate the effect of multipath they use a wireless emulator that enables both realistic and repeatable experimentation [13]. Their experiments suggest that multi-path fading due to reflections in the radio environment are an important cause for intermediate loss rates. The paper presents the following major conclusions for the wireless MAC and routing protocol design:

- 1) Links with intermediate loss rates are common, with no sharp transition between high and low packet loss rates.
- 2) Inter-node distance is not strongly correlated with whether nodes can communicate.
- 3) Most links have non-bursty loss patterns.
- 4) Links with very high signal strengths are likely to have low loss rates, but in general signal strength has little predictive value.
- 5) A link is likely to have a significant loss rate at its optimum 802.11b bit-rate.
- 6) Multi-path fading greatly affects outdoor links and

helps explain intermediate loss rates.

It can be concluded from their work that simulation models of wireless links which are based on these theoretical models will not accurately reflect the actual network conditions are likely to yield misleading results.

Cavin et al. [14] present the results of the simulation of a simple flooding algorithm using three popular mobile ad-hoc network simulators. Their simulations show important divergences between the simulators used. The divergences were not only in terms of the numerical results obtained from their experiments, but also in terms of the general behavior of their protocol. These observations led them to remark that “This observation makes the simulation phase less credible as it is difficult to tell which simulator describes the reality better”. They conclude that standalone simulations do not really fit the actual needs of wireless application developers. Instead of simulations, they suggest a hybrid approach where only the lowest layers and the mobility model are simulated and higher layers are executed on dedicated hosts. They also sense that there is a lack of real experiments to prove the feasibility of wireless network protocols.

Several other works have studied or commented on the correctness and accuracy of simulation models for wireless propagation, including [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36]

In this work we present experimental results from several field experiments we conducted. Using the results obtained we created empirical models for a wireless link when the nodes are mobile. Further, we incorporate these models to calculate *packet error probability* and received signal strength in the Georgia Tech Network Simulator. (*GTNetS*). The *packet error probability* indicates whether a packet sent from a mobile node will be a successful transmission.

Most analytical calculations derive *packet error rate* from *bit error rate* using the simple relation

$$PER = 1 - (1 - BER)^n \quad (1)$$

where n is the number of bits in a packet. However this relationship is hardly accurate in practice, because bit errors are not completely independent and often occur in bursts. Moreover, the errors do not exactly conform to a uniform distribution. When creating a abstracted network simulation model, it is more useful to think in terms of packet errors than bit errors. When a packet is sent in a medium which does not have interference from any other nodes, the only parameters that affect the successful delivery are the modulation and coding rate used, size of the packet, the distance between communicating nodes apart from the environmental factors like weather. Our intuition is based on the principle that when the physical layer conditions are relatively less conducive for a MAC data frame to be transmitted, it will be retried more number of times. If the frame is dropped after the number

of retries mandated by the specification (which is 7), then the physical layer characteristics were not good enough for the frame to be transmitted. If a packet is received successfully, we use the received signal strength model to calculate the received strength. This model is limited to the environment in which we have done our experiments and the methodology we have followed to conduct the experiments. These are described in the subsequent sections.

II. MEASUREMENT STUDY

In this section, we provide an overview of methodology and the measurement setup used to conduct our experiments.

A. Experimental Setup

To obtain measurements of actual packet reception probability for various operating conditions and transmission distances, we designed an experiment using a single base station and a single mobile device (laptop) at varying distances from the base station. We used wireless adaptors based on the Atheros chipset [37] and the RaLink [38] Chipset in our experiments. For accurate location measurements, we used a Garmin V [39] GPS device. The laptops use the NetBSD-current operating system. We wrote an NMEA (National Marine Electronics Association) line discipline to obtain the raw NMEA data from the GPS device. We instrumented the RaLink(ral) and the Atheros(ath) drivers with ring buffers to store the retry statistics that we needed for our measurements. When the Atheros and the RaLink cards signal the completion of the transmission of a MAC frame, they indicate to the host if the transmission was ACKed. If the transmission was successful (ACK was received) the descriptor also indicates how many retries were needed. NetBSD also provides a *radiotap* interface which allows us to obtain per packet signal and noise measurements as the driver stamps it. We also disabled the bit-rate adaptation algorithms that are enabled by default in both the drivers so that we can operate the card in the desired mode. The RTS threshold was set to a sufficiently high value to disable the RTS/CTS exchanges.

The measurement application is multi-threaded. While the main thread keeps up with the job of reading the actual statistic, the slave thread keeps up with the GPS device for the current location readings. The accuracy of the GPS device was accurate within 10 feet in our experimental environment. Each entry in our logs was stamped with the time as well as the location when it is stored.

Since we are conducting essentially link-level measurements, it does not matter whether we are operating in ad-hoc mode or the infrastructure mode. We set the transmit power of the radios to 20 dBm and it was kept constant during the entire set of experiments.

B. Measurement Environment

All experiments were carried out in the sports field adjacent to the Campus Recreation Center at Georgia Tech. A number of precautions were taken to make sure that the interference from miscellaneous sources is minimal. We took care so that, the orientation of the network adaptors do not change during the course of measurements. We also made sure that there is always line-of-sight maintained between the two communicating stations. For this reason, all experiments were conducted when the football field was unoccupied. The reason for this is that once we get measurements that are as ideal as possible, we can inject interferences and disturbances into our model as needed. On the other hand, the reverse may not be always possible.

It is important to shield the experiments from various interferences. This enables us to constrain the number of parameters affecting our measurements. Control and Data frames in another Service Set Identifier (SSID) can cause our candidate transmission to falsely retry. The resulting retries will not be representative of the path characteristics but of the congestion in the medium. Interference from communications occurring in neighboring channels and in the same channel can provide false readings especially when retries are being measured. For this reason, we operated in channel 16 of the ISM band, which is rarely used in commercial 802.11 applications. We insured that this channel is spatially separated enough that cross-channel interference is not a concern by measuring the *physical errors* as reported by the cards over an extended period.

We verify the data rates at which the radio is operating by checking ping latencies of large sized packets. The data sizes that are actually being sent into the radio are verified by looking at the retry statistics which gather this information from the DMA descriptors.

C. Experiments

We conducted two sets of experiments for measuring the received signal strengths of successfully delivered packets and the number of retries associated each successful transmission of a data frame.

1) *RSSI Measurements*: In the first experiment, we stationed an access point 2 meters above the ground level and 10 meters away from any obstruction on a pole. It was set to send beacons every 100 milliseconds. The transmit power of the radio was set to 20 dBm. We used a laptop with Atheros AR5212 chipset based card as well as the RaLink RT2570 chipset based cards to move around in the field in different directions with random mobility. Throughout the experiment we kept the orientation of the antenna of the laptop constant even while the laptop was mobile. We also made sure that there is always a line-of-sight maintained during the course of an experiment. As each beacon was received, we logged the measured received signal strength, the time of the measurement, and the GPS reported location point. We

gathered four sets of measurements with two different cards so that we can be sure that our measurements are not affected by the design of the chipset. The laptop moved across the field in a fixed pattern giving a wide variation in distance from the access point. We traversed the same pattern three times to get a larger sample size.

2) *Retries Measurements*: In the second experiment, we stationed the laptop acting as an access point 1 meter above the ground such that we can easily access it for varying the bitrates and the mode in which it operates. From the client laptop we then send continuous UDP frames of constant size at the rate of 10 per second to the access point. We leave a certain time interval (10 seconds) in the beginning so that the *probe frames* and *association frames* are exchanged. Since the RTS/CTS exchanges were disabled, the only data that's being transmitted during the course of our experiment are our UDP packets. We verified that this is indeed the case in a laboratory setup.

In this experiment, we made sure that the spacing between successive beacons is greater than 1 second. Though this is not configurable in the cards that we were using, we modified the interrupt handler which indicates when a beacon is supposed to be sent. This makes sure that our data transmissions are not affected significantly by the periodic beacons that our own access point sends in the channel in which we are operating.

For each of the 802.11b data rates (1, 2, 5.5 and 11 Mbps) we performed one experiment of mobility for a given packet size. The packet sizes that we chose for our experiments was 128, 256, 512 and 1024. In these 16 experiments we traverse our mobility pattern twice. The kernel logger logs the retry statistic and the packet size in each transmit complete interrupt handler. Our user space logger then copies them into a logfile using the *kvm* interface.

III. RESULTS AND DISCUSSION

In this section we discuss the lessons we learned when doing the experiments as well as the results we obtained.

A. Received Signal Strength

Ideally in free space, the average signal strength should fade with distance according to a power-law model [40]. This relationship holds if we consider ideal conditions that the physics behind the relation holds true. However, in practice a real environment is a poor match to the ideal conditions assumed. Variations due to obstruction, reflection, refraction, scattering, fading and shadowing in practice cause substantial deviation from ideal behavior.

When conducting this experiment, we kept the mobile node's orientation with respect to the access point constant, and made sure that the orientation of the network card remains the same throughout the mobility path. The distance vs. signal strength plot of the resulting values is shown in Figure 1.

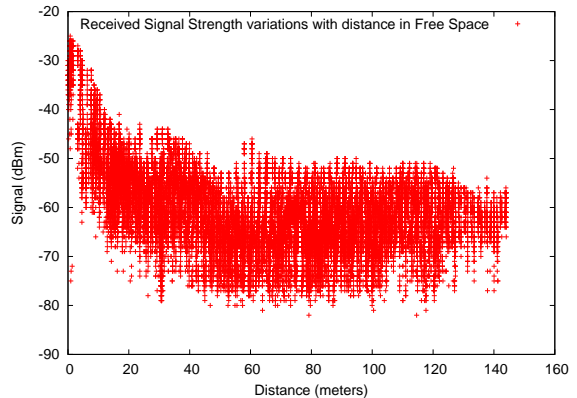


Fig. 1. RSSI Variation

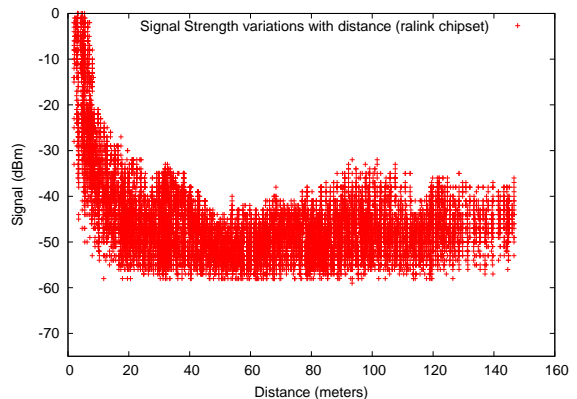


Fig. 2. RSSI Variation (Ralink chipset)

It is clear from Figure 1 that if we create ideal conditions, we can see that at smaller distances, the signal strength will be higher and at larger distances the signal strength will be weaker. The slope of the curve is linearly decreasing in the initial portion of the curve indicating that at short distances signal strength in dBm drops off linearly with distance. However, after a certain distance, the signal strength remains almost constant with about 20 dBm variation. It is also clear from Figure 1 that at a given distance the variation (difference between the maximum and the minimum value) of the signal is almost 20 dBm.

In order to make sure that the variations and the patterns we see are not due to chipset design decisions, we changed the roles of the nodes acting as access point and as mobile nodes. This allowed us to use the card based on the RaLink chipset as the mobile node. Again, we repeated the experiment making sure that we keep the antenna orientation and the line-of-sight. The variations in signal strength with varying distance when the node is mobile is for the Ralink card is shown in Figure 2. It can again be seen from this plot that in the shorter distances, the decay in signal strength in dBm decreases linearly with distance. However for the significant latter portion of the distance range farther apart, the signal strength remains constant.

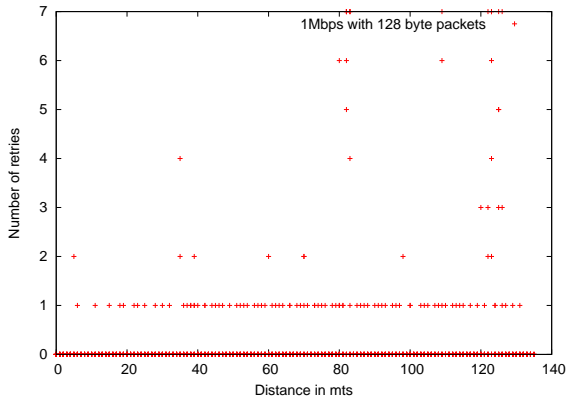


Fig. 3. Retry Count, 128 byte packets, 1Mbps

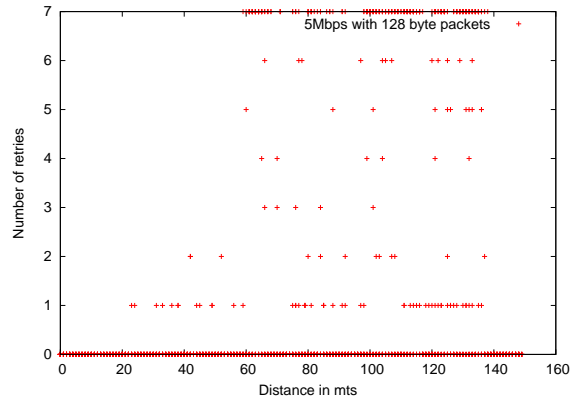


Fig. 5. Retry Count, 128 byte packets, 5Mbps

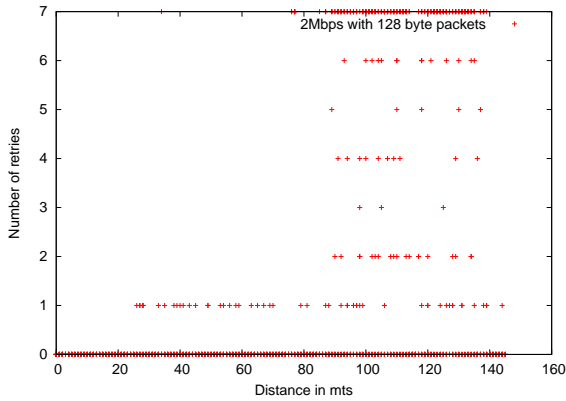


Fig. 4. Retry Count, 128 byte packets, 2Mbps

It must be noted that this signal strength is measured only for the successfully received beacons. Thus the variation in signal strength that we see in the plots above cannot be concluded to be the absolute variations in the signal. These are signal variations for successfully received packets. Thus, these can only denote variations from a receiver node's perspective.

B. Retry Measurements

The second set of experiments were designed to understand the variation in packet error rate varies with respect to changing distance, modulation and packet sizes. Sixteen runs of the experiment were done for each combination of data rate (DS1, DS2, DS5, DS11) and packet sizes(128, 256, 512, 1024). For each of the combinations, we measured the number of retries as the mobile node moves across the field in a given mobility path. In the interest of space, we only present results for the 128 byte packet sizes, for the two lowest data rates. The results are shown in Figures III-B, III-B and III-B. The results for the other combinations are similar. It can be easily concluded from the above graphs, that as the distance increases, the number of retries needed to send a particular frame increases. At locations farther from the access point node, the retries are more pronounced than at nearer locations. As a retry is attempted only

when a previous try has failed, it can be only because of a PHY error. It is worth noting that we are doing our experiment in a frequency band (channel 16) where there was no MAC layer interference from other wireless nodes operating. Also, the beacons being generated from the access point node were way too sparse to cause any noticeable effect on our measurements. It can also be seen from the plots that, for a given distance range, there are more retries for a packet to be sent at the highest rate (DS11) than at the lowest rate (DS1).

To understand this clearly, we present a few representative plots to show the probability that a given packet sent to a destination node at a given distance reaches the destination successfully. These plots plot the distance versus the retry probabilities. It is clear from the Figure 6 that as the distance increases, the probability that a packet requires larger number of retries to achieve a successful transmission increases. We calculated that of all the packet transmissions that went to 7 retries, only a small fraction succeeded (0.001). Thus, we can conclude that as the distance increases, the probability that a packet is delivered without an error decreases. It is also clear that the number of retries have relatively little, but significant, presence in the plots. Thus, we can conclude that although a significant number of packets do have errors while being transmitted at a given distance, they do get eventually delivered after a few retries.

IV. SIMULATION MODEL AND RESULTS

In this section, we discuss the stochastic physical layer model for wireless propagation that we incorporated into our *GTNetS* simulator. This new model is based on the empirical measurement study discussed in the previous section.

A. Radio Propagation Model

We used the received signal strength measurements to create radio propagation models for the receive paths. Although these models are independent of the topology, they are definitely a characteristic of the environment in which the experiments were conducted. The RSSI measurements were collected into bins of 10 meters each.

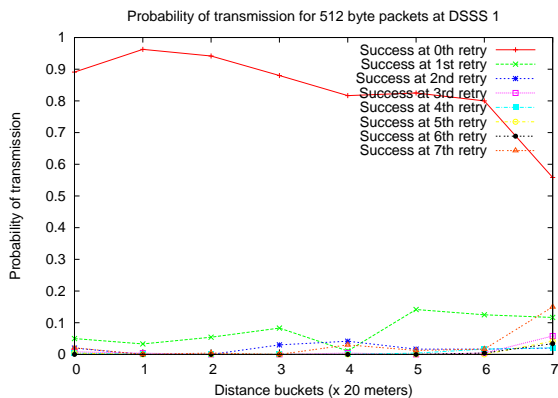


Fig. 6. Frame Retries Probabilities, 1Mbps

For each bin, we then construct a cumulative distribution function (CDF) of the received signal strength variation. The model has the following assumptions:

- 1) Signal strength is a characteristic of the environment and the distance between the signal source and the measurement point.
- 2) Signal strength that could not be detected by the measurement apparatus does not cause any interference.

The second assumption can be discounted if the measurements were made using a spectrum analyzer. However, the measurements as exported by the 802.11 physical layer convergence layer is what is available for the higher layers if they want to make any decisions based on signal strength. A good example of using this information is when mobile nodes operating in infrastructure mode decide when to disassociate with an access point and associate with another. In our investigations of hardware, we could not find any commodity 802.11 hardware that exports the signal strength values that the CCA (Clear Channel Assessment) algorithm uses to determine. Only the prism chipset [41], [42] exports that value, but it does so only when it successfully receives an 802.11 frame.

We extended the existing propagation models in GT-NetS to provide an empirical propagation model. We use this model to determine the signal strength at a given distance. The model essentially calculated the bin from which the signal strength has to be sampled. As discussed earlier, each bin has an associated CDF of RSSI values.

B. Packet Error Rate Model

We used the packet retries to derive a packet error rate model for the transmit paths. The measurements from the second experiment have the number of retries for each combination of datarate (DS1, DS2, DS5 and DS11) and packet size with varying distance. At each distance we note the number of retries required for a packet transmission to succeed. The methodology we followed to derive the models is as follows.

We categorize all our distance measurements into 20 meter buckets. Since the maximum distance that we measured is about 155 meters, all our measurements fit into 8 buckets (0-7). Using the retry counts, we then calculate the probability of success of a packet transmission for each retry count at the given datarate, packet size and distance. The probability of failure is the reverse of the success probability. This probability of failure is therefore the packet error rate. Since, it is the packet error rate only that we are concerned in discrete-event network simulation when transmitting the packet over a link, we need not decipher the bit error rate from this. It must be noted that this is the probability of success of a transmission. And a successful transmission in our case is the exchange of a DATA frame as well as an ACK. Therefore, when creating the simulation model, we assume that the data frames are transmitted with this packet error rate, but the ACK frames have zero probability of an error.

An alternate method would have been to simply use broadcast frames in our experiments so that we could accurately calculate the error probabilities of ACK frames as well. However, the hardware we used in our experiments did not send the retry counts or the success indications in the processed DMA descriptors. Thus we had to use unicast frames for our measurements.

C. Simulation Results

In this section we discuss the simulation experiment we conducted to validate our simulation models described above.

In the first simulation experiment we simulate received signal strength. The topology consists of two nodes, one of which acts as the access point and the other mobile. The mobility pattern was simple, with the mobile device moving in a straight line from near the access point, to approximately 140 meters away, and back again. The fixed node (access point) transmits beacon frames at 10 frames per second. The received signal strength at the mobile node is measured continuously for each received packet. The signal strength measurements obtained in the simulation as a function of varying distance are shown in Figure 7.

The second simulation experiment simulates throughput and packet loss. The topology is identical to that used in the first experiment. One of the node is stationary and the other moving. Both the nodes are initially positioned 1 meter apart. The mobility pattern is the same as before. The moving node moves away from the static node for a radial distance of 141 meters and then returns back to its original position. Since our model does not take into account the directional variations in the propagation and assumes that the speed is constant at 1.5 meters per second, our simulation experiment uses the same scenario. We send UDP frames at 10 packets per second from the mobile node to the static node. We sent 128, 256, 512 and 1024 byte frames at various datarates in our simulation experiment.

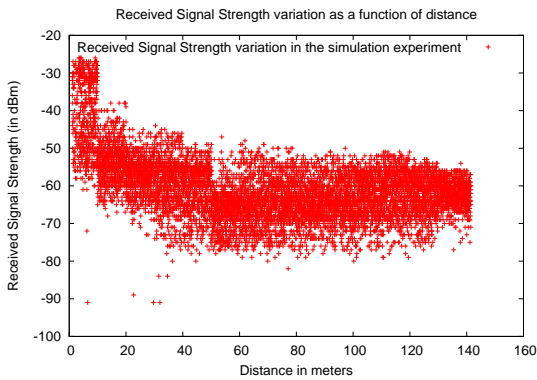


Fig. 7. Received signal strength variations as a function of distance(simulated)

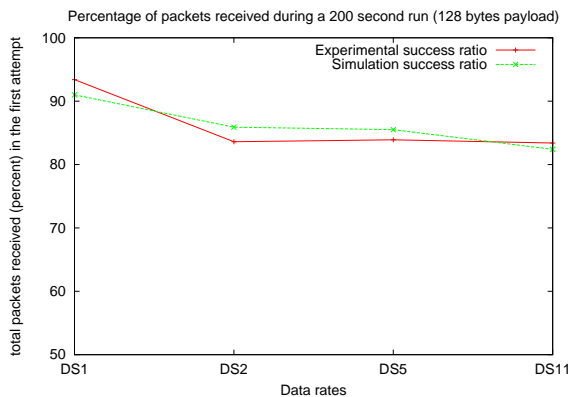


Fig. 8. Percentage of frames with no retries, 128 byte packets

We present the results of 128 byte transmissions and 1024 byte transmissions in Figures 8 and 9. It can be seen from the plots that the throughput measurements from the simulation model closely reflect the results of the field experiment. For the same mobility, the increase in payload size decreases the number of packets successfully transmitted in the first attempt by almost two-thirds. We believe that the differences in the model are due to experimental randomness that cannot be fully reproduced in the model. A much larger dataset might help bridge the graphs further. We omitted for brevity the comparisons of other packet sizes, but the results were similar.

V. CONCLUSIONS

This work is a study of an IEEE 802.11 wireless link behavior in a obstruction free outdoor environment. Our work mostly concentrates on low-speed mobile nodes. We define two sets of measurements to separate out the transmit and receive path characteristics. While the receive path characteristics are defined by the radio propagation losses, the transmit path characteristics are defined by the packet error rate when a packet of a given size is transmitted at a given power level and modulation mechanism. We derived this packet error rate from the number of retries it takes to send a given packet. We

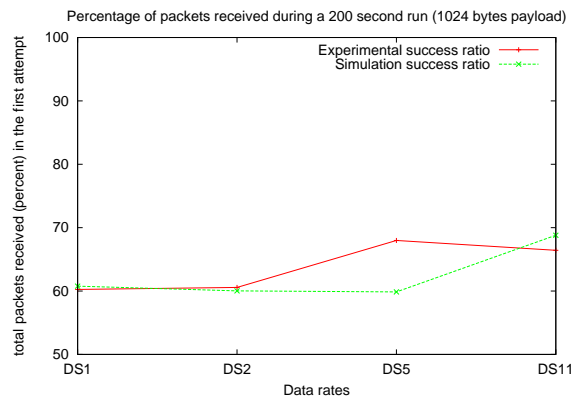


Fig. 9. Percentage of frames with no retries, 1024 byte packets

infer that the decay of signal strength with distance is not strictly an exponential decay but a rather long tailed decay. Thus, we use an empirical distribution to model it. We model the transmit path as a packet error probability derived from the retry statistics. We incorporated these models in the Georgia Tech Network Simulator. To validate our models, we conducted experiments with two nodes without any contention resolution (of the 802.11 MAC) involved. Our simulation results are a close match to those that were measured during the experiments. It should be noted that the radio propagation models have been constructed using only the RSSI values of successfully received frames.

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