Detailed OFDM Modeling in Network Simulation of Mobile Ad Hoc Networks[*]

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Abstract

In mobile ad hoc network (MANET) studies, it is imperative to use highly detailed device models as they provide high layer protocols with good prediction of underlying wireless communication performance. However, such studies often utilize abstract models for execution speed and simplicity. This paper first shows that physical layer variables including path loss, shadowing, multipath, Doppler have significant effects on the predicted overall networking performance. It then proposes an approach to simulate details of wireless propagation and radio characteristics in networking studies while still maintaining a reasonable simulation execution time. Through our runtime performance studies with detailed OFDM Simulink / MATLAB models and QualNet network simulator, it is shown that the proposed approach can improve the simulation runtime performance by three to four orders of magnitudes without compromising the fidelity of simulation results.

1. Introduction

Network simulation is commonly used for the evaluation of wireless network protocols. Discrete event simulators typically model the network activities on a packet-by-packet basis, in time granularity of tens of microseconds, and include a model for each layer of the entire protocol stack. Abstract models can be acceptable if they do not significantly compromise accuracy of the simulation results. However, even if abstract models may compromise the accuracy, they are often in place because detailed models are too difficult to implement and to run efficiently.

Studies on physical layer techniques and their performance evaluation under varying channel conditions often use highly specialized mathematical tools such as MATLAB, Simulink, Maple, and Mathematica [1][2][3]. These software packages provide a rich set of built-in libraries and standard building blocks for use in rapid development of prototypes, allowing users to model channel, modulation, and demodulation with different parameters. However, this highly detailed simulation of receiving every bit transferred across the wireless channel comes at a high computing cost and a very long execution time.

An abstract model may effectively replace a detailed model if such a model does not produce inaccurate results. Such an example would be the recently proposed fluid-based analytical model to determine queue sizes for high capacity wired networks [4][5]. In other cases, detailed simulation models may be necessary to accurately predict network performance. This is especially true for the physical layer in wireless networks where slight inaccuracy may become magnified by higher layer protocols. In [6], the authors show that consideration of the physical layer is necessary to determine ad hoc routing network performance. However, even with very strong evidence at hand, current network simulators apply abstract models to simulate the propagation layer and radio device characteristics. They favor abstract, simple models for the sake of execution speed and efficiency.

There is significant information to be gained in detailed simulation of the physical layer however. In a wireless medium where channel condition changes frequently, nanosecond time granularity simulation of communication devices together with the propagation medium provides valuable insights that otherwise would be lost in abstract modeling. This paper presents an approach to develop an appropriate interface between a packet-level simulator, QualNet [7], and a MATLAB /

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Simulink model for an OFDM (Orthogonal Frequency Division Multiplexing) radio and associated channel, two simulators of dramatically different time scales and execution speed.

Pervious attempts to integrate heterogeneous simulators for network studies include [8][9][10]. In [8], the authors developed a backplane that enables the user to bring multiple network simulators together and harness their models in a single experiment. The split protocol stack methodology for network simulation presented in [9] allows network researchers to run different layers of the network stack on different simulators. In [10], the MAYA network modeling framework is used to emulate a distributed multimedia application. A combination of discrete event simulation, analytical modeling, and physical network emulation are tied together to form a heterogeneous modeling paradigm. The focus of these pieces of work differs from the one described in this paper in that we concentrate on the problems associated with tying a physical radio simulator with a network simulator.

Our integration of a highly detailed physical layer model and a packet-level simulator demonstrates that detailed simulation of the physical layer significantly affects the performance prediction of higher layer protocols. Specifically, it is shown that the number of MAC (Medium-Access-Control) retransmissions may significantly differ when the abstract model and the detailed model are compared at various data rates. This, in turn, causes a varying degree of impact on the packet delivery ratio.

The rest of the paper is organized as follows. Section 2 briefly describes OFDM and the IEEE 802.11 MAC followed by a discussion of the OFDM model and the network simulator, QualNet. Section 3 presents the integration technique of the OFDM model into QualNet. Simulation experiments and results are presented in Section 4. Section 5 follows with our conclusion.

2. OFDM and IEEE 802.11 Overview, OFDM Model and QualNet Network Simulator

2.1. OFDM Technology and IEEE 802.11

In order to understand the necessity of the integration effort, we briefly describe the IEEE 802.11a MAC and the OFDM (Orthogonal Frequency Division Multiplexing) PHY (Physical) layer. Readers interested in the details of the standard should refer to [11][12][13][14]. The IEEE 802.11a uses OFDM as its underlying radio technology. A combination of different modulation and coding schemes is used to give the IEEE 802.11a the wealth of data rates. Operating at the 5 GHz band, it supports rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps.

OFDM is a modulation scheme that converts a wideband signal into a series of independent narrowband signals placed side-by-side in the frequency domain. Modulation is the process of translating an outgoing data stream into symbols for transmission by the sender. The main benefit of OFDM is that the subcarriers can actually overlap one-another. The basic idea is to split the data to be transmitted into *n* parallel data streams, each of which is modulated for a subcarrier. The entire allocated channel is occupied by the sum of the narrow orthogonal sub-bands. Due to implementation complexity, OFDM applications have been scarce until recently with the advances in DSP technology.

OFDM communication systems naturally alleviate the problems of multipath propagation with its low data rate per subcarrier as it is only a fraction of conventional single carrier systems having the same throughput. However, when the transmitter or receiver is moving relative to one another, Doppler shifts occur and can cause significant problems in OFDM systems as the transmission technique is inherently sensitive to carrier frequency offsets. Pilot tones are often used for channel estimation refinement. In the IEEE 802.11a, four of the 52 subcarriers are designated as pilot tones for correcting residual frequency offset errors that tend to accumulate over symbols. The PHY layer also pre-pends the physical preamble to the data frame, modulates, and codes the data frame at the MAC specified data rate. The physical preamble is used to allow the receiver to detect start of packet transmission and to synchronize to the transmitter's clock.

The IEEE 802.11 MAC is primarily responsible for avoiding collisions due to simultaneous transmissions by CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). Upon detecting a transmission by a neighboring node, a node sets a NAV (Network Allocation Vector) to yield the channel to the neighbor, avoiding the potential collision. Optionally, another medium reservation mechanism is implemented with the RTS/CTS (Request-To-Send / Clear-To-Send) [15] message exchange. Nodes that overhear an RTS or a CTS do not transmit data until the corresponding NAV expires. This can alleviate the hidden terminal problem, thus is typically used in MANETs. The timing sequence for the RTS/CTS exchange is shown in Figure 1.

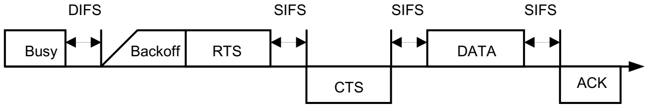

Figure 1. Timing sequence for an RTS/CTS exchange.

By integrating an OFDM model in MATLAB with the IEEE 802.11 MAC protocol implemented in QualNet, we can now predict the performance of OFDM radio technology in CSMA/CA networks with details of the physical layer and device characteristics.

2.2. OFDM Simulator

An OFDM simulator is built using MATLAB Simulink. Simulink is a simulation and prototyping environment for modeling dynamic systems [16]. The OFDM simulator contains a large set of parameters that lead to a myriad of channel conditions and, hence, BER (*B*it *E*rror *R*ate) rates. The relevant variable parameters for the purpose of this study include:

- Modulation type – BPSK, 4-QAM, 16-QAM, 64-QAM
- Multipath – up to six channel tap delays and loss
- Number of effective subcarriers – 33-1024 subcarriers
- Number of symbols in cyclic prefix and cyclic postfix
- Transmitter antenna gain, receiver antenna gain
- Mean transmit power, receiver noise figure
- SINR (*S*ignal to *I*nterference and *N*oise *R*atio)
- Frequency offset

These parameters describing channel characteristics are first fed into MATLAB. A channel is then realized in Simulink. A picture of the OFDM simulator is shown in Figure 2.

The transmitter model in Simulink, upon the start of simulation, generates a stream of bits and modulates them by the specified modulation scheme. Pilot tones are added and the last OFDM symbol is zero-padded prior to the IFFT. Guard blocks are added by cyclically pre-pending and post-pending the specified number of data samples to the beginning and end of each individual OFDM symbol. Each data symbol is 4.0 μs long. A preamble is then generated which consists of training symbols for packet detection, frequency offset, and channel estimation at the receiver.

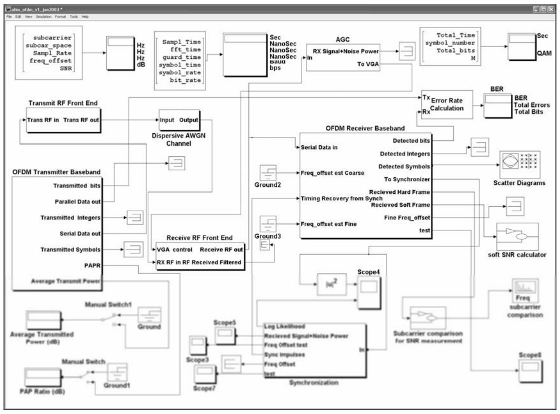

Figure 2. GUI of OFDM Simulator.

The symbols are then brought to the transmitter RF front-end and simulated across the wireless channel. In wireless communication, signals are subjected to distortions generated by the signals' interactions with obstacles and terrain conditions. Under the assumptions of multiple propagation paths to the receiver, the channel is characterized by time-varying propagation delays, attenuation factors, and Doppler shifts.

On the receiver side, the receiver must decide which of the possible digital waveforms most closely resembles the received signal, taking into account the effects of the channel. The OFDM receiver synchronizes to the incoming signal and the baseband processor demodulates the signal back to the stream of bits. The receiver first performs time synchronization and removal of cyclic prefix and postfix. After a FFT, pilot tones are removed from the data frame and the data is then reordered back to the original unscrambled sequence. The transmitted and receive bits are compared and BER is calculated based on the number of error bits and the total number of bits send. Furthermore, the receiver calculates the SINR per OFDM subcarrier seen at the receiver baseband. The average received effective SINR is calculated at the end of simulation. Simulation of 100 OFDM symbols takes about 50 seconds on 2.4 GHz Intel Xeon machine equipped with 512MB of memory.

2.3. OFDM Simulator

QualNet [7] is a discrete-event network simulator that includes a rich set of detailed models for wireless networking. QualNet is the next generation of the GloMoSim simulator [17]. GloMoSim was designed to simulate large-scale wireless networks with thousands of mobile nodes, each of which may have different communication capabilities. QualNet has extended GloMoSim's capabilities to simulate wired networks as well as mixed wired and wireless networks.

QualNet includes models of popular protocols used in each network layer. These ranges from commonly used applications like file transfer (ftp) and web browsing (http), to transport, and MAC layer protocols. QualNet defines simple APIs between neighboring layers for modular composition of protocol models developed at the different layers by different designers. A number of statistical metrics at each layer are collected automatically by the simulator and can be subsequently used by the analysts to analyze the experiment results. QualNet implements the IEEE 802.11a MAC and PHY reference standard. While the MAC layer is simulated inside the simulator, the PHY layer is abstracted to a BER based signal reception model.

The BER versus SNR performance tables were generated using the OFDM simulator from [14]. The tables were created by running the OFDM model and statistically generating the results over a number of trial runs at a specified modulation and coding rate. The abstract PHY model takes the SNR calculated by QualNet channel model and looks up the corresponding BER for that data rate. It then probabilistically determines whether each node receives a frame without errors. The error probability is then calculated using (1), where *numBits* is the number of bits simulated for the particular BER.

$$errorProbability = 1 - (1 - BER)^{numBits} \tag{1}$$

A uniformly distributed random number is then generated in QualNet. If the error probability is greater then the generated random number, that packet is presumed to have an error.

3. Integration of OFDM Model into QualNet

This section discusses implementation issues with the integration of the OFDM model with QualNet. To interface these two simulators, the time scale and execution speed differences must be carefully considered. As QualNet is developed using a layered approach, we can modify the implementation details at a particular layer without affecting other layers. To integrate the OFDM model, the physical layer in QualNet was modified to invoke the OFDM model when necessary as shown in Figure 3.

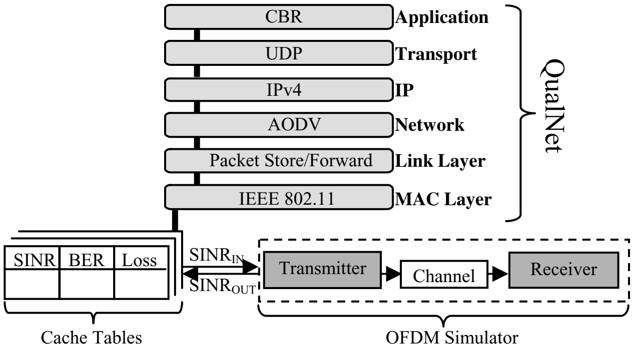

Figure 3. Integration of OFDM Simulator with QualNet.

When a QualNet node detects an incoming signal, it first determines if that signal is above the receiving threshold (RXT). If the signal is above the specified RXT value, the radio tries to receive the signal. SINR is calculated from the strength of the signal and the interference plus noise in the channel. The baseline QualNet model does not currently model Doppler, multipath, or frequency offset effects. Hence, the integration of the OFDM model is carried out as follows: the QualNet node's original SINR, $SINR_{IN}$, is fed into the detailed OFDM model. In combination with the user specified multipath, Doppler, frequency offset, and the relative speed of the nodes calculated in QualNet, a dynamic channel is generated. The OFDM model is then simulated and the resulting SINR, $SINR_{OUT}$ seen at the receiver baseband, is used to calculate the *loss* defined in (2). This *loss* value, as we will explain later, is then stored in a table inside QualNet. The new SINR result is then used to calculate weather or not the packet includes errors.

$$SINR_{out} = \frac{Signal_{in} - Loss}{Noise_{in} + Loss} \tag{2}$$

As mentioned earlier in Section 2.2, simulation of the OFDM model is time consuming. While bit level simulation in wireless environments is desirable, large-scale network simulations must trade off between simulation execution time and accuracy. Simulation time of this integrated system is considerably reduced via two methods: simulation of only a portion of the data frame and a caching mechanism to cache similar scenarios.

While evaluating the OFDM simulator, it is noticed that the simulated resulting receiver SINR value does not change significantly (within 1%) after the simulation of a certain number of OFDM symbols. This is because the transmission duration is less than the coherence time. The coherence time of the channel is a measure of the speed at which the channel characteristics change. This duration of this time is on the order of multiple frame transmissions. Using this fact, the OFDM simulation was stopped after the SINR measurement stabilized, which was after 40 OFDM symbols. This reduced simulation time as typical packet transmission length might last for 100s of OFDM symbols. For example, a 1472 byte packet modulated at 6 Mbps would transmit 503 OFDM symbols.

More significantly, a caching mechanism was developed to take advantage of scenarios with similar SINR and channel conditions. That is, after running the OFDM simulator at a given SINR and channel condition, the *loss* resulted from that run would be saved. The *loss* value is the signal strength loss; it becomes part of the noise. When a similar SINR and channel condition transmission occurs, the resulting SINR is calculated using (2) with the *loss* value previously cached. The *loss* is cached initially instead of the resulting SINR value because the granularity of the input SINR is rounded to the nearest integer; an input SINR of 11.5 dB and 12.4 dB would map to the same *loss* value, not the same SINR. Caching the original resulting SINR value would be inaccurate because of the large granularity; but using the *loss* calculated, a realistic effective SINR value that includes the effects of device and channel is obtained. With the new SINR value, the corresponding BER is retrieved. The error probability for the packet is then calculated and the packet is tested for error. Simulation runtime is sped up considerably with this caching mechanism.

4. Simulation Studies

4.1. MANET Simulation Scenarios

This section quantifies the effects of the OFDM radio and channel modeling on typical scenarios used in the performance evaluation of MANETs. Scenarios for this comparison are created as follows: each scenario is configured with a stationary 50-node network uniformly distributed over a 1000m x 1000m terrain. Twenty-five nodes are randomly chosen to be CBR (Constant Bit Rate) sources, each of which generates 512-byte data packets to a randomly chosen destination at a rate of 5, 10, 20, 40, and 60 packets per second for 180 seconds. The network uses AODV (Ad Hoc On-Demand Distance Vector Routing) [18] for each CBR source to discover a route to the destination. Each data point represents the average value from seven runs with different random number seeds. With different seeds, the node placement and CBR sessions in the network differ. Other common parameters are listed in Table 1. The transmission power and receiver sensitivity are taken from [19], an actual commercial implementation of the IEEE 802.11a.

Table 1. Parameters used in QualNet and OFDM simulation.

Channel frequency		5.2 [GHz]
Effective Subcarriers		48
Data rate		24 Mbps, ARF
Antenna gain		0 [dBi]
BPSK	**TX Power**	20.0 [dBm]
	RX Sensitivity/Threshold	-85.0 [dBm]
QPSK	**TX Power**	19.0 [dBm]
	RX Sensitivity/Threshold	-83.0 [dBm]
16-QAM	**TX Power**	18.0 [dBm]
	RX Sensitivity/Threshold	-78.0 [dBm]
64-QAM	**TX Power**	16.0 [dBm]
	RX Sensitivity/Threshold	-69.0 [dBm]

Table 2. Set of parameters used in OFDM simulation.

Fading model	Rayleigh
Doppler Spread	250.0 [Hz]
Number of Cyclic Prefix	20
Number of Cyclic Postfix	1
Path loss exponent	3

In this evaluation, two data rate types, 24 Mbps and ARF, were chosen. First, every node is set to transmit only at 24 Mbps. This corresponds to the 16-QAM modulation in the OFDM model. Second, each node uses the Auto Rate Fallback (ARF) [20] algorithm for automatic data rate adjustment to best match the varying channel conditions. The basic idea of the ARF protocol is to keep track of the number of successful transmissions, and only after a number of successful attempts, the sender sends the data packets at the next higher data rate. The sender also keeps a timer; when the timer expires, the sender tries to send the next packet at the next higher data rate. The protocol decreases the sender's transmission rate either when it misses two consecutive ACKs or when it fails to receive an ACK immediately after raising the transmission data rate. The timer value, 60 ms, is experimentally found to be optimal in [21]. In order for ARF to achieve good performance with RTS/CTS frame exchange, the sending node should count the missed CTS packet as an "ACK failure" when a node fails to receive the CTS after a RTS transmission. Thus, two missed CTS packets would lead to a subsequent data rate decrease.

Using the ARF rate-adjusting algorithm, the OFDM constellation will vary between BPSK, 4-QAM (QPSK), 16-QAM, and 64-QAM depending on the data rate.

Table 2 contains a list of parameters fed into the OFDM model by QualNet, considered as typical outdoor conditions. All the variables are chosen to mimic the IEEE 802.11a parameters.

4.2. Packet Delivery Ratio and MAC Total Retransmission with Fixed Data Rate

Figures 4 and 5 respectively show the PDR (Packet Delivery Ratio) and the number of retransmissions with the fixed data rate observed in simulation with and without the integrated OFDM model. As shown in Figure 4, The PDR performance of the integrated OFDM model simulation is significantly lower than that of the original abstract model when the transmitting data rate is fixed. As the network load increases, the PDR decreases considerably due to packet transmission errors and channel congestion. At the highest packet rate scenario, the integrated OFDM simulation produces PDR that is only two-fifths of that of the original abstract model. In Figure 5, the difference between the integrated model and abstract model is obvious. The number of retransmission attempts is significantly higher for the integrated OFDM simulation. This correlates well with the lower PDRs depicted in Figure 4. At 40 and 60 packets per second per flow, the number of MAC retransmission attempts is closer to that of the abstract model. This substantial difference in simulation results with the integrated OFDM model clearly demonstrates the need for detailed simulation of physical layer models in network system level simulation.

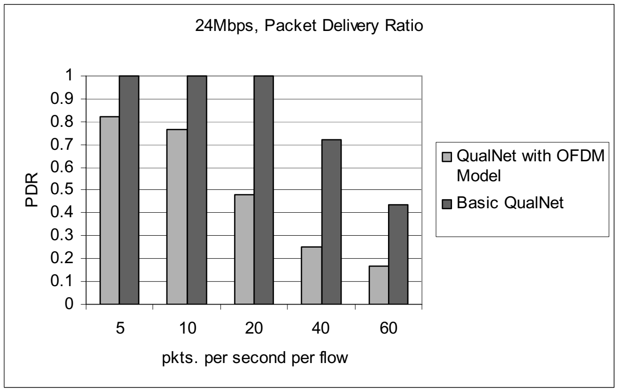

Figure 4. PDR with and without detailed OFDM model using 24 Mbps data rate transmissions.

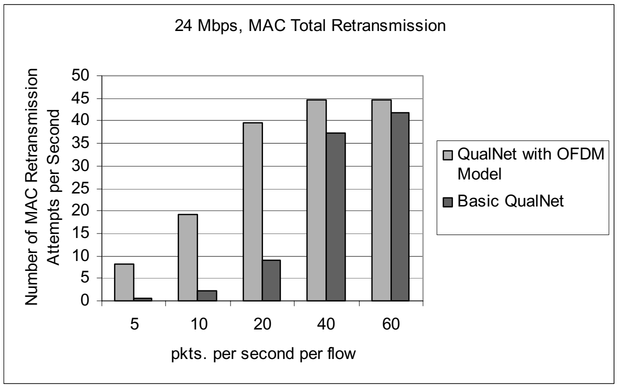

Figure 5. Number of retransmissions with and without detailed OFDM model using 24 Mbps date rate transmissions.

4.3. Packet Delivery Ratio and MAC Total Retransmission Using Auto Rate Fallback

Figures 6 and 7 show the same metrics discussed in the previous section with ARF. The results are quite different when each node uses ARF as its data rate control algorithm. For the two different simulation models, the PDR and the number of retransmission attempts match each other closely as shown in Figure 6 and Figure 7. Because ARF adjust data rates based on channel conditions, in sparse network scenarios, ARF can lower the node's transmitting data rate to ensure packet delivery without overloading the transmission medium. By comparing the PDR of Figure 4 and that of Figure 6 at 5, 10, and 20 packets per second per flow, it is easily seen that ARF takes advantage of the sparse traffic to ensure packet delivery. It is also clear that the gradual PDR decrease from the OFDM model in Figure 4 is caused by other wireless network traffic interference. ARF adapts to light load noisy environments well. However, as the packet rate increases, ARF is actually detrimental to PDR performance. Notice that the PDR performance in Figure 4 at 40 and 60 packets per second per flow is higher than that of Figure 6. By lowering the data rate, ARF, in highly congested environments, causes longer packet transmission duration and, in effect, longer delays and more queue overflows. This leads to a lower PDR ratio in congested scenarios when compared with the fixed data rate setting.

While the observation of ARF performance itself is interesting, the difference in simulation results with and without the detailed OFDM model is much smaller than that shown in the previous section. Although this particular case does not seem to require the detailed OFDM model to predict the network performance, there is no good way to determine whether the detailed physical layer model is essential, as it highly depends on the protocol characteristics. Further, the quantification of such difference in predicted performance cannot be done unless simulation results with and without the detailed model are compared.

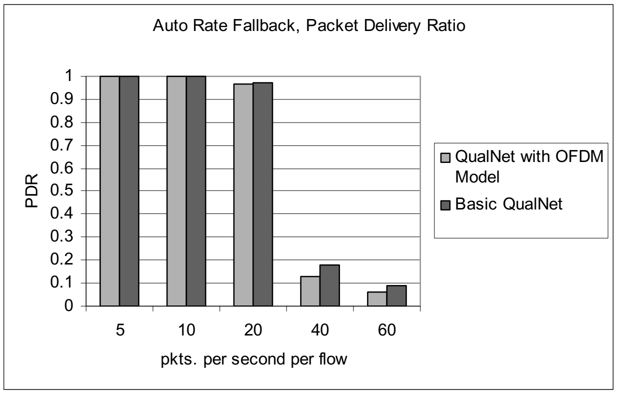

Figure 6. PDR with and without detailed OFDM model using Auto Rate Fallback.

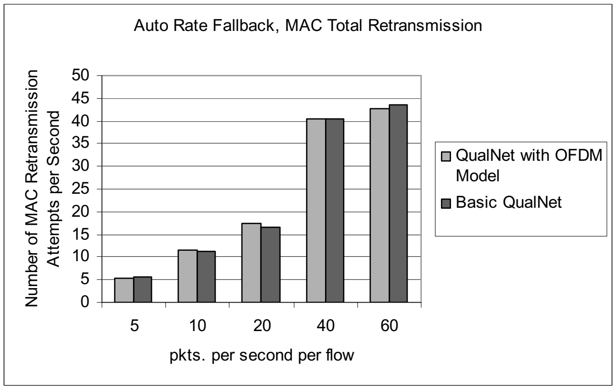

Figure 7. Number of retransmissions with and without detailed OFDM model using Auto Rate Fallback.

4.4. Runtime Performance of Caching Technique

As previously noted, link level OFDM simulation is very computationally expensive. While detailed simulation of every bit of the network is desirable, one cannot expect to use the OFDM simulator to simulate every packet in the network for large MANET scenarios. Our integration technique (described in Section 3) of caching the signal loss and partial transmission simulation alleviate the problem as it captures the interactions of the wireless channel with the radio device and yet still maintains a reasonable execution time to allow for large MANET simulations. Figure 8 and Figure 9 depicts the execution speedup benefit of using the cache detailed model method as opposed to using the OFDM model to simulate every single bit in the network. In the simulation, a stationary 25-node network is placed over a 500m x 500m terrain. Fifteen nodes are randomly chosen to be CBR sources, each of which generates 512-byte data packets to a randomly chosen destination at a rate of 1, 5, 10, 20, 40 and 60 packets per second and using AODV routing. The simulation was stopped when the execution time per simulation second stabilized. One can easily see the benefits of the caching; the improvement in execution time ranges from 2,000 times to over 75,000 times.

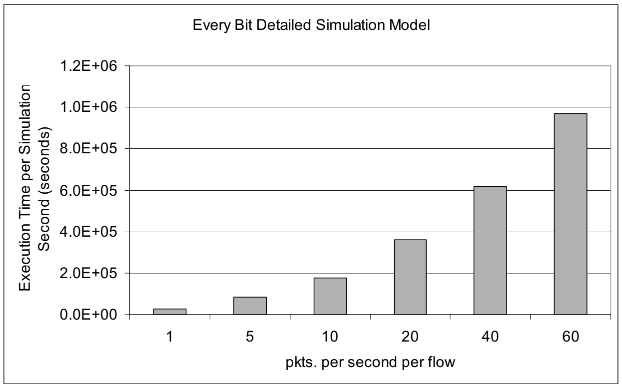

Figure 8. Execution time per simulation second, without caching results from detailed OFDM model.

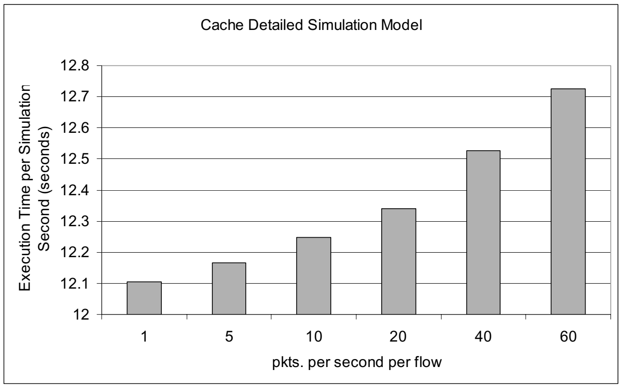

Figure 9. Execution time per simulation second, with caching results from detailed OFDM model.

Caching detailed OFDM model is able to scale with the abstract model. The X-axis in Figure 10 shows the average number of signals locked on by each receiver. Detailed simulation of every bit is infeasible for MANETs while the cache detailed simulation model is able to scale even with the abstract model. When the OFDM model is used to simulate every bit of the network, it took over 370 hours for each node to just lock on to and simulate just over 1000 radio signals.

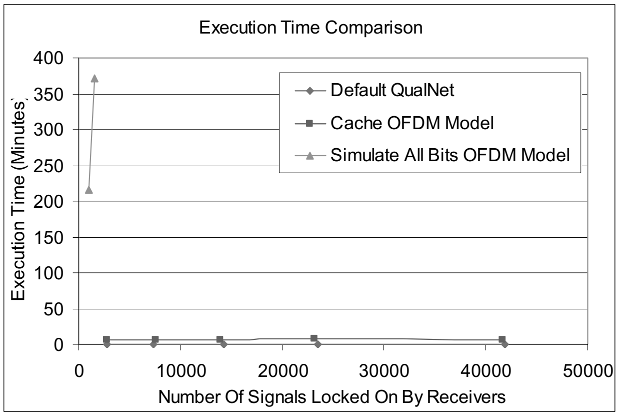

Figure 10. Comparison of execution times.

4.5. Validation of Caching Technique

Caching detailed OFDM simulation is only valid if the cache saved does not compromise the accuracy of the simulation. Our next experiment validates this model with the simulation of all bits using the link level OFDM model in the network. Since simulating every bit in the network is very computationally expensive, as shown in the previous section, the experiment scenarios were limited to light network traffic situations. The same 25-node network is placed on the 500m x 500m terrain. Three nodes are randomly chosen to be CBR sources, each of which generates 512-byte data packets to a randomly chosen destination at a rate of 0.1, 0.5, 0.8, and 1 packet per second using AODV routing for 30 seconds. Even with these lighter traffic scenarios, simulating all bits with the OFDM model with just three CBR sessions and one packet per second per flow took over 32 hours on a modern Intel 2.4 GHz machine. Figure 11 shows the number of physical layer signals received successfully and forwarded to the MAC layer per second. When a physical layer frame is deemed error free by the OFDM simulator or the cache OFDM model, it passes that frame to the MAC layer for higher layer processing. The experiment shows that using the cache OFDM simulation model results in no more than 2% difference in the number of signals received successfully by the radio when compared to using the OFDM simulator to simulate every bit of the network. Hence, our cache model is well justified and we are able to speed up execution time to scale similarly to execution with the abstract model, while still preserving the fidelity and accuracy of detailed OFDM radio and wireless channel simulation.

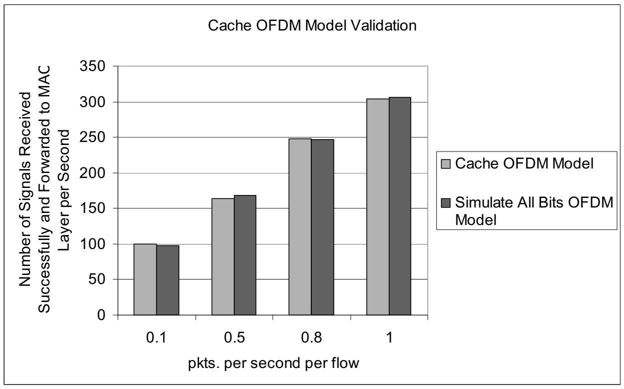

Figure 11. Validation of caching technique against simulation without caching.

5. Conclusion

This paper has presented on the effects of detailed OFDM and channel modeling on the performance evaluation of higher layer protocols. Our integration of an OFDM simulator with QualNet provided a realistic yet efficient model of the propagation and device layer for network performance analysis without compromising simulation accuracy. The results show that device and wireless channel can impact packet delivery ratios and even point out a deficiency of the ARF protocol. Traditionally, radio engineers have analyzed the performance of their designs against others only on point-to-point performance evaluations under various channel conditions. The integration brings an accurate physical layer model to dynamic network simulation that includes the effects of path loss, shadowing, multipath, Doppler fading, and delay spread, to allow protocol and radio designers to evaluate the effects of their designs on a full-scale system level with an eye for cross layer interactions. In addition, the integration delineates a method in which simulators of dramatically different time granularities are combined using simple APIs.

In terms of performance, our integration technique and cleanly defined interface are clearly beneficial in any MANET networking studies. Link level OFDM model to simulate every bit in the network is too computationally expensive and leads to an unacceptably long execution time. Our technique scales along with the basic abstract model and still captures the essence of the radio device and its performance characteristics in varying wireless channels. The results show that significant benefits can be obtained from our caching technique, while careful evaluation of what to cache must be properly understood.

With advances in antenna, modulation, and coding technology, it becomes increasingly important for higher-level network layers to understand their interactions with the physical device and media. It is equally important for designers to understand the innovations that are being made in each layer of the network stack and to understand how these innovations might complement or conflict with their designs. Future work on the integration method includes enhancements to the caching scheme, dynamic channel and fading characteristics utilizing detailed 3-D terrain models and movement of the nodes.

6. Acknowledgment

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7. References

[1] MATLAB User’s Guide, http://www.mathworks.com/.

[2] Waterloo Maple User’s Guide, http://www.maplesoft.com/.

[3] Mathematica User’s Guide, http://www.wolfram.com/.

[4] Vishal Misra, Weibo Gong, Don Towsley, "Fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED", in Proceedings of ACM/SIGCOMM, 2000.

[5] Tak-Kin Yung, Jay Martin, Mineo Takai, Rajive Bagrodia, “Mixed fluid flow and packet level simulation models for large scale networks”, in Proceedings of SPIE, Vol 4523, August 2001.

[6] Mineo Takai, Jay Martin, Rajive Bagrodia, “Effects of wireless physical layer modeling in mobile ad hoc network,” in Proceedings of MobiHoc 2001, pages 87-94, October 2001.

[7] QualNet User’s Manual, http://www.scalable-networks.com/.

[8] Riley, G. F.; Ammar, M. H.; Fujimoto, R. M.; Perumalla, K.; Xu, Donghua, “Distributed Network Simulations using the Dynamic Simulation Backplane,” in Proceedings of International Conference on Distributed Computing Systems, April 2001 (ICDCS'01).

[9] Xu, Donghua; Riley, G. F.; Ammar, M. H.; Fujimoto, R. M., “Split Protocol Stack Network Simulations using the Dynamic Simulation Backplane,” in Proceedings of the Ninth International Symposium on Modelling, Analysis, and Simulation of Computer and Telecommunication Systems, 2001 (MASCOTS'01)

[10] Junlan Zhou, Zhengrong Ji, Mineo Takai, Rajive Bagrodia, “Maya: a Multi-Paradigm Network Modeling Framework,” in Proceedings of PADS 2003.

[11] IEEE 802.11 WG, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Standard, IEEE, August 1999.

[12] IEEE 802.11 WG, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHz Band, Supplement to IEEE 802.11 Standard, September 1999.

[13] Richard Van Nee, Ramjee Prasad, *OFDM for Wireless Multimedia Communications*. Boston, MA: Artech House, 2000.

[14] John Terry, Juha Heiskala, *OFDM Wireless LANs: A Theoretical and Practical Guide*. Indianapolis, IN: Sams Publishing, December 2001

[15] Vaduvur Bharghavan, Alan Demers, Scott Shenker, Lixia Zhang, “MACAW: A media access protocol for wireless LAN’s,” in Procedings of SIGCOMM, 1994.

[16] Simulink User’s Guide, http://www.mathworks.com /products/simulink/.

[17] Lokesh Bajaj, Mineo Takai, Rajat Ahuja, Rajive Bagrodia, "Simulation of large-scale heterogeneous communication systems," in Proceedings of MILCOM'99, November 1999.

[18] Charles. E. Perkins, Elizabeth. M. Royer, “Ad-hoc on-demand distance vector routing,” in Proceedings of 2nd IEEE Workshop on Mobile Computing Systems and Application, pages 90-100, 1999.

[19] SMC2755W – EZ Connect 802.11a Wireless Access Point User Guide, http://www.smc.com/drivers_downloads /library/SMC2755W_MN.pdf/.

[20] A. Kamerman, L. Monteban, “WaveLAN-II: A high performance wireless LAN for the unlicensed band”, Bell Labs Technical Journal, Vol. 2, No. 3, pages 118-113, Summer 1997.

[21] Gavin Holland, Nitin Vaidya, Paramvir Bahl, “A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks," in Proceedings of MobiCom 2001, July 2001.