Spatial Stationarity of Link Statistics in Mobile Ad Hoc Network Modelling

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Abstract

The performance evaluation of ad hoc network components through simulation allows for isolation of parameters, easy access to global quantities and a statistically significant number of repeatable trials. In designing network protocols, it is important to investigate the relationship between global network performance and the underlying locally observed network characteristics. Mobility models are used to define the movement of nodes in the simulation space. A wide variety of mobility models exist, and the choice of mobility model has significant influence over locally observed metrics. Unfortunately, many mobility models exhibit spatial and temporal non-stationarity of important metrics, such that global averages of certain metrics are not representative of local observations. This finding impacts on the development of adaptive ad hoc architectures.

This paper explores the spatial stationarity of frequently used mobility models. It focuses on the importance of stationarity in relation to the evaluation of performance studies. The spatial non-stationarity of link statistics, and the impact of this artefact on network performance evaluation is examined for the Toroidal Random Waypoint and Random Direction mobility models. We show that the Toroidal Random Waypoint model exhibits spatial stationarity of link statistics. Furthermore, we demonstrate that network performance studies in spatially stationary environments produce dissimilar results to those produced by non-stationary environments. This shows the importance of spatial stationarity when investigating global network performance and locally observed network characteristics.

1 Introduction

A mobile ad hoc network is a collection of wireless mobile nodes that dynamically form a temporary network on an as needed basis without the use of any existing network infrastructure. As a developing technology, issues regarding the implementation of ad hoc networks are subject to examination.

Limitations apply to the real-world analysis of ad hoc networks. The specification of system inputs to the analysis is difficult. The quality of the wireless channel is subject to unpredictable change due to multipath effects, fading effects, atmospheric effects or obstruction. Measurement of system performance is a distributed process. The lack of any god-like observer to the system eliminates trivial calculation of global performance metrics. The reportability of the results of any study requires a statistically significant number of trials to be carried out. This is a major challenge to real-world studies of ad hoc networks.

The artificial simulation of ad hoc nodes is a viable means of assessing the performance characteristics of ad hoc networks. Simulation offers greater control over input parameters and easy access to performance metrics. Furthermore, simulations can be run many times, thus providing a statistically significant number of repeatable trials and valuable, reportable results.

It is widely reported in the literature that ad hoc network performance is highly dependent on nodal mobility [9, 10, 24]. Relative node movement leads to a dynamic network topology caused by link formation and failure. The dynamic network topology is a critical factor in the performance of the routing protocol, and ultimately the performance of the network. Network mobility on a local level manifests itself in the stability of the communication links. Nodes must react to link instability to route packets effectively.

Performance studies commonly evaluate global network performance in terms of network mobility. To ensure the reportability of global performance results, the global link statistics must be representative of local link statistics at all times and all locations in the simulation space. Therefore, local link statistics must exhibit spatio-temporal stationarity. The movement of nodes in the simulation is dictated by a *mobility model*. The choice of mobility model is therefore significant to the interpretation of simulation results.

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A wide variety of mobility models exist in the literature, and they can be classified according to their unique characteristics. Camp *et al* [7] define *entity* mobility models as those in which node movement is autonomous, while models exhibiting correlation in their node movement are termed *group* mobility models. Bettstetter presents a comprehensive classification technique for mobility models in [1]. Zheng *et al* use Bettstetter's classification technique to distinguish three degrees of randomness in mobility models.

Trace based models are built upon traces of actual real-world movement. These models are completely deterministic, however the lack of availability of trace data limits the use of such models. *Constrained topology based* models exhibit partial randomness. The choice of node speed, node direction or node destination is a stochastic process, however the topology of the simulation space is restricted by obstacles. Recent work in mobility model design has focused on contrained topology based models. The aim is to produce more complex mobility patterns to mimic real-life movement. *Statistical* models allow unobstructed free movement of the nodes around the simulation space. The movement of nodes is determined stochastically. The popular *Random Walk*, *Random Waypoint* and *Random Direction* models are included in this class. Statistical models are of particular interest in this paper, as the stochastic movement patterns and lack of obstacles help to facilitate spatio-temporal stationarity in network statistics.

This paper investigates the importance of stationarity, and in particular spatial stationarity, in ad hoc network simulation. A metric is temporally stationary if its statistical properties do not change over time. Spatial stationarity assumes constant statistical properties at all points in the simulation space. The temporal non-stationarity of average node speed in the Random Waypoint model is well documented in the literature [17, 18, 27, 28], while spatial non-stationarity of node density in the Random Waypoint model has been addressed in [1, 8, 25].

The importance of spatial stationarity in the simulation environment is demonstrated by examining the spatial stationarity of link statistics in statistical mobility models. It is found that spatial stationarity of link statistics is not guaranteed for all statistical models. The border behaviour impacts on observed local link statistics and influences performance results. This artefact of simulation has implications for the development of adaptive ad hoc architectures, where local metrics are used to infer the optimal stack configuration. The authors advocate the use of stationary statistical models for performance studies and in the evaluation of adaptive architectures. Specifically, spatial stationarity of link statistics across the simulation space should be observed.

In Section 2, the authors present an overview of frequently cited statistical mobility models, and the reported stationarity issues associated with each of them. Section 3 describes the relevance of link statistics to network performance. A brief survey of existing work in the area of adaptive ad hoc schemes details the importance of link statistics in this emerging field. The experimental design is presented in Section 4, and the results advocate the Toroidal Random Waypoint model as a model exhibiting spatial stationarity of link statistics. The importance of spatial stationarity is discussed in Section 5.

2 Background and Related Work

A wide variety of mobility models exist. A survey of many of these is found in [1, 7, 14]. Statistical models are commonly used in performance studies, and this section presents a selection of frequently cited examples.

The Random Walk model [7, 30] produces movement similar to Brownian motion. Each node undergoes a stochastic selection process by choosing a speed and direction from the permitted ranges of $[vmin, vmax]$ and $[0, 2\pi)$ respectively. The nodes travel with the chosen velocity for a set time or distance and then repeat the selection process. Nodes leaving the simulation space reflect back off the border.

The Random Waypoint (RWP) model is widely used in the literature. It is initially described by Johnson and Maltz in [16], and refined in [6]. Each node begins the simulation in a *paused* state, and remains in that state for *pausetime* seconds. The nodes then select a destination (or waypoint) within the simulation area and move to that destination at a speed distributed uniformly in the range $(0, vmax]$. Then nodes enter the paused state again and the process repeats itself until the simulation ends. The border is never reached by nodes, and so a border behaviour specification is not required.

This model and its derivitives are widely used. The RWP model is found to display non-uniform distribution of nodes. Royer *et al* notice this effect in [25]. Nodes choose a random destination within the simulation space and therefore they pass through the centre of the simulation space with a greater probability than any other area. This is known as a *border effect* [1, 29]. Bettstetter and Wagner verify the non-uniformity of node distribution in [3], and Bettstetter *et al* develop an expression for the p.d.f. of node location in [2]. Research shows that increased *pausetime* helps reduce the non-uniformity of the node density [4].

Chu and Nikolaidis [8] show that the node density depends on the average mobile node speed. As average node speed increases, the density becomes more uniform. This dependence between average node speed and density arises from the RWP model, and is not accounted for in the majority of reported simulations.

Transient *density waves* are also observed in the *average neighbors per node* metric [25]. As all nodes begin movement at the same instant, they converge and diverge on the centre until the simulation time has progressed sufficiently. Other implementations of the Random Waypoint model begin with approximately half the nodes in the paused state, which speeds up convergence to a stationary regime [22].

Yoon *et al* [27] highlight yet another artefact of the Random Waypoint model. The average node speed is found to consistently decrease over time. The independance of speed and distance between waypoints ensures that the average node speed consistantly decays under the model. This decay is attributed to nodes selecting both a low speed and a distant waypoint. The nodes then become ”stuck” at this low speed until the destination is reached. As the simulation progresses, more and more nodes enter this low speed state, reducing the average node speed. This transient behaviour has longer decay periods under smaller minimum speed values. Yoon *et al* propose a number of possible solutions to the problem of average node speed decay. Instead of sampling the choice of speed from the range $(0, vmax]$, we sample from $[vmin, vmax]$ and set vmin sufficiently large to reduce the decay period. The period of the initial transient is reduced, and can be removed from the analysis. Alternatively, the speed can be correlated to the distance between successive waypoints. In this solution, nodes travelling longer journeys move faster. Yet another solution is to sample the node speed from the steady state distribution for node speed, thus starting the simulation in steady state.

Sampling initial node speeds from the steady state distribution has proved an effective solution to the temporal non-stationarity of node speed [17, 18, 21, 22, 28]. However, the spatial non-stationarity of node density is an artefact of the RWP model itself, and cannot be eliminated completely.

The Random Direction model is first proposed in [25] in response to the temporal and spatial non-stationarity of node density present in the random waypoint model. Nodes are uniformly distributed about the simulation space. Nodes choose a direction from a uniform distribution, and travel in that direction at a randomly chosen speed. The travel time is allocated depending on the exact Random Direction model implementation. Nodes must travel to the simulation boundary in [25], while other implementations allow nodes to travel to any point in the simulation space [17, 18, 20, 25]. Nodes then pause for a given pause time and the process repeats itself until the simulation ends. The Random Direction model restores temporal and spatial stationarity to the node density metric [25].

Variations on the aforementioned statistical models are produced by changing the border behaviour of the nodes. Nodes leaving the simulation area can re-enter from the opposite side. In effect, this ”wrap-around” border behaviour changes the geometry of the simulation area. Instead of a rectangular 2-D simulation area, the simulation space can now be viewed as toroidal in shape. This is demonstrated in Figure 1.

On a toroidal space, choosing a waypoint and choosing both a direction and travel time become equivalent concepts. Border effects associated with choosing a waypoint are eliminated, and therefore node density is spatially stationary under both schemes. Implemented on a toroidal space, the Random Direction and Random Waypoint model are collectively referred to here as the *Toroidal Random Waypoint* (TRW) mobility model.

3 Stationarity of Link Statistics

Existing studies of the spatial and temporal stationarity of network statistics are discussed in the previous section. The dependence of performance evaluations on stationarity is demonstrated in the literature. One of the main contributions of this paper is an exploration of link statistics with regard to stationarity and their subsequent impact on performance studies.

Performance studies evaluate the performance of a protocol at a certain mobility level. The mobility is often defined in terms of average node speed or average relative node speed. While the average node speed metric may be spatially stationarity across the simulation space, underlying topological changes may not. Obstacles and border effects limit the number of neighbors a node may have, and consequently the link stability and communication potential of nodes in the vicinity of borders and obstacles is affected.

Statistical mobility models do not include obstacles in the simuation space, but border effects exist. This section examines the spatial stationarity of link statistics in statistical mobility models.

3.1 Link Statistics

The performance of routing protocols is highly dependent on their ability to adapt and reconfigure to topological changes in the network [9, 10]. Therefore, it is important not only to look at macroscopic metrics such as node speed or relative velocity, but also to study the nature and impact of underlying link statistics in the simulation environment.

Link statistics are used to measure the stability of links in ad hoc networks, and two frequently used metrics are *link change rate* (LCR) and *average link duration* (LD). The LCR metric is defined as the number of communication links forming and breaking in a given period, while LD is the average lifetime of communication links in the simulation environment.

Link stability has a significant impact on the results of performance studies, both for general protocol assessment and in the field of adaptive ad hoc networking. It is therefore important to ensure stationarity of link statistics in the simulation environment.

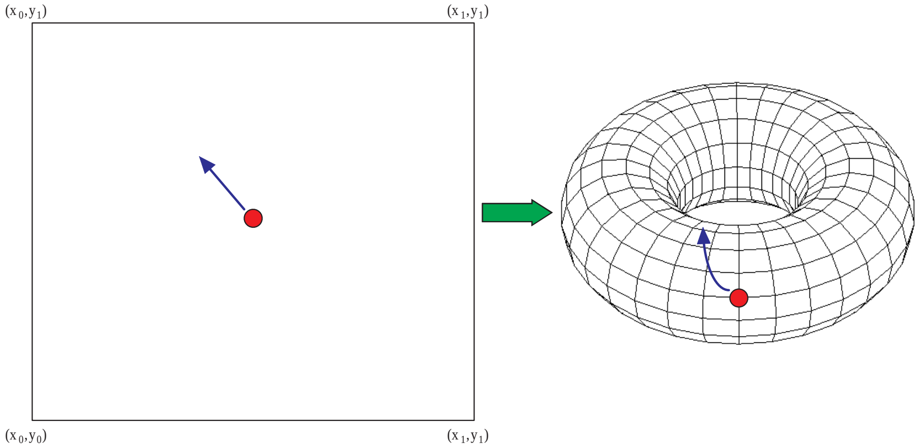


Figure 1. Wrap-around Border Behaviour produces Toroidal Simulation Area

3.2 Temporal Stationarity of Link Statistics

The temporal stationarity of average node speed has been extensively studied in [17, 18, 21, 22, 27, 28]. It is found that any random mobility model that independently chooses speed and destination suffers from average node speed decay [28]. The subsequent impact of this temporal non-stationarity on performance results is also reported in the literature. As link statistics are dependent on network mobility, it is not surprising that link statistics also exhibit transient behaviour. Lin and Midkiff demonstrate the temporal non-stationarity of LCR and LD in [19]. Temporal non-stationarity of link statistics is eliminated by restoring temporal stationarity to the average node speed statistic, as detailed in Section 2.

3.3 Spatial Stationarity of Link Statistics

Spatial stationarity of link statistics is of particular importance in the field of adaptive ad hoc networking. Under an adaptive architecture, nodes react to local observations to optimize protocol performance [23]. One of the main factors influencing protocol performance is node mobility [24], and therefore locally observable link statistics such as LCR and LD are used to motivate change [5].

Implementation of such an architecture requires prior knowledge of protocol performance under different link conditions. Simulations can provide this information, however it is important that spatial stationarity is observed in the link statistics. If two distinct regions of the simulation space exhibit different link statistics, a clear one-to-one relationship between observed link statistics and performance cannot reliably be inferred.

Boleng *et al* examine both LCR and LD as metrics to facilitate adaptation in ad hoc protocols [5]. Boleng's simulations use the Random Waypoint mobility model to dictate node movement.

Samar and Wicker derive properties relating to various link statistics with a view to analyzing network performance and optimizing protocol configurations [26]. In [26], they design an updating strategy for proactive routing protocols based on LCR statistics. Results are evaluated using the Random Direction model with reflection.

Gerharz *et al* use the LD metric to identify stable links for communication [12]. This study uses the Random Waypoint, *Gauss-Markov* [7] and *Manhattan Grid* [11] mobility models. In [13], end-to-end connectivity is improved by adapting OLSR routing protocol parameters to observations of link duration. The Random Waypoint, *Reference Point Group* [7] and Manhattan Grid mobility models are implemented in these simulations.

This paper contends that the border behaviour dictates the homogeneity of link statistics in the simulation space. A reflective border behaviour inhibits link breakage around the border area, leading to higher link stability in border regions. The authors note that existing studies of adaptive schemes have implemented mobility models with reflective border behaviour. Wrap-around border behaviour models the simulation space as a toroid and so link statistics are stationary at all points. The spatial non-stationarity of reflective models is empirically demonstrated, and the performance of reflective and wrap-around mobility models is evaluated.

We compare the performance results of the Random Direction model and the Toroidal Random Waypoint. The Random Direction Model exhibits spatial stationarity of node density, as previously discussed, and we highlight the fact that the spatial non-stationarity of link statistics is a separate and independent artefact of simulation which must be accounted for.

4 Experimental Design

Simulations are performed using a discrete event simulator based on the architecture in [23]. At the core of the system is a dynamic modular communication stack that runs on each of the nodes of the ad hoc network. Layers of the stack can be independently designed in a standalone fashion. A generic layer interface allows the dynamic assembly of these layers to form a network communication stack consisting of the relevant hardware and software elements. The inter-layer interface is very simple, consisting of primitives to send information upwards or downwards through the stack. Nodes route packets according to the DSR routing protocol [16]. We assume ideal MAC and PHY layers. Thereby we ensure independence from unwanted artefacts of the MAC or PHY implementations. Nodes access the medium on demand, with no collisions or interference. The transmission range for all nodes is fixed at 250 meters, a figure commonly used and consistant with WLAN technology. Free space propogation is assumed.

Traffic is generated by constant bit-rate (CBR) sources that select a uniformly random destination for each stream of 10 packets. One packet is presented to the network layer every second, and traffic density is dictated by the number of nodes acting as CBR sources. Protocol performance experiments consist of 20 nodes, of which 5 are CBR sources.

Nodes exist on an obstacle-free simulation space. Border behaviour may be set as wrap-around, reflective or delete-and-replace, as specified in [1]. The Random Direction model implements reflective border behaviour, while the Toroidal Random Waypoint model implements wrap-around behaviour. Although the nodes may wrap-around in toroidal space, the network traffic remains in two dimensional rectangular space. Traffic is not permitted to wrap-around to the other side of the simulation area.

Both models dictate node movement identically, only the border behaviour differs. Nodes are initially distributed randomly. A node chooses a direction from a uniform distribution on $[0, 2\pi)$. Node speed is fixed within a particular trial to ensure constant average node speed and temporal stationarity of link statistics. We assess the performance of the routing protocol at a particular mobility level by setting the constant node speed between $1m/s$ and $5m/s$ in repeated trials. The duration of node travel is such that a node may reach any destination in the simulation area from any starting point. This specification is necessary for the equivalence of Random Direction and Toroidal Random Waypoint node movement. The *pausetime* parameter of both models is set to 0 seconds.

We simulate the movement of 100 nodes in a $1000 \times 1000\ m^2$ simulation area under both mobility models. For each mobility model, we divide the simulation area into a 20×20 grid and count the number of link changes in each grid square for the entire 10000 seconds of simulation. The 3-D plot of the cumulative link changes in the simulation area reveals the effect of border behaviour on the spatial stationarity of link statistics.

Protocol performance is measured by evaluating the *delivery ratio*. The delivery ratio is the fraction of packets presented to the network layer for transmission that reach their intended destination. Only packets for which a route exists to the destination are included in the calculation. Node speed is varied from $1\ m/s$ to $5\ m/s$ on a $750 \times 750\ m^2$ simulation area for each mobility model, and the delivery ratio is assessed. Twenty 1000 second trials were evaluated for each mobility level. This analysis highlights the effect of border behaviour on protocol performance.

Lastly, we demonstrate the effect of border behaviour on the link statistics. We plot the expected LCR and LD metrics against the average node speed for both models.

5 Results and Discussion

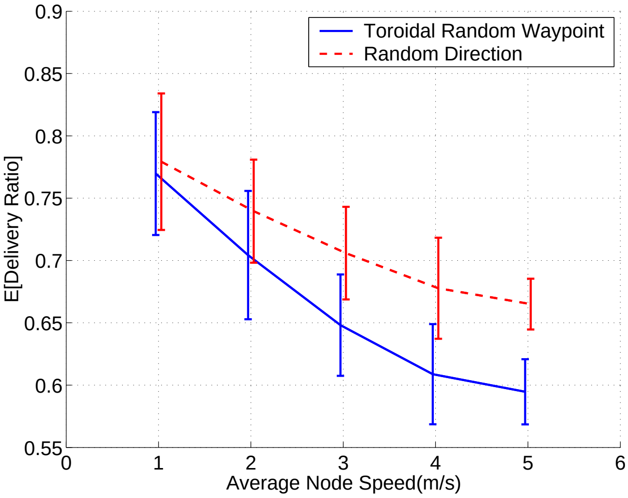
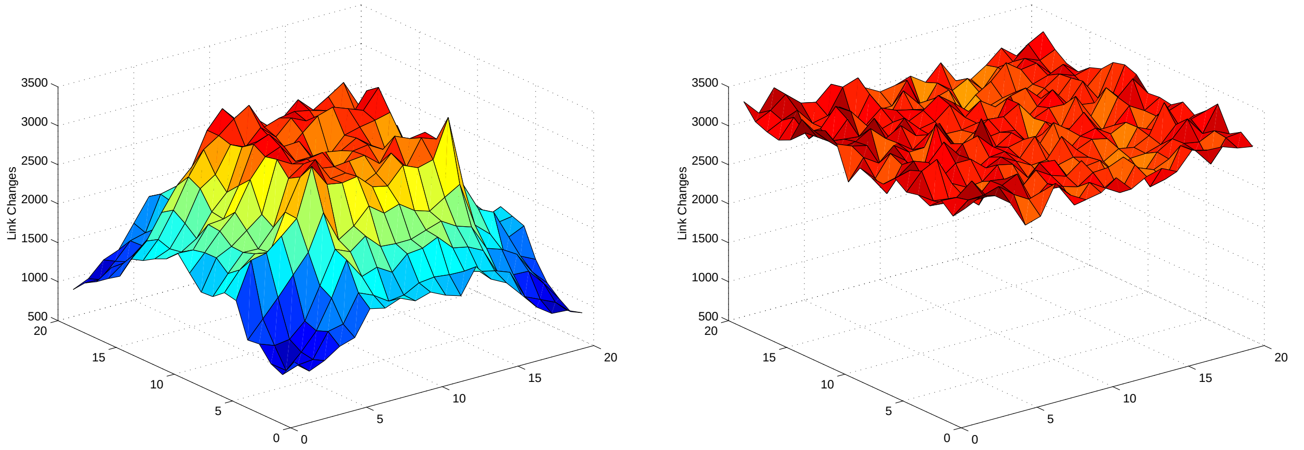


Figure 3. Protocol Performance Versus Mobility for the Toroidal Random Waypoint and Random Direction Models

The link change count is calculated for each grid square in a $1000 \times 1000\ m^2$ simulation area under reflective and wrap-around mobility models. The spatial non-stationarity of link changes in the Random Direction mobility model is shown in Figure 2(a). Nodes experience a higher link stability in the border regions due to the reflective border



(a) Random Direction Mobility Model

(b) Toroidal Random Waypoint Mobility Model

Figure 2. Link Change Count for a $1000 \times 1000\ m^2$ Simulation Area (Grid Size 20×20)

behaviour. Nodes impinging on the border remain within the transmission range of neighboring nodes as they reflect back into the simulation space. Therefore, nodes within transmission range of the border experience less link changes and consequently higher link stability than nodes in other regions of the simulation space. We can see in Figure 2(a) that the link change count begins to decrease 5 grid squares, or 250 meters, from the border as expected. These results can be generalized for all mobility models implementing reflective border behaviour, or including obstacles in the simulation space. Spatial stationarity of link statistics is not guaranteed and nodes in distinct regions of the simulation space experience different link stability.

The Toroidal Random Waypoint model experiences spatial stationarity of link statistics due to the wrap-around border behaviour, and this can be observed in Figure 2(b). Global averages of link statistics are representative of the locally observed metrics. It is therefore preferable to use the Toroidal Random Waypoint model in performance studies, as the results present a true reflection of the network performance under a given link stability. The degree with which performance results diverge under alternate border behaviour models is shown in Figure 3. The expected delivery ratio is evaluated over all trials and shown with error bars equal to one standard deviation. The expected delivery ratio for the Random Direction model is consistently higher than that of the Toroidal Random Waypoint. Performance converges at low node speeds, where the effects of the border behaviour become negligible. These results emphasize the increased link stability in the border regions of reflective models, and highlight the divergence of performance results from both models as average node speed increases.

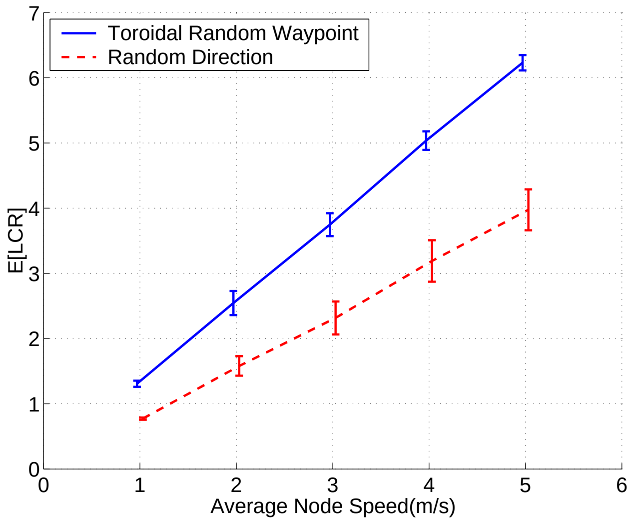


Figure 4. Expected LCR Versus Average Node Speed for the Toroidal Random Waypoint and Random Direction Models

The effect of border behaviour on the observed link statistics is demonstrated in Figures 4 and 5. Multiple trials yield expected values for LCR and LD. The expected LCR and LD metrics differ significantly under the Random Direction and Toroidal Random Waypoint models. We see that the spatial non-stationarity of link statistics not only affects performance results, but also impacts on observations of link statistics which may be utilized in adaptive ad hoc architectures. The expected LCR for the Random Direction model is consistently lower than that of the Toroidal Random Waypoint model, and the two curves diverge at higher mobility levels. Longer LD is experienced by nodes in the Random Direction model. Both the longer LD and lower LCR are indicators of the increased link stability in border regions of the Random Direction model.

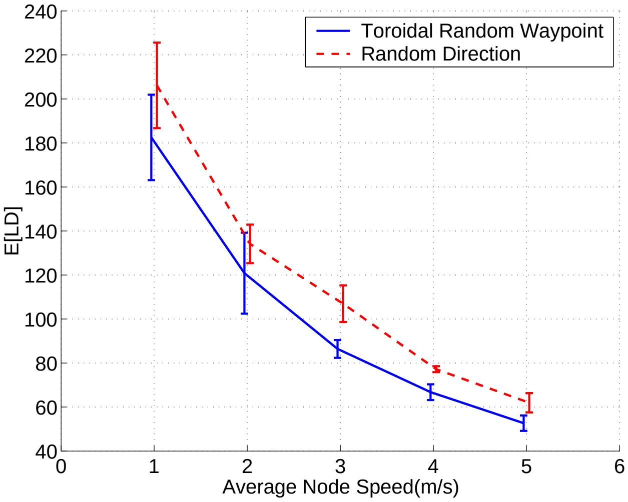


Figure 5. Expected LD Versus Average Node Speed for the Toroidal Random Waypoint and Random Direction Models

It should be noted that real ad hoc networks may not exhibit spatial stationarity of link statistics. However, the aim of this research is to develop simulation techniques capable of unbiased performance analysis. Spatial non-stationarity of link statistics introduces simulation artefacts into the analysis. Global metrics are unrepresentative of locally observed values due to the variance of link statistics throughout the simulation space. The degree with which spatial non-stationarity affects the performance results is dependent on the exact implementation of the simulation. The performance results under such conditions are difficult to interpret and their validity for use in real-world applications is questionable. Spatial stationarity of local link statistics allows for easy interpretation of performance results. Furthermore, these performance results can be used as prior information in adaptive architectures, where local observations of LCR and LD can be used to infer the optimal protocol configuration.

We view the Toroidal Random Waypoint model as a microcell of a larger ad hoc network environment. This concept is introduced in [25]. While network statistics may vary across the larger environment, within our simulation they are spatially stationary. The larger network may be viewed as a patchwork of spatially stationary Toroidal Random Waypoint mobility models. Nodes at the edge of a microcell observe the same link statistics as those in the center of the cell. Nodes approaching the border of the microcell do not reflect but continue on their journey and the links between it and other nodes in the cell fail. The node re-enters the simulation space on the opposite side from which it exited, ensuring constant node density and connectivity in the simulation space. A full route discovery process is required to re-establish communication with this node.

In reflective border schemes, nodes impinging on the border remain in the same general neighborhood, thus at most a local route salvage process is required to continue communication. The link stability in border areas is artificially high compared to that of a spatially stationary regime. Links at the core of the simulation area are more unstable than those at the border. Indeed, nodes in the border regions can be considered to provide a more stable backbone for network communication. By including reflective border behaviour, these simulation artefacts are introduced. This behaviour is not indicative of our microcell viewpoint, and has spurious effects on performance evaluations.

The authors note that although nodes in the Random Waypoint mobility model do not reach the border, they are considered to have a reflective behaviour within the border region, and consequently the RWP model also exhibits spatial non-stationarity of link statistics.

6 Conclusion

Statistical mobility models are a practical and useful tool for evaluating the performance of ad hoc networks. A wide variety of mobility models exist, and the choice of mobility model has significant influence over locally observed metrics. Unfortunately, many mobility models exhibit spatial and temporal non-stationarity of important metrics, such that global averages of certain metrics are not representative of local observations. This has important consequences for research in adaptive ad hoc architectures, where nodes are designed to adapt to local network observations. Spatial and temporal non-stationarity of metrics may also lead to the misinterpretation of performance results.

In designing network protocols, it is important to investigate the relationship between global network performance and the underlying locally observed network characteristics. This paper examined the spatial stationarity of link statistics in statistical mobility models. Spatial non-stationarity of link statistics under reflective border behaviour models is highlighted, and the impact of this artefact on network performance results is explored.

The Toroidal Random Waypoint model is shown to exhibit spatial stationarity of link statistics. Global averages of link statistics are representative of the local observations in each region of the network. For this reason, the authors propose the Toroidal Random Waypoint model as a good candidate for use in adaptive ad hoc research and network performance studies.

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