Effects of Wireless Physical Layer Modeling in Mobile Ad Hoc Networks

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ABSTRACT
In most studies on mobile ad hoc networks (MANET), simulation models are used for the evaluation of devices and protocols. Typically, such simulations focus on the specific higher layer protocols that are being proposed, and tend to ignore details of models at other layers, particularly the interactions with physical layer models. In this paper, we present the set of factors at the physical layer that are relevant to the performance evaluations of higher layer protocols. Such factors include signal reception, path loss, fading, interference and noise computation, and preamble length. We start the discussion with the comparisons of physical layer models in ns-2 and GloMoSim, two commonly used simulators for MANET studies, and then quantify the impact of the preceding factors under typical scenarios used for the performance evaluation of wireless ad hoc routing protocols. Our experimental results show that the factors at the physical layer not only affect the absolute performance of a protocol, but because their impact on different protocols is non-uniform, it can even change the relative ranking among protocols for the same scenario.

1. INTRODUCTION
Simulation is commonly used for the evaluations of wireless network protocols and devices under specific conditions, as the complexity of recent protocol and device implementations makes it harder to build accurate analytical models. However, even in simulation models, it is often the case that only the specific protocol that is being evaluated is modeled in detail, and the effect of interactions with other layers are not accounted for sufficiently. This may introduce substantial inaccuracies in the model predictions, particularly for wireless protocols.

In MANETs (Mobile Ad Hoc Networks), although most of the recent performance studies consider the effects of multiple layer interactions, they tend to consider only interactions with the layer that directly interact with the protocol being evaluated. For instance, many studies on the ad hoc routing protocols consider the effects of outgoing queues and MAC protocol overheads, but few studies account for the physical layer effects such as preamble length, interference and noise which may have a greater impact on the operation of the routing protocols. In fact, our preliminary studies that compare multiple simulation tools revealed that different simulation tools yield quite different results even when they are configured with the same set of protocols, and such differences are mostly derived from different assumptions made at the physical layer.

This paper addresses the issue of multiple layer interactions and identifies the modeling factors of the physical layer that make the most difference in the simulation results. The paper also quantifies such differences under typical scenarios used for the performance evaluation of wireless ad hoc routing protocols. The physical layer models considered in this paper are those of *ns-2* [11][18] and GloMoSim [3][5], which have been commonly used for MANET studies. The experimental results show that some of the modeling factors of the physical layer can change the simulation results significantly, and can even change the relative ranking of routing protocols for specific scenarios.

The remainder of this paper is as follows; the next section describes the primary factors that are relevant in modeling the physical layer in mobile wireless systems. Section 3 demonstrates that differences in the modeling of this layer can lead to very different predictions of protocol performance under typical MANET scenarios, and also gives insights into the causes of such different results. Section 4 is the conclusion.

2. MODELING FACTORS OF WIRELESS PHYSICAL LAYER

2.1 Physical layer preamble
The length of signal preamble and header for the physical layer (simply physical layer preamble hereafter) has a non-negligible effect on the performance of higher layer protocols, and this is particularly true for wireless communication media because they require long preambles to assess the channel condition prior to each transmission. For instance, the IEEE 802.3 standard [6], which defines a common wire line medium, only requires 8 bytes as the preamble of the physical layer, while the IEEE 802.11 standard [8] requires 192 microseconds for the physical layer in its DSSS (Direct Sequence Spread Spectrum) reference

configuration. Besides the fact that the latter overhead is already three times longer than the former at the speed of 1Mbps, the latter standard specifies the amount of overhead in microseconds regardless of its medium speed. This is because different medium speeds are realized by different modulation schemes, and the modulation scheme to be used for the frame is specified in the physical layer header. Thus the header (48 bits) and the preceding preamble (144 bits) must be transmitted at the lowest speed (1Mbps) using the DBPSK (Differential Binary Phase Shift Keying) modulation. Therefore, if the highest rate[1] (11Mbps) currently available in the market is used, the consideration of physical layer preamble and header can increase the size of MAC short control frames (14 bytes) by a factor of 20 because the overhead (preamble + header) is worth 264 bytes at that rate. Clearly, the accurate consideration of the physical layer preamble is essential to calculate the right transmission duration of each radio signal.

2.2 Interference computation and signal reception

Computation of interference and noise at each receiver is a critical factor in wireless communication modeling, as this computation becomes the basis of SINR (Signal to Interference and Noise Ratio) or SNR (Signal to Noise Ratio) that has a strong correlation with FER (Frame Error Rate) on the channel. The power of interference and noise is calculated as the sum of all signals on the channel other than the one being received by the radio plus the thermal (receiver) noise. The resulting power is used as the base of SNR, which determines the probability of successful signal reception for a given frame. For a given SNR value, two signal reception models are commonly used in wireless network simulators: SNR threshold based and BER based models. The SNR threshold based model uses the SNR value directly by comparing it with an SNR threshold (SNRT), and accepts only signals whose SNR values have been above SNRT at any time during the reception. The BER based model probabilistically decides whether or not each frame is received successfully based on the frame length and the BER (Bit Error Rate) deduced by SNR and modulation scheme used at the transceiver. As the model evaluates each segment of frame with a BER value every time the interference power changes, it is considered to be more realistic and accurate than the SNR threshold based model. However, the SNR threshold based model requires less computational cost and can be a good abstraction if each frame length is long.

2.3 Fading and path loss

While propagation models such as fading, shadowing and path loss are not part of the radio physical models, they control the input given to the physical models and have great impact on their performance, and including these models is relevant to the emphasis of multiple layer interactions in this paper.

Fading is a variation of signal power at receivers, caused by the node mobility that creates varying path conditions from transmitters. Fading models with Rayleigh or Ricean distributions are commonly used to describe the MANET environments. The fading with the Rayleigh distribution is for highly mobile conditions with NLOS (No Line Of Sight) between nodes, while the latter accounts for the LOS (Line Of Sight) path between nodes. The signal power from the LOS path with respect to the power from NLOS paths can be controlled by a parameter called Ricean K factor. The AWGN (Additive White Gaussian Noise) model is referred to as an idealistic channel condition where no signal fading occurs.

Another important factor to model the signal propagation is path loss, which defines the average signal power loss of a path on the terrain. The two-ray path loss model is suited for LOS microcell channels in urban environments [16], and its use for MANETs can be justified by the environmental similarities (low transmit power and low antenna height). The free space model is used as a basic reference model and is also considered to be idealized propagation model. With this path loss model, even nodes far from the transmitter can receive packets, which can result in fewer hops to reach the final destination in MANETs. Therefore, simulation results with the free space path loss model tend to be better than with other path loss models. However, as signal propagation with little power loss may cause stronger interference for concurrent transmissions, it does not necessarily yield the best performance under all scenarios.

2.4 Physical layer models of common simulation tools

Table 1 summarizes the physical layer models currently available in GloMoSim (2.02), *ns-2* (2.1b8) and the standard radio model package of OPNET [12]. Although this study does not use OPNET, it is included in the table as a reference because it is used for several MANET studies. Please note that this table lists only the features in their standard packages, and does not indicate the infeasibility to implement specific models in these simulation tools. Also note that the paper used an old version of *ns-2* [18] for the study, which includes fewer models than the latest *ns-2* for the physical layer.

Table 1: Physical layer and propagation models available in GloMoSim, ns-2 and OPNET

Simulator	**GloMoSim**	***ns-2***	**OPNET**
Noise (SNR) calculation	Cumulative	Comparison of two signals	Cumulative
Signal reception	SNRT based, BER based	SNRT based	BER based
Fading	Rayleigh, Ricean	Not included*	Not included
Path loss	Free space, Two ray, etc.	Free space, Two ray	Free space

* Ricean and Rayleigh fading models [15] are available for *ns-2* [1], but they are not included in *ns-2* (2.1b8), thus the table does not list them.

There are substantial differences in the noise calculation and the signal reception among these three simulators. Both GloMoSim and OPNET radio models calculate the interference and noise

[1] This data rate is proposed in the IEEE 802.11b standard [7], which also provides a shorter preamble option (96 microseconds).

power as described in Section 2.2, and SNR for a given signal is recalculated every time the interference power changes during each signal reception. The *ns-2* radio model does not calculate the noise power like the others, but calculates pseudo SNR values by treating a signal that has arrived prior to the receiving signal to represent the noise on the channel, which may end up estimating better channel conditions than the other two tools. *ns-2* then applies the SNR threshold based model to determine the successful reception of each signal. The OPNET standard radio model includes only the BER based signal reception model, and GloMoSim includes both signal reception models.

Both GloMoSim and *ns-2* radio models are implemented based on the DSSS PHY reference configuration in the IEEE 802.11 standard [8], except that *ns-2* used in this study set parameters for an old version of WaveLAN whose radio frequency is at 914 MHz. The IEEE 802.11 standard is commonly used in MANET studies as well as actual wireless LANs. Its MAC protocol is based on CSMA/CA and has an option of RTS/CTS to avoid the hidden terminal problem, which occurs frequently in MANET environments. Besides the standard, both simulators refer to the same network card (WaveLAN) and define two thresholds at the physical layer to avoid unnecessary attempts of receiving low power signals [10]. The carrier sense threshold (CST) defines the power level that the radio can sense and defers transmission of pending frames. The receiving threshold (RXT > CST) defines the minimal power level at which the radio tries to receive the signal.

3. EFFECTS OF DIFFERENT PHYSICAL LAYER MODELS

This section quantifies the effects of physical layer models described in Section 2 on typical scenarios used in the evaluation of ad hoc routing protocols. We first compare the physical layer models provided by *ns-2* [18] and GloMoSim [5], in order to identify the differences in the physical layer modeling among the two simulators. The two simulation tools have a common set of wireless protocol models, including the IEEE 802.11 PHY and MAC, as well as ad hoc routing protocol models like AODV [14] and DSR [9]. This facilitated our study of the impact of the physical layer models using the two simulators, without the need for developing new protocol models.

Scenarios for this comparison are created as follows; each scenario is configured with N (= 50, 100, 200) network nodes. We assume that the scenario simulates a flat terrain that is gridded into a standard pattern with $10 \times N / 10$ cells; each radio is placed randomly within a unique cell. As the default transmission range of the radio is set to 250m, we define the cell size to be 125m to ensure that the network is never partitioned. The average number of neighbors ($250^2\pi / 125^2$) for a node is approximately 12 at this node density. As the primary purpose of these scenarios is to compare the physical layer models of *ns-2* and GloMoSim, the configuration for other layers is simplified as much as possible. Routing information for each node is precomputed by executing *ns-2* for every scenario with the DSDV routing protocol [13], and the resulting (identical) routing information is fed into both *ns-2* and GloMoSim. This static routing information is used to avoid a timing problem where even identical implementations of a routing protocol can generate completely different routing information due to slight differences in the order of control packet arrivals, caused by differences in the random number generations. By using the precomputed routing information, we ensure that traffic flows in the two simulators are consistent. Mobility is disabled in these scenarios because of this static routing approach. At the beginning of simulation, each node randomly chooses a destination in the network and transmits CBR (Constant Bit Rate) traffic at a rate of P (= 1, 2, 5, 10) 512byte data packets per second to the destination. Three networks are created for each set of N and P with different random number seeds, which result in 36 scenarios.

Both *ns-2* and GloMoSim use the same set of models for these scenarios: the two-ray path loss model, the SNR threshold based signal reception model, the IEEE 802.11 PHY DSSS (Direct Sequence Spread Spectrum) and MAC DCF (Distributed Coordination Function). In this study, the RTS/CTS control messages are used for all the unicast packets regardless of their sizes. The parameters for the physical layer models are also set to be identical: SNRT = 10 dB, CST = -78 dBm, RXT = -64 dBm, 914 MHz radio frequency and 24.5 dBm transmit power, all of which are defined in *ns-2* by default. To minimize differences in simulation results caused by different random number sequences, the only use of random numbers in the scenario is to determine back off times for MAC DCF (Distributed Coordination Function) in the IEEE 802.11 standard.

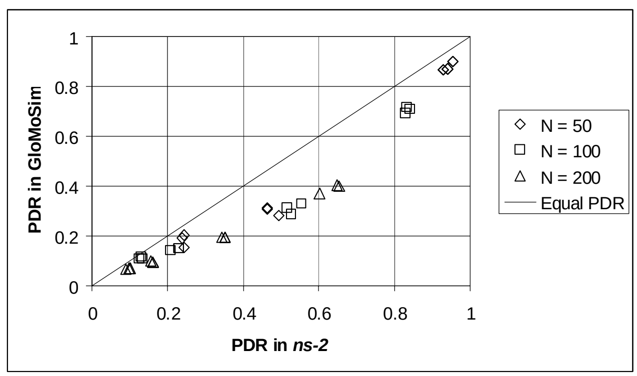

Figure 1: PDRs yielded by *ns-2* and GloMoSim for the same scenarios (prior to modeling changes)

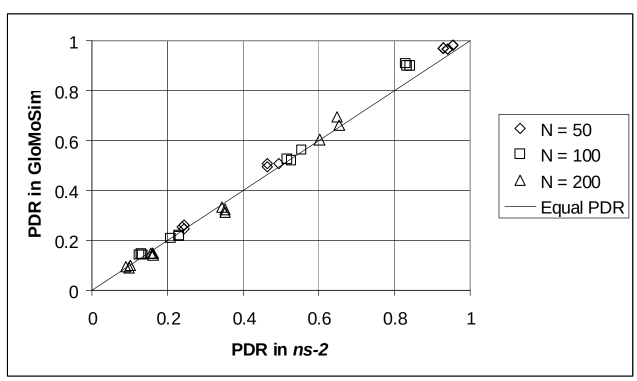

Figure 2: PDRs yielded by *ns-2* and GloMoSim for the same scenarios (after modeling changes)

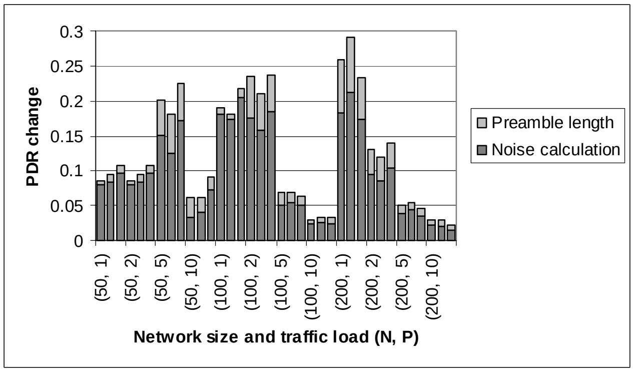

Figure 3: PDR increases when the GloMoSim PHY model is modified to be consistent with *ns-2*

Figure 1 shows the packet delivery ratios (PDR) yielded by *ns-2* and GloMoSim for these 36 scenarios. PDR, defined as the number of packets received by the CBR destinations over the number of packets sent by the CBR sources, is widely used as the primary metric for the evaluation of ad hoc routing protocols with CBR traffic. In the figure, only the network sizes of data points are shown for the visibility, but as a trend, the PDR value becomes lower for larger network sizes, and also becomes lower for heavier traffic loads. As seen from the figure, although the difference of the two PDR values yielded by *ns-2* and GloMoSim is small for most scenarios with very low or high PDR values, the GloMoSim PDR values are consistently lower than those of *ns-2*. Also, scenarios with *ns-2* PDR of 0.3 to 0.9 have significantly different PDR values from the two simulators, with the worst case difference being more than 25% of total packets sent in the scenario (*ns-2* PDR: 0.654, GloMoSim PDR: 0.401 for N = 200 with P = 1). This implies that the two simulators yield similar performance predictions when the network condition is either very good or severe, while they predict quite different network performance when its condition is not extreme. Importantly, the non-extreme network condition is where many researchers also find the most performance difference in their higher layer protocols.

Every model used for these scenarios was analyzed to identify the causes of this divergence in the simulation results. Two factors were identified for the difference in the predicted results: physical layer overhead and noise calculation. Figure 2 shows the PDRs yielded by *ns-2* and GloMoSim for the same scenarios after the GloMoSim models are adjusted to be consistent with *ns-2* in these modeling factors. As shown in the figure, with the new settings, these two simulators yield very similar results for all the scenarios, and the remaining differences can easily be attributed to differences in the random number sequences. This indicates that the observed differences in Figure 1 are due essentially to these two modeling factors at the physical layer. Note that the decision to make adjustments to GloMoSim rather than *ns-2*, was driven primarily by our deeper familiarity with GloMoSim, and is not meant to indicate that one simulator was more accurate.

Figure 3 shows how each of these two modeling factors contributes to the overall changes in the PDR values. The height of each bar indicates the PDR increase when the GloMoSim physical layer models are modified to be consistent with those in *ns-2*, and the two colors in each bar show the contribution levels of the two modeling factors to the overall PDR change. The chart shows a general trend that the noise calculation has greater impact on the PDR changes than the preamble length. The following two subsections describe how these modeling factors contribute to the observed PDR changes.

3.1 Physical layer preamble

Both *ns-2* and GloMoSim use the same parameters for the IEEE 802.11 DSSS PHY except that *ns-2* regards the physical layer preamble to be transmitted at the same speed as the frame data. As described in Section 2.1, this is not an accurate modeling as the length of the physical layer preamble is specified in microseconds regardless of the data rate in the standard. As the transmission speed used in *ns-2* is 2 Mbps by default, the duration time used in *ns-2* for the physical layer preamble results in 96 microseconds, exactly half the length defined in the standard. Although changing the preamble size in the model is straightforward, as shown in Figure 3, setting the duration time for the preamble to 192 microseconds (default value in GloMoSim) from 96 microseconds (default value in *ns-2*) degrades the PDR values by 0.7% to 7.2%. Figure 4 further breaks down this increase of packet drops into two primary causes: outgoing queue overflow, and the IEEE 802.11 MAC retransmission limits. The PDR degradation is defined as the reduction in the number of packets received over the total number of packets sent (PDR_{before} – PDR_{after}). The figure indicates that the longer transmission duration increases the packet drops due to outgoing queue overflow as it reduces the effective channel capacity for data, which is why such drops occur significantly for larger network sizes or heavier traffic loads. However, the packet drops due to the MAC retransmission limits are reduced since the total number of packets transmitted in each scenario is reduced because of more drops at the queue.

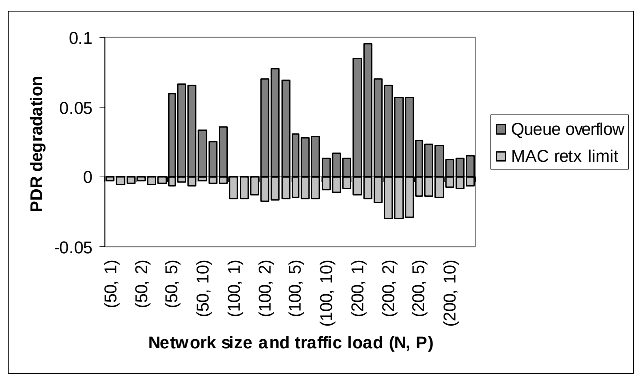

Figure 4: PDR degradation due to the longer physical layer preamble

One could argue that the choice of a specific value for the physical layer preamble does not really matter if it affects the overall network performance equally for all protocols. To answer this question, we executed a set of simulation runs to measure the PDRs for two widely used ad hoc routing protocols, AODV [14] and DSR [9], as a function of the physical layer preamble length. The simulation is carried out using the default setting of GloMoSim for a scenario where one hundred nodes with random waypoint mobility (0 to 30 m/s with 100 s pause time) are placed randomly over a flat terrain (3300 × 900m), and 20 or 40 CBR sessions are given to the network. This configuration is based on the experiments described in [4], and the parameters such as the mobility speed and the terrain size are scaled to reflect the difference in the communication ranges of radio models in *ns-2* (250m) and GloMoSim (376m). Each CBR session transmits 512 byte data packets between a randomly selected source and a destination at a rate of 4 pps for 20 CBR cases and 2 pps for 40 CBR cases. This scenario is similar to the scenario used in [4] for the performance comparison of AODV and DSR, and is typical for the evaluation of ad hoc routing protocols. The results are shown in Figure 5, which plots the PDR for each protocol as a function of the length of the physical layer preamble. Note that the implementations of AODV and DSR in GloMoSim have not incorporated all the optimizations suggested in their latest Internet drafts, but our objective is to demonstrate the impact of changes in physical layer models on protocol level comparisons, not the performance comparisons of these protocols.

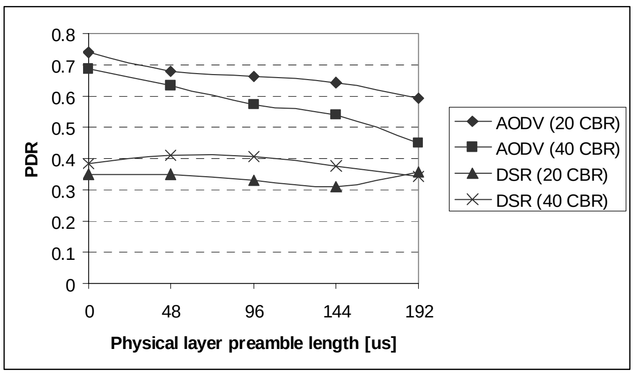

Figure 5: PDRs of AODV and DSR with different lengths of physical layer preamble

As shown in Figure 5, the AODV performance is affected much more by variations of the physical layer preamble length, while the performance of DSR is relatively independent of this factor. Although AODV consistently outperforms DSR in this set of experiments, the percentage difference in PDR with the two protocols changes dramatically from 39% for no preamble to 23% for 192-microsecond preamble for the 20 CBR cases. As the larger physical layer overhead lowers the effective channel capacity, this indicates that the network performance with AODV is actually bounded by the channel capacity while DSR does not appear to fully exploit the maximum network capacity. This is also supported by the fact that the scenario with AODV has significantly less packet drops due to the MAC retransmission limits than that with DSR, suggesting that AODV provides better route information to the network than DSR does in this scenario. This demonstrates that the length of physical layer preamble can affect the network performance of different protocols differently.

3.2 Interference and noise calculation

Since there is no noise calculation in the *ns-2* physical layer model, it yields better signal reception rates than GloMoSim resulting in higher PDR values as described in Section 2.4. Figure 6 breaks down the PDR degradation into the two factors in the same way as shown in Figure 4 in the previous subsection for the physical layer preamble. Although both noise calculation and longer physical layer preamble reduce the PDR values in all the scenarios, by comparing Figure 4 and Figure 6, their effects on the PDR degradation are quite different. Due to the IEEE 802.11 MAC retransmission limits, the consideration of interference and noise significantly increases the data packet drops as the accumulated power of interference signals and noise can increase the probability of frame drops including MAC control frames. As the dropped data packets are not forwarded further to the destinations over multiple hops, the increase in the packet drops at the MAC layer reduces the overall traffic given to the network, resulting in the decrease in the packet drops due to the outgoing queue overflow. This is the opposite effect of the longer physical layer preamble observed in the previous subsection, where the longer preamble causes more queue overflows due to the reduction of the effective channel capacity, resulting in less packet drops due to the MAC retransmission limits.

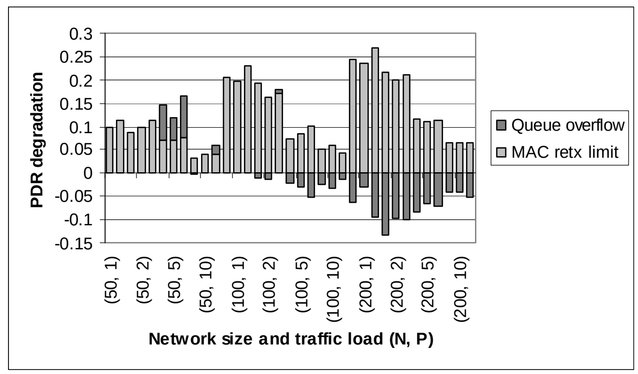

Figure 6: PDR degradation due to the interference and noise

3.3 Signal reception, path loss and fading models

The previous two subsections described how the two modeling factors at the physical layer caused differences in estimated network performance from *ns-2* and GloMoSim. In general, a number of other modeling factors can affect overall network performance as described in Section 2. In this subsection, we demonstrate that changes in the signal reception, path loss, and fading model can have a substantial impact on the predicted performance of higher layer protocols.

A scenario similar to the one in the previous subsection is used to examine the effects of these changes; a hundred nodes with random waypoint mobility (0-20 m/s with 100 s pause time) are placed randomly over a flat terrain (1200 m × 1200 m), and 40 CBR sessions (512 byte data, 2.666 packets/sec) are given to the network. A path loss model {Free space or Two ray}, a fading model {None (AWGN), Ricean (K Factor of 5) or Rayleigh}, a signal reception model {SNR threshold based or BER based}, and an ad hoc routing protocol {AODV or DSR} are used to configure each simulation run. For Ricean and Rayleigh fading models, the coherence time is assumed to be larger than the time for a packet and the associated MAC control packets (RTS, CTS and ACK), i.e. the fading is kept constant during the frame sequence for each data packet. While this assumption may be invalid for this rapid mobility scenario stressing the routing protocol, it is reasonable for scenarios with more realistic and thus slower node mobility. The BER based model used BER values derived from the DBPSK modulation. For the SNR threshold based model, SNRT was set to 9.1dB which corresponds to the SNR value needed for a 0.5 probability of successful reception using DBPSK for a 568 byte + 192 microsecond length data packet. Note that for the SNR threshold based model, this SNR gives a lower probability of arrival for short control packets than the BER-based model, as the FER is a function of frame length and BER.

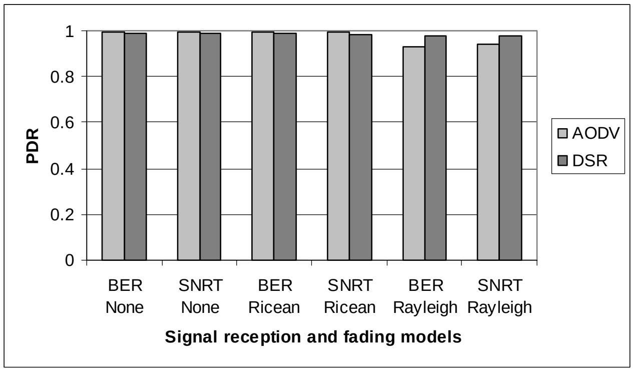

Figure 7: PDRs of AODV and DSR with different signal reception and fading models (Free space)

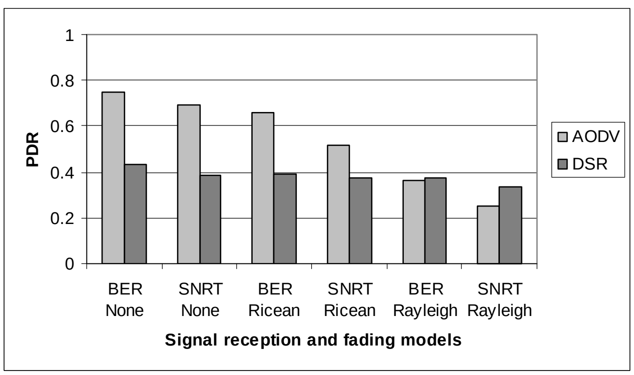

Figure 8: PDRs of AODV and DSR with different signal reception and fading models (Two ray)

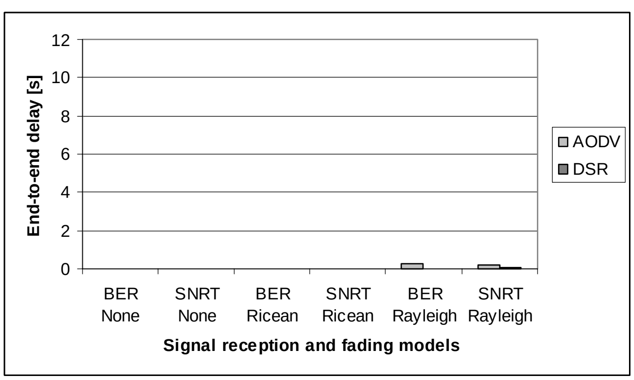

Figure 9: End-to-end delays of AODV and DSR with different signal reception and fading models (Free space)

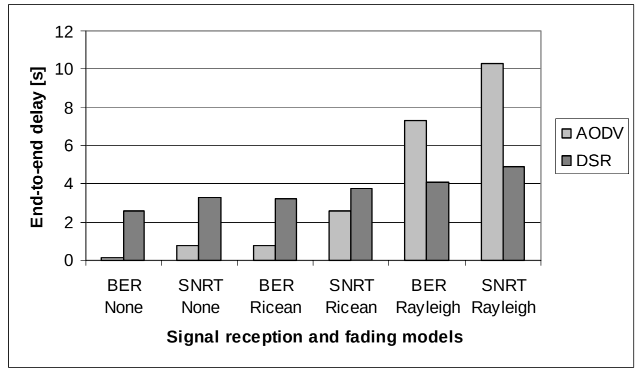

Figure 10: End-to-end delays of AODV and DSR with different signal reception and fading models (Two ray)

Figure 7 and Figure 8 show the PDR with different signal reception and fading models, and Figure 9 and Figure 10 show the average end-to-end delay for the corresponding cases. Each data point represents the average value from 8 runs with different random number seeds. With the different seeds, the mobility pattern as well as the CBR sessions in the network are set differently.

As shown in these four charts, both routing protocols perform very well with the free space path loss model. Note that all other physical layer parameters were kept constant for this experiment, thus each node with the free space path loss has a larger communication range (627m) than it does with the two ray path loss (376m). This results in shorter routes to the destinations and thus fewer packet drops as described in Section 2.3. However, if the transmit power is adjusted to have the same communication range as with the two ray path loss, the network performance with free space path loss is expected to become worse than that with two ray path loss due to stronger interference. The time scale of Figure 9 is adjusted to be consistent with that of Figure 10, and this avoids magnifying small changes in the end-to-end delay with the free space path loss model. Although it is illegible in the figure, the end-to-end delay increases as the estimated channel condition becomes more severe (AODV: 0.01 to 0.22 s, DSR: 0.01 to 0.04 s).

With the two ray path loss model, the PDR values from the two routing protocols change more significantly with different signal reception and fading models. As expected, PDR values with the SNR threshold based model are always lower than those with the BER based model due to higher control packet loss noted earlier in this subsection. The PDR values also decrease, as the fading models become more extreme from no fading to Rayleigh. Interestingly, the PDR with AODV decimates under increasingly harsh channel conditions (from 75% to 24%), while the performance with DSR, although starting much lower for the least stressful condition, is much more consistent (from 43% to 33%).

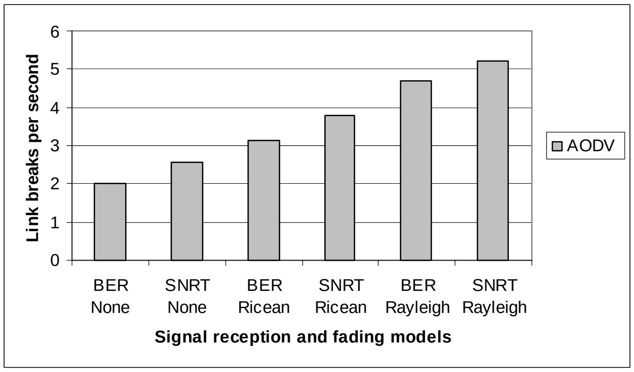

Figure 11: Number of link breaks in AODV with different signal reception and fading models (Two ray)

To identify the cause of this performance deterioration with AODV, we examined the number of link breaks. The link break happens when the MAC protocol fails to transmit a data packet, thus the routing protocol must find an alternative route to the destination. Note that a single link break can cause multiple route breaks as the link can be used for multiple routes. Figure 11 shows the number of link breaks with AODV for different signal reception and fading models. These numbers in the figure are from the same mobility pattern, thus the differences in the number of link breaks are solely derived from the different channel conditions estimated by the signal reception and fading models. As shown in the figure, AODV has more than two times the number of link breaks for the worst case (SNRT, Rayleigh) than for the best case (BER, None), and this link break increase can easily reduce the PDR by more than 50% as shown in Figure 8.

Note that the number of link breaks with DSR for the same cases is not included in the figure, as DSR reacts to the link breaks differently and the direct comparison of these two protocols with this metric is not very meaningful. In AODV, the node that had the link break initiates the alternative route discovery process by propagating the link break notification back to all the sources with routes through that link, and the sources start route discovery floods. In DSR, on the other hand, the node first looks into its local route cache and tries to salvage the packets going out on that link with alternative routes. It also propagates the link error notifications back to the packet sources, but unlike AODV, the source can simply look into its cache of routes to find another without having to flood the route requests. With these differences in their route discovery processes, AODV has more protocol overhead than DSR for each link break. In the comparative study of these two routing protocols using *ns-2* [4], the DSR route discovery using the cache did not work well, as the cause of link breaks in *ns-2* is most likely due to the mobility that can change the connectivity to all neighboring nodes. In such cases, all routes in the cache may be obsolete and thus the node is unlikely to find an alternative route in the cache. However, if the packet drop is due to the interference and noise, the link break does not necessarily imply the unreachability to the other nodes, thus the cache contents may still be useful to find alternative routes. These results demonstrate again that the consideration of physical layer models is important even if the radio communication range is not changed, and those modeling factors may change the conclusions of protocol evaluations.

4. CONCLUSIONS

This paper has focused on the effects of physical layer modeling on the performance evaluation of higher layer protocols, and has demonstrated the importance of the physical layer modeling even if the evaluated protocols do not directly interact with the physical layer. The paper has also described details of physical layer modeling in the three simulation tools commonly used for MANET studies, and shown the impacts of their differences on the overall network performance for scenarios typically used for the evaluation of ad hoc routing protocols. Future work includes the validation of physical layer modeling against real wireless ad hoc networks, and the evaluations of recent wireless device technologies such as transmit power controls or smart antennas, particularly for their impact on the overall performance of MANET.

5. ACKNOWLEDGMENTS

This work is supported in part by the Defense Advanced Research Projects Agency through the Maya project under contract number N66001-00-1-8937, and the Office of Naval Research through the MINUTEMAN project under contract number N00014-01-C-0016. We would like to thank Yunjung Yi and other members of UCLA Parallel Computing Laboratory and Wireless Adaptive Mobility Laboratory, for the data collection of *ns-2* / GloMoSim comparison, and the contribution of protocol models necessary to carry out this work.

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