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Effects of Correlated Shadowing Modeling on Performance Evaluation of Wireless Sensor Networks

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Abstract—Wireless links are typically modeled in isolation as independent and parallel links. However, in reality, there is often a correlation in defects and impairments between collocated links. The spatial correlation of shadowing among proximate wireless links has been frequently observed. Although different types of correlated shadowing models have been proposed for wireless channels, these models are not present in popular network simulators. Ignoring such correlations results in the diversity of adjacent links being over-estimated. Our hypothesis is that this could lead to incorrect results when evaluating the performance of wireless systems and network protocols. In this paper, the ns-3 simulation environment has been enhanced with a prototype correlated shadowing model developed in our previously published work. We study the end-to-end packet delivery ratio and delay in wireless sensor networks using both correlated and independent propagation models. Simulation results show that correlated and independent shadowing models produce significant differences in network performance. Moreover, we compare the complexity of different modeling options. It is shown that this correlated propagation model in ns-3 can improve simulation realism without inducing any considerable degradation of scalability.

Keywords—spatial correlation; shadowing; ns-3; performance evaluation; wireless sensor networks

I. INTRODUCTION

Recent years have witnessed increasing interest in the development and evaluation of Wireless Sensor Networks (WSNs). Three main methods, namely theoretical analysis, test-bed experimentation and simulation, are typically used to evaluate the performance of wireless systems and network protocols. Due to the high complexity of WSNs, analytical studies usually focus on one or two network layers, ignoring other layers. Although testbed experimentation can provide valuable insight into real world deployments, setting-up the testbed is a tedious and expensive task. Moreover, these experiments are restricted in size and limited to existing technologies. A simulation platform offers a highly controllable and repeatable environment. It also allows the creation of complex networks without suffering from the time, space and cost restrictions of a physical testbed. For these reasons, simulation is generally considered the most convenient approach to investigate the behavior of WSNs [1]. Nevertheless, an appropriate choice of the propagation model

is required to provide an accurate performance evaluation of a wireless network.

Most propagation models used in simulation work today assume independent wireless links. However, in reality, there is often a correlation in defects and impairments between collocated links. For example, an interference source or shadowing obstruction will affect several links around it, not just one. This spatial correlation of shadowing among proximate wireless links has been frequently observed in cellular systems [2] [3], satellite systems [4] and wireless multi-hop networks (WMHNS) [5]. Previous work shows that shadowing correlation significantly affects handover behavior [6], interference power [7], the performance of macrodiversity schemes [8], network connectivity [9] and redundant node deployment [10]. Although several models for correlated shadowing already exist, these models are not present in popular network simulators such as ns-3 [11] and QualNet [12]. Ignoring shadowing correlations results in the diversity of adjacent links being over-estimated, and this could lead to misleading simulation results that will not be achieved when a real system is deployed (often at considerable expense), meaning that it may fail to meet its requirements and even mission-critical objectives.

This paper contributes a prototype correlated propagation model in the ns-3 [11] simulation environment. In particular, we implement the correlated shadowing model that was developed in our previously published work [13]. We evaluate the effects of correlated shadowing modeling in the context of WSNs, performing studies on WSNs of different sizes and topologies. Simulation results show that independent propagation models generally overestimate end-to-end packet delivery ratios and underestimate delay. The differences produced by correlated and independent shadowing models are more pronounced in large networks with line topologies. In addition, we compare the computational effort of both modeling options. This correlated propagation model in ns-3 enables more realistic performance evaluation without inducing a large computational overhead.

The remainder of the paper is organized as follows: Section II gives a brief description of the channel model used in this work. In Section III, we introduce the correlated propagation model in ns-3, as well as its parameters for our simulation study. In Section IV, simulation results from various scenarios

are presented and explained. Finally, we conclude and discuss future research directions in Section V.

II. CHANNEL MODEL

In a wireless channel, three mutually independent propagation phenomena can usually be distinguished: path loss, shadowing and fading. The effects of path losses cause the signal strength to vary gradually due to attenuation. The received power is also subject to shadowing due to obstacles between the transmitter and receiver. Fading is caused by multi-path propagation where different copies of the same signal arrive at the receiver via a variety of paths. The path loss effects determine a received power averaged over an area of tens or hundreds of meters. Shadowing introduces fluctuations, so the received local-mean power varies around the area-mean. Here ‘local-mean’ denotes the signal level averaged over a few tens of wavelengths. Multipath propagation leads to additional fluctuations of the phase and amplitude of the signal in the order of a wavelength.

To describe the channel, we consider two nodes A and B that are located at a relative distance of d_{AB} . Node A transmits a signal with power P_t dBm. The mean received power at node B is given by an empirical formula as [14]

$$\bar{P}_r(d_{AB}) = P_t - PL(d_0) - 10\alpha \log\left(\frac{d_{AB}}{d_0}\right) \quad (1)$$

where $PL(d_0)$ is the path loss at a short reference distance d_0 from the transmitter antenna, and α is the path loss exponent. The path loss exponent depends on the environment. The value of α is 2 for free space, less than 2 for waveguide-like environment and larger when obstructions are present.

Because of the shadowing effect, the received power will vary from its mean. Shadowing on a dB scale is commonly modeled by a zero-mean Gaussian random variable. Thus augmenting (1) to include contributions from shadowing gives

$$P_r(d_{AB}) = P_t - PL(d_0) - 10\alpha \log\left(\frac{d_{AB}}{d_0}\right) - X_\sigma \quad (2)$$

where X_σ is a zero-mean Gaussian random variable with standard deviation σ .

However, in reality, shadowing is spatially correlated and (2) fails to capture this. In this paper, we use a correlated shadowing model that was developed in our previous work [13]. It has been shown to agree with the empirically observed single-link and cross-link shadowing properties in WMHNS. In this section, we outline briefly its main components and properties for the sake of completeness.

This model was developed under the assumption that the shadowing losses experienced on links in a WMHN are a result of signals passing through an underlying shadowing environment. A shadowing map is used to model the underlying environment in which the network operates. Then link shadowing is calculated deterministically from the map. By connecting the shadowing losses with the environment, we

model the correlation characteristics that exist between wireless links in the real world.

As in prior literature [5], we assume that the underlying shadowing map is a stationary and isotropic Gaussian random field with zero-mean and exponentially decaying spatial correlation. In this paper, we simulate a Gaussian random field $f(x)$ on a rectangular grid of size $n \times m$ as the shadowing map. Let Δd denote the spacing along the grid. The shadowing map will cover a simulation area of size $L \times W = n\Delta d \times m\Delta d$. In particular, we will generate a zero-mean Gaussian random process on each of the grid points $\{(i\Delta d, j\Delta d), i = 0, \dots, n-1, j = 0, \dots, m-1\}$ corresponding to a covariance function given by

$$\text{cov}(f(s), f(t)) = \sigma^2_s \exp\left(-\frac{\|s-t\|}{\delta}\right) \quad (3)$$

where σ^2_s is the variance of the shadowing map, δ is the de-correlation distance, and $\|s-t\|$ is the Euclidian distance between s and t . We can describe the de-correlation distance as a measure of the size of obstructing objects in the environment.

Although it is intuitively correct to approximate the link shadowing loss as the weighted sum of individual shadowing values along the communication path, the weighting coefficients need to be determined carefully. In the real world, obstacles that are close to the antenna have higher impacts on link shadowing. This is because the relative loss of diffracting or scattering over or around the object is greater for the obstacles near the antenna. Therefore, the weighting coefficients must be distance-dependent to reduce the impact of obstacles in the middle of a link on the shadowing loss. We further abstract this empirical observation by assuming that the link shadowing is dominated by the shadowing values in the near field at both ends of the link. The following function is proposed for the shadowing loss X_{AB} of the link L_{AB} as

$$X_{AB} = \frac{1 - \exp\left(-\frac{d_{AB}}{\delta}\right)}{\sqrt{2} \sqrt{1 + \exp\left(-\frac{d_{AB}}{\delta}\right)}} (f(A) + f(B)) \quad (4)$$

where d_{AB} is the Euclidian distance between nodes A and B , and $f(A)$ and $f(B)$ represent the shadowing values in the near field of nodes A and B respectively.

Finally, the total received power at node B considering path loss, correlated shadowing and fading becomes

$$P_r(d_{AB}) = P_t - PL(d_0) - 10\alpha \log\left(\frac{d_{AB}}{d_0}\right) - X_{AB} - 20 \log Y_{AB} \quad (5)$$

where X_{AB} is calculated by (4) and Y_{AB} is a random variable which describes multipath fading. Three stochastic models, Rayleigh, Rician and Nakagami, are typically used to represent multipath fading [14]. Rayleigh fading is most applicable when there is no dominant propagation along a line-of-sight between

the transmitter and receiver. If there is a dominant line-of-sight, Rician fading may be more applicable.

III. IMPLEMENTATION IN NS-3

In this section, we describe how the ns-3 simulation environment has been enhanced with a prototype correlated shadowing model. Parameter settings for the simulation study are also provided.

A. Simulation Framework

Fig. 1 illustrates the building blocks of our simulation environment. In this work, we modify the channel model in ns-3 to allow correlated path-loss files to be read at the beginning of simulations. The rest of the simulation models stay the same. Before starting the network simulation, the Correlated Path Loss Model in Matlab processes a set of input parameters capturing the environment, e.g., path loss exponent α , shadowing standard deviation σ and de-correlation distance δ . As mentioned in Section II, the link shadowing losses are calculated deterministically from the underlying shadowing map. We first generate shadowing maps with the covariance given in (3) using the Circulant Embedding method [15]. Link shadowing losses are then calculated from the pre-generated maps using (4). Combined with the log-distance path loss given in (1), this model returns a set of correlated path losses ready to be fed into the Propagation Loss Model in ns-3.

B. Simulation Setup

We describe now the network configurations, parameter settings and definition of performance measures for our performance study.

In this paper, we focus on static node placement where IEEE 802.11b wireless ad-hoc nodes are arranged in a line and in a grid, as shown in Fig. 2 (a) and (b) respectively. A numbered circle denotes the node, while a number with an L to the left stands for a link between two nodes. We consider one traffic flow from source (e.g., node 3) to sink (node 0) to isolate the effects of correlated shadowing from contentions.

In TABLE I. some important model parameters fixed throughout our simulation study are listed. Besides path loss and correlated shadowing, we also add Rayleigh fading to the

Fig. 2. (a) 4 nodes arranged in a line; (b) 4 nodes arranged in a grid.

Propagation Loss Model. Note that we have adopted a data rate of just 1Mbps because our focus is WSNs, which implies low data rate, low power and robust signal requirements. Other internal protocol parameters use default values specified in the ns-3 simulator. The *OLSR* routing protocol is used throughout this study.

The performance of WSNs is evaluated in terms of end-to-end packet delivery ratio (PDR) and end-to-end delay. PDR is the ratio of the number of packets received by the sink node to the total number of packets generated by the source node. End-to-end delay is the average delay for a single packet from source to sink. For every simulation with the same input parameters, we run 1000 independent replications with different shadowing and fading instances. The mean value of PDR and delay is then calculated and plotted as a single point in the graph. Error bars represent the 95% confidence interval.

IV. SIMULATION RESULTS

In this section, the simulation results using both the correlated and independent shadowing models are presented and discussed. We designed three scenarios to compare the network performance using both correlated and independent

Fig. 1. Simulation framework implementing a correlated path loss model.

TABLE I. FIXED MODEL PARAMETERS

Propagation model parameters	
Path loss exponent	3.0
Shadowing standard deviation	8.0dB
De-correlation distance	2.0m
Inter-node distance	10.0m
PHY module parameters	
Data rate	1Mbps
Transmitter power levels	-20, -16, -12, -8, -4, 0dBm
Application module parameters	
Packet frequency	1 packet/s
Packet size	100 bytes
Max. no. of packets transmitted	100

shadowing models. In each case, the transmit power varies from -20dBm to 0dBm .

The first scenario is a 4-node network with two different node placements, line and grid, as illustrated in Fig. 2. The second one compares line network with different number of nodes, 4 and 6. Finally, the grid structure was studied with two network sizes, 4 nodes and 16 nodes. The PDR and delay for each scenario are plotted in Fig. 3 to Fig. 8 respectively.

As can be seen from Fig. 3 and Fig. 4, using a correlated shadowing model (green traces) result in a lower PDR and a longer Delay than the independent equivalents (red traces). Line topology (the solid traces) is more sensitive to correlated shadowing than the grid topology (the dashed traces). When the link is weaker (i.e., lower value of P_{tx} , to the left of both figures), a larger difference between the independent (red traces) and correlated model (green traces) can be observed.

Fig. 5 and Fig. 6 show that when the network size is larger (6 nodes in this case, the dotted lines), effects of correlated shadowing (the green traces) are magnified. The difference in PDR using independent (red) and correlated (green) shadowing models can be as big as 21% for a six-node-line network when the transmit power is -20dBm . The delay under-estimation is around 80ms, which is not desirable in latency sensitive

applications. In the four-node-line network (solid), the differences are less pronounced, but nonetheless still apparent.

As shown in Fig. 7 and Fig. 8, even though a grid structure is more robust to correlated shadowing, the correlation still needs to be considered if the network size grows larger. With greater numbers of nodes, the effects of ignoring shadowing correlation are clearly even more pronounced.

Finally Fig. 9 illustrates the computational effort induced by using both the independent (the red bars) and correlated (the green bars) propagation loss models. For comparison, we use the log-distance propagation loss model and the random loss model (with Gaussian distribution) to model distance-dependent path loss with independent shadowing. In general, we observe that the computational effort grows exponentially with network size. Moreover, the processor time, expressed in the number of clock ticks, is more with a larger transmit power (the darker bars). We expect this behavior since the transmitter will reach more nodes with a larger power, thus generating more simulation events. We also observe that the correlated model (green bars) consumes similar processor time as its independent equivalent (red bars). This is because the complexity of the correlated path loss model is handled in Matlab before starting the simulation in ns-3. Furthermore, for

Fig. 3. PDR for 4-node network with different node placements.

Fig. 5. PDR for line network with different sizes.

Fig. 4. Delay for 4-node network with different node placements.

Fig. 6. Delay for line network with different sizes.

a grid network of 16 nodes, the proposed model in MATLAB only needs 2.7s to generate 1000 samples of correlated pathloss on a 2.8GHz Intel Core i7 processor. For a network size of 100, the simulation time is 38s. For more details on the computational requirements for the correlated shadowing model, we refer the reader to [13].

Fig. 7. PDR for grid network with different sizes.

Fig. 8. Delay for grid network with different sizes.

Fig. 9. Processor time using independent and correlated path loss model.

V. CONCLUSIONS

This paper implemented a prototype correlated shadowing model in ns-3 simulator. The proposed model can improve simulation realism without inducing any considerable degradation of scalability. Simulation results indicate that the independent propagation model generally overestimates end-to-end packet delivery ratio and underestimates delay in WSNs. In this work, we considered one traffic flow from source node to sink node with periodic traffic to isolate the effects of correlated shadowing from contentions. For future work, we plan to investigate the effects of correlated shadowing with higher number of traffic flows and different traffic models.

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