VANET Topology Characteristics under Realistic Mobility and Channel Models

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***Abstract*—Developing real-time safety and non-safety applications for vehicular ad hoc networks (VANET) requires understanding the dynamics of the network topology characteristics since these dynamics determine both the performance of routing protocols and the feasibility of an application over VANET. Using various key metrics of interest including node degree, number of clusters, link duration and link quality, we provide a realistic analysis of the VANET topology characteristics. In this analysis, we integrate real-world road topology and real-time data extracted from Freeway Performance Measurement System database into the microscopic mobility model in order to generate realistic traffic flows along the highway. Moreover, we use more realistic, recently proposed, obstacle-based channel model and compare the performance of this sophisticated model to the most commonly used more simplistic channel models including unit disc and log-normal shadowing model. Our investigation on the key system metrics reveal that largely used unit disc model fails to realistically model communication channel, while parameters of simplistic models like log normal can be adjusted to match the corresponding system metrics of more complex and hard to implement obstacle based model.**

I. Introduction

Vehicular Ad-Hoc Network (VANET) is a promising Intelligent Transportation System (ITS) technology that offers many applications such as safety message dissemination [1], [2], [3], dynamic route planning [4], content distribution, gaming and entertainment [5]. Majority of the VANET research effort on protocol design has relied on simulations due to the prohibitive cost of employing real world test-beds. Building a realistic simulation environment for VANET is therefore essential in judging the performance of the protocols proposed at various layers.

A realistic simulation environment requires an accuracte representation of both the vehicular mobility and signal propagation among the vehicles. Different vehicle mobility and signal propagation models should be compared through various metrics including node degree, number of clusters, link duration and quality [6], [7], [8], [9]. Recent studies on the analysis of VANET topology characteristics have incorporated large-scale mobility models based on either statistics performed by the urban planning and traffic engineering communities [10] or mobility traces gathered through various measurement campaigns [11], [12]. However, none of these studies analyze VANET topology characteristics on a large-scale highway considering real data based traffic demand of vehicles using microscopic mobility model.

Realistic representation of the signal propagation can be achieved by sophisticated methods like ray-tracing model [13], [14]. However, such models are impractical since they require a detailed description of site-specific propagation environment. Stochastic models on the other hand determine the physical parameters of the vehicular channel in a completely stochastic manner without presuming any underlying geometry [15]. Most of the channel modeling activities try to take average of the additional attenuation due to obstacles, resulting in a log-normal distribution around the mean received signal power [16], [17]. Although some of these models estimate different variations of the large-scale fading distribution at low and high traffic densities [17], mechanisms for taking into account the effect of vehicles and static obstacles on the received signal power have been recently proposed in [18] and [19] respectively. Finally, for small-scale fading models, various distributions have been proposed, including Rice [20], Nakagami [16] and Weibull [21], [17] distributions.

Although signal propagation has great impact on the performance of the communication protocols, most of the recent work on the analysis of VANET topology characteristics either use unit disc as the signal propagation model [6], [7], [10], [9], [22] or use more sophisticated stochastic signal propagation models including both large-scale fading [9], [23] and small-scale fading [24], [23]. However, none of these models incorporate the effect of vehicles on the signal propagation.

The goal of this study is to analyze the evolution of the VANET topology characteristics on a large highway section by using realistic mobility traces generated using real-world road topology and accurate microscopic mobility modeling. We use real-data based traffic demand and realistic channel models, taking into account the effect of vehicles on the received signal power, when comparing the performance of this realistic scenario to the commonly used more simplistic channel models.

The contributions of this paper are as follows. To the best of our knowledge, this is the first study that:

- incorporates real-world road topology and real-time data from Freeway Performance Measurement System (PeMS) database into the microscopic mobility model provided by Simulation of Urban Mobility (SUMO).
- incorporates more realistic recently proposed obstacle-

based channel model into the analysis of VANET topology characteristics, and compare its performance with commonly used more simplistic channel models including unit disc and log-normal shadow fading models.
- analyzes the effect of using the obstacle-based channel model on the VANET topology characteristics.

The rest of the paper is organized as follows. Section II describes the generation of the realistic vehicle mobility using PeMS database. Section III provides the implementation of different radio channel models including unit disc, log-normal shadowing and obstacle-based model. Section IV provides the simulation results. The main results are summarized and future work is given in Section V.

II. Vehicle Mobility Model

Realistic representation of the vehicle mobility requires using accurate microscopic mobility modeling, real-world road topology and real-data based traffic demand modeling as detailed next.

Microscopic Mobility Modeling: SUMO [25] is used to simulate the microscopic mobility of vehicles. SUMO is an open-source, space-continuous, discrete-time traffic simulator developed by the German Aerospace Center capable of modeling the behavior of individual drivers. The parameters of the simulator that determine the driver's acceleration and overtaking decisions include the distance to the leading vehicle, the traveling speed, the acceleration and deceleration profiles, and dimension of the vehicles.

Traffic Demand Modeling: PeMS collects historical and real-time data from freeways in the State of California with the goal of computing freeway performance measures thus providing managers with a comprehensive assessment of freeway performance [26]. The flow and speed data are collected in real time from over 25,000 individual detectors located over all major metropolitan areas in the state of California. The sampling rate of the flow and speed data ranges from 30 seconds to 5 minutes. Fig. 1 shows the road sensors located on I-880S in Alameda County.

Realistic Mobility Generation: The first step in the generation of the realistic mobility model is to determine the input of SUMO for the assignment of the vehicular traffic flows over the road. The data from 419 road sensors on highway I880-S, as shown in Fig. 1, are extracted for both high traffic density i.e. 121 vehicles/km at $18:00$, and low traffic density i.e. 11 vehicles/km $01:00$ using PeMS database. For the simulation using SUMO, the parameters of the vehicles injected (i.e. maximum speed, start speed, acceleration, deacceleration, type, distance to the leading vehicle) are selected such that traffic flow and average speed values determined by simulation and PeMS database agree with each other.

III. Vehicular Channel Models

Realistic representation of the signal propagation among the vehicles located on the highway requires incorporating the effect of the moving obstacles (i.e. vehicles) on the received signal power due to their dominating influence as illustrated in

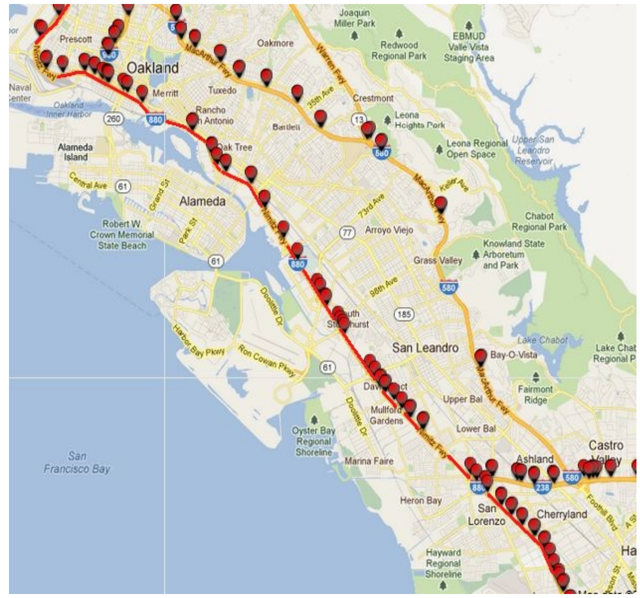

Fig. 1. Road sensors located on I-880S in Alameda County

[18]. Following the description of the commonly used more simplistic channel models including unit disc and stochastic large-scale fading, the algorithm for estimating the additional attenuation caused by the surrounding vehicles is explained.

A. Unit disc Model

In unit disc model, the vehicles can communicate with each other if they are within a threshold distance and cannot communicate otherwise. Although this model is widely used in the analysis of the VANET topology characteristics due to its simplicity [6], [7], [10], [9], [22], the sharp cut-off at the threshold distance fails to capture the random noise that can make even nearby nodes unreachable and account for the effect of obstacles on the received signal strength.

B. Stochastic Large-Scale Fading Model

Stochastic large-scale fading model aims to take average of the additional attenuation caused to the obstacles. The resulting distribution of these variations has been found to be log-normal formulated as follows [16], [17]:

$$P_{rx}(d) = P_0 - 10n\log_{10}\frac{d}{d_0} + N \tag{1}$$

where d is the distance between the transmitter and the receiver, d_0 is the reference distance, $P_{rx}(d)$ is the received signal power at distance d (in dBm), P_0 is the received signal power at the reference distance d_0 (in dBm) , n is the path loss exponent and N is zero mean Gaussian random variable with variance σ^2. A vehicle can communicate with another vehicle if P_{rx} is greater than a certain threshold value [27]. Note that the log-normal shadowing model reduces to the unit disc model if $\sigma = 0$. The parameter P_0 of the log-normal model is chosen such that the mean transmission range is equal to the threshold distance in the unit disc model to have a fair comparison, while the parameter values of n and σ of the model are chosen based on the channel measurement results reported in [28], [16], [17]: $n = 4.45$, $\sigma = 14.40$dB. These values are adjusted such that the log-normal model behave similar to obstacle based model.

C. Obstacle-based Channel Model

Obstacle-based channel models propose mechanisms to incorporate the effect of the surrounding obstacles, such as other vehicles, walls and buildings, on the received signal strength [18], [17] rather than averaging the additional attenuation due to these obstacles using stochastic large-scale fading model. Since there are few buildings around the highway mostly far from the vehicles, we only consider the impact of the surrounding vehicles as obstacles. Additional obstacles around the road can only further reduce the received signal strength so this approach can be considered as a best case analysis for the effect of obstacles on received signal strength as stated in [18].

The algorithm proposed and validated in [18] is implemented for calculating the additional attenuation caused by other vehicles. This algorithm consists of three main parts as shown in Algorithm 1. First, the vehicles which can potentially obstruct the LOS between the transmitter vehicle i and receiver vehicle j are determined ($getPotentialObs(i, j)$): If the distance from the center of the vehicle to the LOS line between vehicles i and j is less than half the width of the vehicle, the vehicle is considered as a potential obstacle as illustrated in Fig. 2-a.

Algorithm 1 Obstacle Based Model: Calculation of the additional attenuation between vehicles i and j due to surrounding vehicles as obstacles

$[PotentialObs] = getPotentialObs(i, j)$ {Determine potential obstacle vehicles}
if $size([PotentialObs]) \neq 0$ **then**
  $[ObsVeh] = getLOSobs([PotentialObs])$ {Determine LOS obstructing vehicles}
  if $size([ObsVeh]) \neq 0$ **then**
    $addAttenuation = calAttenuation([ObsVeh])$ { Calculate additional attenuation caused by obstructing vehicles}
  else
    $addAttenuation = 0$
  end if
else
  $addAttenuation = 0$
end if

Second, the vehicles that obstruct the LOS between vehicles i and j are determined from the set of the potential obstructing vehicles determined in the previous step ($getLOSobs([PotentialObs])$): From the prospective of the electromagnetic wave propagation, if there exist a visual sight line between transmitter and receiver vehicle, it does not guarantee that LOS exist. Transmitted signal gets effected only if other vehicle obstructs the Fresnel ellipsoid. The effective height of the LOS line that connects vehicles i and j at a potential obstacle vehicle, considering the first Fresnel ellipsoid, is given by

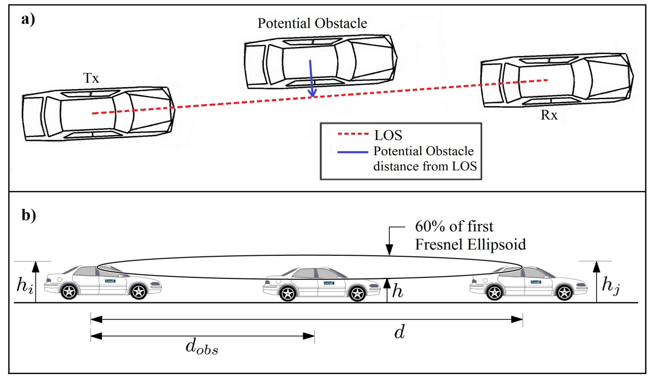

Fig. 2. Determining the vehicles that: a) Potentially obstruct the LOS between transmitter and receiver b) Obstruct the LOS between vehicles i and j (Vehicle antenna heights (h_a) are not shown for simplicity).

$$h = (h_j - h_i)\frac{d_{obs}}{d} + h_i - 0.6r_f + h_a \tag{2}$$

where h_i and h_j are the heights of the transmitter vehicle i and receiver vehicle j respectively, d_{obs} is the distance between the transmitter and the obstacle, d is distance between the transmitter and receiver, h_a is the height of the vehicle antennas, and radius for the first Fresnel zone ellipsoid r_f is given by

$$r_f = \sqrt{\frac{\lambda d_{obs}(d - d_{obs})}{d}} \tag{3}$$

where λ denoting the wavelength. Fig. 2-b illustrates these parameters. Since the height of each potentially obstructing vehicle is known beforehand, the vehicle is considered to obstruct the LOS between the transmitter and receiver if h is greater than its height. Based on the assumption that the vehicle heights follow a normal distribution as assumed in [18], the probability of the LOS for the link between vehicles i and j is calculated as

$$\Pr(LOS|h_i, h_j) = 1 - Q(\frac{h - \mu}{\sigma}) \tag{4}$$

where μ and σ are the mean and standard deviation of the height of the obstacle vehicle.

Third, the additional attenuation in the received signal power is calculated for the LOS obstructing vehicles determined in the previous step ($calAttenuation([ObsVehicles])$). The existing models to calculate the attenuation vary from pessimistic [30], [31] to optimistic [29] approximations. Additional attenuation is calculated by using ITU-R method based on multiple knife edge model [32] as suggested in [18].

IV. Simulation Results

The goal of the simulations is to compare the effect of different channel models including unit disc, log-normal fading and obstacle-based on the topology characteristics of VANETs on a large-scale highway by comparing node degree, number of clusters, link duration and link quality metrics of the resulting communication graphs.

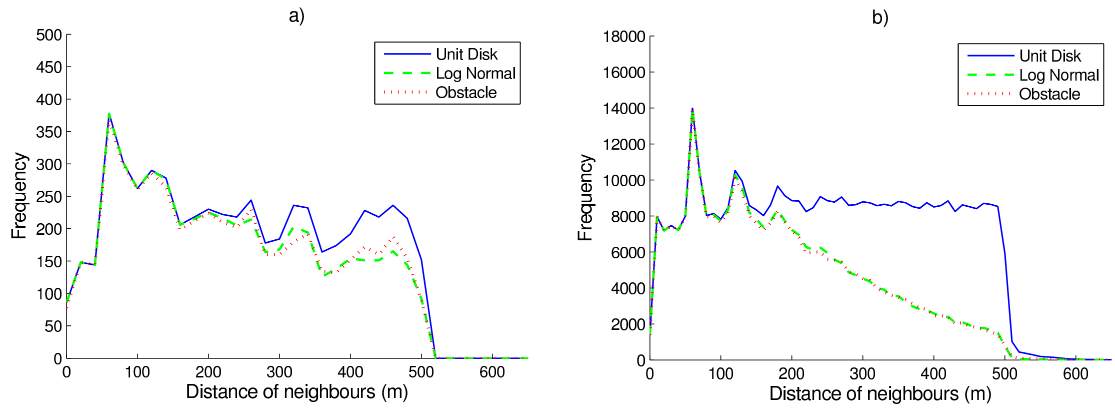

Fig. 3. Average number of vehicles that can communicate with a transmitter vehicle at different distances for a) low density network b) high density network, where the transmission range is 500m

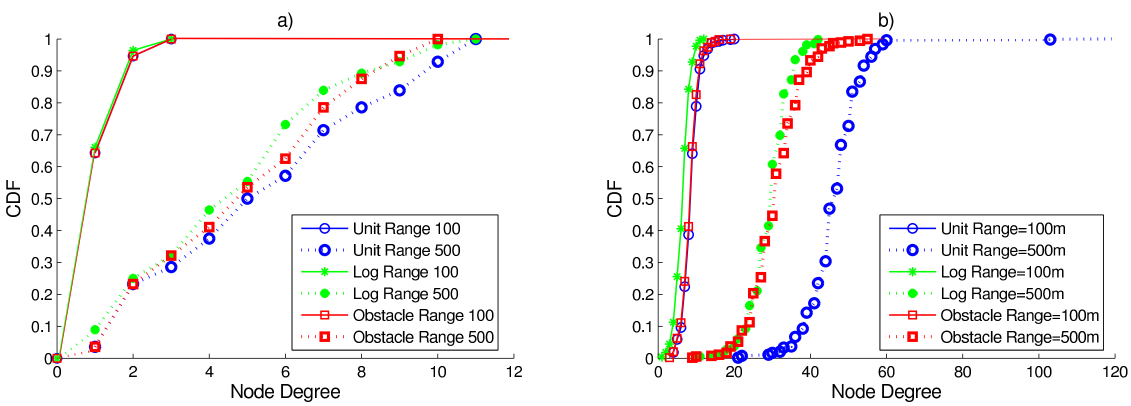

Fig. 4. Cumulative density function of the node degree metric for different channel models and transmission ranges in a) low density network b) high density network ($t_{window} = 5sec$).

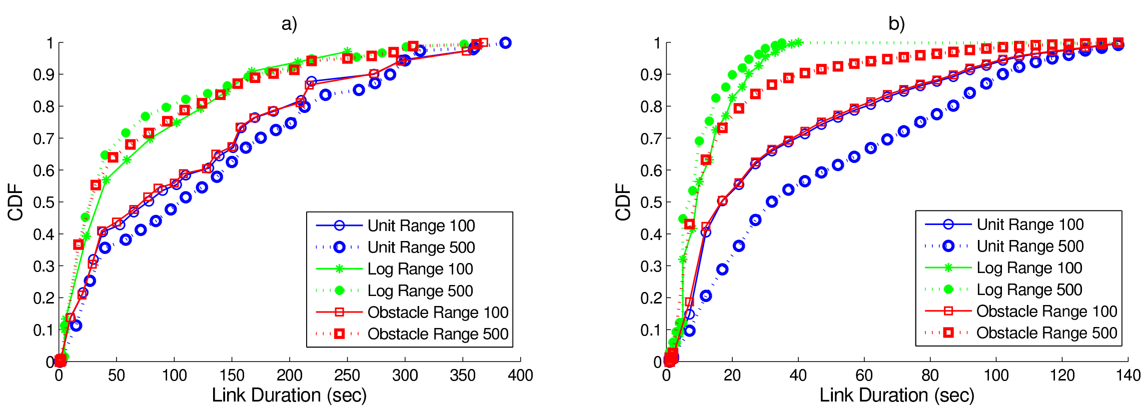

Fig. 5. Cumulative density function of the link duration metric for different channel models and transmission ranges in a)low density network b)high density network

Fig. 3 shows the average number of vehicles that can communicate with a transmitter vehicle at different distances for low and high density networks. Log-normal model has been configured so that it behaves similar to more realistic obstacle based model. As the density of vehicles increases, the fading increases as shown by obstacle based model and log-normal model. However, more commonly used unit disc model fails to capture the effect of high density for transmission range greater than 100m.

Fig. 4 shows the cumulative density function of the node degree metric for different channel models and transmission ranges in low and high density networks. Node degree of a vehicle is defined as the number of neighboring vehicles it can communicate with. In this study, we consider not only the

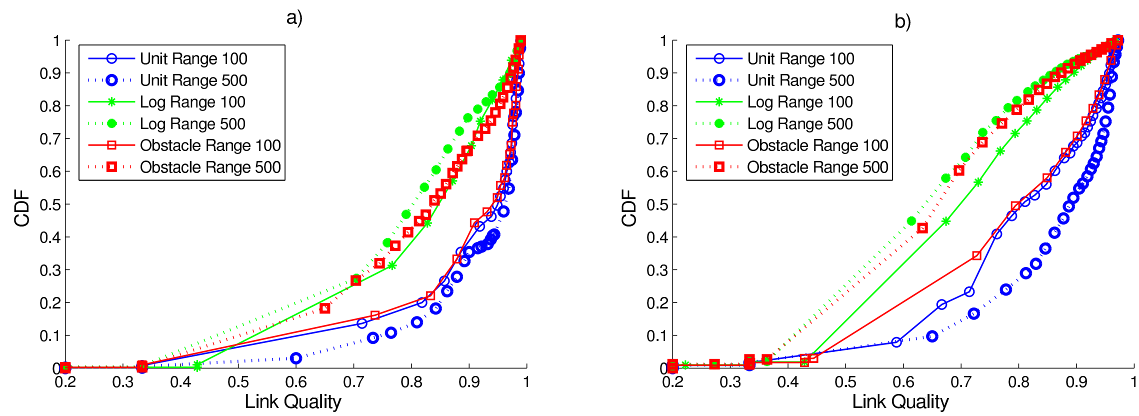

Fig. 6. Cumulative density function of the link quality metric for different channel models & transmission ranges in a)low density network b)high density network

neighboring vehicle that the transmitter vehicle can currently communicate with but also the neighboring vehicles that the transmitter vehicle was able to communicate during the past t_{window} time. The degree of a vehicle v_i at time T is then mathematically defined as $N(v_i) = \bigcup_{t=T-t_{window}}^{T} R_t(v_i)$ where $R_t(v_i)$ is the set of all neighboring vehicles the node v_i can communicate with at time t. As the vehicle density increases, the discrepancy between the obstacle based and log-normal model, and commonly used unit disc model increases as expected from the difference observed in the neighbor distribution of Fig.3-b. However, log-normal model behave close to obstacle based model for both low and high density traffic.

Fig. 7 shows the cumulative density function of the number of clusters metric for different channel models and transmission ranges in low density network. Number of clusters is defined as the number of co-existent, non-connected groups of nodes at a given instant. Since the number of clusters is 1 for high density networks for range between 100m and 500m, we did not include separate graph for high density networks. The distribution of the number of clusters formed by using the unit disc model, log-normal model and obstacle based model are very close to each other. The main reason for this similarity even at different transmission ranges is that the vehicles acting as obstacles between two vehicles at the same time act as bridges between them, resulting in an indirect connection through obstructing vehicle.

Fig. 5 shows the cumulative density function of the link duration metric for different channel models and transmission ranges in low and high density networks respectively. The definition of the link duration follows from the definition of node degree: If two vehicles can communicate with each other, the link between the two vehicles is considered to be established. If these vehicles cannot communicate for a time period greater than t_{window}, the link between the vehicles is considered broken. The link duration l_{ij} between vehicles v_i and v_j is then defined as $l_{ij} = T_c - T_o$ where T_0 and T_c are the times when the link is established and broken respectively, and $l_{ij} \geq t_{window}$. For higher transmission range in high density network (Fig. 5-b), the link duration for obstacle based model is smaller than that of the unit disc model and larger than that of the log-normal model. The main reason is that the nodes can always communicate with each other within a threshold distance for the unit disc model creating high correlation of the connectivity behavior whereas the connections between the vehicles are determined probabilistically for the log-normal model where the probability is chosen independently in each step, creating low correlation of the connectivity behavior.

Fig.6 show the cumulative density function of the link quality metric for different channel models and transmission ranges in low and high density networks. Link quality is defined as the probability that a message sent by the transmitting vehicle is successfully received at the neighboring vehicle. We observe similar behavior for link quality as the link duration. The link quality for the obstacle based model is closer to the log-normal model for high transmission range.

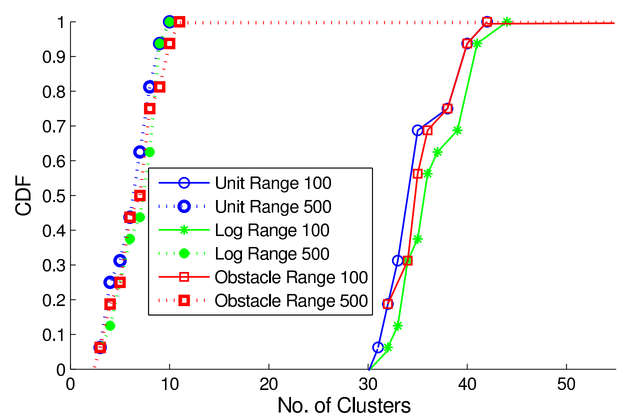

Fig. 7. Cumulative density function of the number of clusters metric for different channel models and transmission ranges in low density network

V. Conclusion

We analyze VANET topology characteristics by using both realistic large-scale mobility traces and realistic channel models. The realistic large-scale mobility traces are obtained by using accurate microscopic mobility modeling of SUMO, determining its input and parameters based on the flow and speed data of the road sensors, extracted from the PeMS database. The realistic channel model is obtained by implementing the recently proposed obstacle-based channel model, that takes all the vehicles around the transmitter and receiver into account in determining the received signal strength. The performance of the obstacle-based model is compared to the most commonly used more simplistic channel models including unit disc and log-normal shadowing model. Investigation of the system metrics including node degree, number of clusters, link duration and quality reveals that tuning the parameters appropriately for more simplistic and easy to implement log normal model provides a good match with more sophisticated obstacle based model. This shows that finely tuned log normal model can be used instead of both commonly used but inaccurate unit disc model, and more accurate but hard to implement Obstacle based model. We are currently working on improving the log-normal model by including time correlations to have a better fit for link quality and duration metrics.

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