Impact of Mobility Patterns on the Performance of a Disruption Tolerant Network with Multi-Radio Energy Conservation

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Impact of Mobility Patterns on the Performance of a Disruption Tolerant Network with Multi-Radio Energy Conservation

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***Abstract*—Frequent partitions, intermittent connectivity and message delivery delay are the commonly observed characteristics of disruption tolerant networks (DTNs). These networks often operate over extended periods since they are regularly deployed in harsh and constrained environments. Efficient energy conservation is therefore necessary to prolong network lifetime. Most DTNs nodes depend on mobility to deliver messages to their destination. The introduction of energy conservation, using a high power radio for data delivery and low power radio for neighbor discover to achieve higher energy savings, coupled with mobility can negatively impact the total connection opportunities. This makes it important to understand the effects that mobility patterns can have on the performance of DTNs when multi-radio energy conservation is used. In this paper we study the effects of random waypoint, Manhattan mobility, message-ferry, human and zebra mobility models on DTNs where a wake-up model multi-radio energy conservation is used. The simulation results show that absolute impact of mobility on energy savings is quite limited. It also appears that in high traffic load dense networks mobility impacts delivery ratios and average delays, while impact in low traffic is not pronounced.**

I. Introduction

Disruption tolerant networks (DTNs) are a class of networks that experience frequent and long lasting partitions which lead to intermittent connections and makes the network prone to disruptions. The increased use of wireless mobile devices in remote and hazardous applications such as, wildlife tracking, military networks, disaster recovery and emergency response systems, has led to the need to develop protocols and methods to improve currently constrained network lifetime, caused by limited energy sources and few-to-none recharging opportunities.

The frequent partitions in network topology of such mobile DTNs means that nodes need to discover neighbors to take advantage of any communication opportunities that may present themselves. Searching for neighbors in sparse DTNs can consume a significant amount of energy compared to the energy consumed by infrequent data transfers. Therefore, energy conservation schemes are needed to conserve energy. While wake-up schemes are commonly deployed to conserve energy, such schemes are a challenge because it is important to have the nodes wake-up in such a fashion that maximizes their connection opportunities. This problem has been addressed by the development of on-demand asynchronous energy conservation schemes [14]. A further enhancement of such energy conservation schemes is possible by using multiple radios, i.e. a high-power high-data rate radio interface for on-demand data delivery and a low-power low-data rate radio interface for neighbor discovery to establish the possible connection opportunities.

Most effort in DTN research is in the routing space, in order to improve the data delivery ratios since mobility and sparsity of nodes can lead to no end-to-end paths in many scenarios. Since most DTN routing schemes assume that there exist some patterns in the movement of the nodes, and exploit these patterns to deliver data, it is safe to say that mobility patterns have a pronounced effect upon DTNs. Furthermore, since employing energy saving schemes utilizing the wake-up model can change the overall connection opportunities existing in a network, this effects the routing protocols, and in turn the energy consumption performance of the network as well.

As such, it becomes important to understand the effects that different mobility patterns can have upon energy conservation in a DTN. Therefore, in this paper a study to understand the effects of mobility patterns on energy conservation in DTNs is presented. This study utilizes an on-demand asynchronous multi-radio energy scheme, as this approach is already known to provide high energy savings without worsening the network performance. The PRoPHET routing protocol [8] is used for routing decisions since it leverages the patterns present in the contact history to predict the probability of future contact and thereby maximizing connection opportunities.

The following sections of this paper present related work in the energy conservation and mobility pattern areas, followed by a brief background on the energy saving scheme used for this study. The different mobility models used for testing are then discussed and the information on the simulation setups is provided in detail. The simulative results of the impact of mobility patterns on a DTN, when a multi-radio energy conservation scheme is used, are also presented.

II. Related Work

Due to the unique characteristics of DTNs most of the work has been concentrated on studying and developing routing protocols that maximize connection opportunities in scenarios where end-to-end connections may not be available. Since most DTNs are known to rely upon their mobility patterns to achieve higher delivery ratios, a lot of effort has been invested into understanding the effects of different mobility patterns on routing protocols developed for DTNs [9], [1]. As a positive side effect, this extensive research has led to the development of multiple mobility models that can easily be used for testing the performance of a DTN.

However, as much work has not been invested into developing energy conservation methods for DTNs. Several ad-hoc network power-management schemes allow nodes to disable their radios when not in use to save energy and to prolong network life time [11], [16]. However, these schemes assume that a node always has another node within its communication range, which is not the case with DTNs. Recent approaches for power management in DTNs focus on saving energy in neighbor discovery mode. Jun et al. [6] presented a power management scheme that assumes synchronized clocks and allows nodes to be in one of three modes, dormant (sleep) mode, search mode, and contact mode based on knowledge of future contacts. The authors of the CAPM scheme [14] propose an asynchronous wake-up model energy saving scheme that relies upon a neighbor discovery mode during which the node's radio is awake. The radio remains in sleep state all other times, besides when data transfer has to take place. They evaluate their scheme against random waypoint and real traces collected from the ZebraNet experiment to track zebra behavior. Most energy conservation schemes, however, are limited to an evaluation with the random waypoint model. This makes it important to understand the effect that different mobility patterns can possibly have upon the performance of a DTN when an energy conservation scheme is used, since such a scheme mostly employs some sort of a radio sleep-cycle which can serve to worsen network connectivity. Coupled with node mobility patterns, it can be quite difficult to achieve acceptable performance from the network.

III. Energy Conservation Scheme

The multi-radio energy conservation scheme used in this paper is a modified version of the CAPM scheme proposed by the authors of [14]. The original CAPM scheme deployed two modes to achieve energy savings. A neighbor discovery mode was utilized in order to discover connection opportunities and a data delivery mode to perform data transmissions once neighboring nodes were identified. Each node maintains it's own individual duty cycle to sleep the radio and neighbor discovery or data transfer are possible only when the radio is active.

By utilizing two radios, instead of one, the CAPM approach could be modified into an asynchronous on-demand energy conservation scheme that eliminates the idle time of a single high-power radio and only allows the high-power radio to consume power in the sleep mode or while it is activated and receiving data. The high-power radio is only called upon to perform data delivery when necessary, while the low-power radio remains active for asynchronous neighbor discovery. Each node periodically wakes up the low-power radio for a period W in a fixed duty cycle of length C to perform neighbor discovery. After K duty cycles have passed, the nodes let their low-power radio remain active for the full cycle length C, in order to provide the greatest contact opportunities to other nodes before reverting back to the regular scenario. The tuple (W,C,K) forms the sleep pattern of the nodes and choosing these values appropriate to the network design is important to achieve the best possible energy savings.

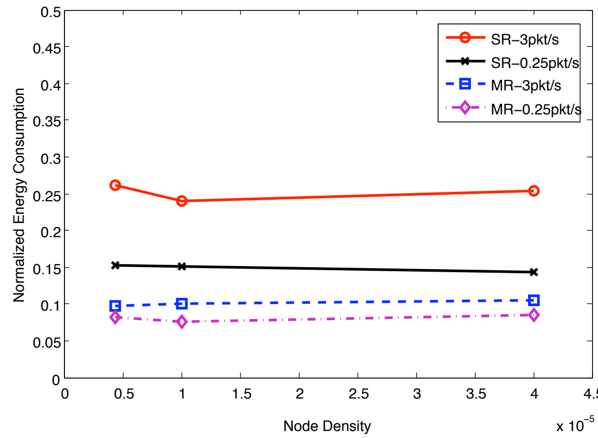


Figure 1. Normalized energy consumption with the multi-radio and single-radio energy conservation schemes. The random waypoint models was used to obtain worst-case performance under a high and low load scenario. Normalization performed against no energy conservation.

In case the target node for data delivery, or a suitable node for forwarding the data, is discovered during the neighbor discovery phase, the high-power radio is woken up to initiate the data transfer between the two nodes. Following such an on-demand wake-up model makes it important to use a routing protocol that can maximize the connection opportunities, and since DTNs generally depend upon mobility for data delivery, it should also be able to utilize this to its advantage. As such the PRoPHET routing protocol, a probabilistic routing protocol which uses a history of encounters and transitivity in order to determine future contact probabilities, was chosen to perform this study. PRoPHET performs well in intermittently connected networks where there is no guarantee that a fully connected path between source and destination exists at any time [8]. Mobility of nodes is expected to create such scenarios and, as such, PRoPHET appears to be a good match to mobile DTNs.

Prior evaluations have shown that using the multi-radio scheme can reduce the energy consumption by 88% to 95% compared to using no energy conservation scheme and by about 55% to 68% compared with a single-radio scheme [12]. A sample result for the effect of traffic load and node density on energy conservation can be seen in Figure 1. Since the multi-radio scheme out-performs the single-radio approach, only the multi-radio scheme was used for this study. Furthermore, the performance comparison of the single-radio and multi-radio approach shown in Figure 1 validates that our simulation results are accurate, since the shape of the curves obtained through the multi-radio scheme are similar to those of the previously published single-radio results.

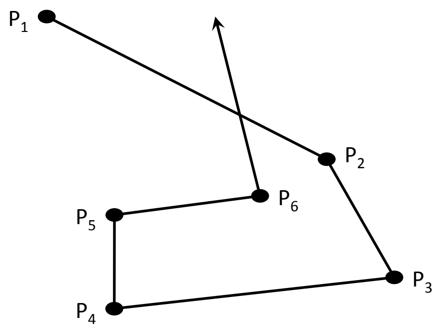


Figure 2. The random waypoint mobility model; $P_1, P_2 \ldots P_6$ represent the positions of a single node over time. The node positions and trajectory changes are random.

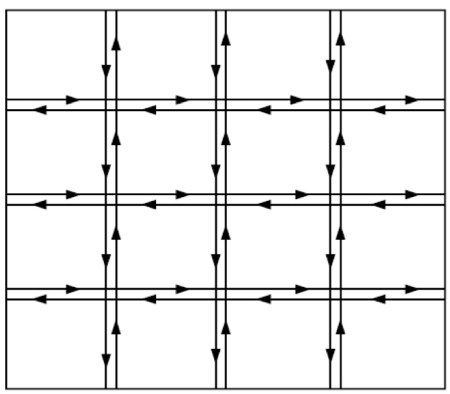


Figure 3. The Manhattan mobility model; each line represents a single-lane in which the nodes may move. The arrows represent the direction in which a node is allowed to move.

IV. Mobility Models

This section presents an overview of the mobility models used in order to test performance of the multi-radio energy conservation scheme.

A. Random Waypoint Model

The random waypoint (RWP) model is a random mobility model used for testing and evaluation in mobile communication systems. The mobility model is designed to provide possible movement patterns of mobile network nodes, and how their location, velocity and acceleration may change over time. As shown Figure 2, the mobile nodes move randomly and freely without restrictions. The destination, speed and direction of each node is chosen randomly and independent of other nodes in the network. As such, the trajectory changes that occur in this model are random and no particular mobility pattern can be deciphered.

This model is a good benchmark for worst-case mobile network performance since most DTN deployments are in scenarios where the mobility of nodes can be predicted with at least some probability.

B. Manhattan Model

The Manhattan mobility model uses a grid road topology, as shown Figure 3. This mobility model is based on the observed characteristics of road traffic in cities, especially in Manhattan. Each node in the simulation is allowed to move with a maximum possible velocity within a lane [5]. The nodes are not allowed to switch lanes unless they reach an intersection, where they may choose to keep moving in the same direction with probability 0.5 and to turn left or right with probability 0.25. Each node may have a different velocity, however the maximum and minimum velocity are restricted along with the maximum acceleration as well.

This model forms a good basis for testing the performance of DTN deployments where the mobile nodes move in a highly structured fashion, thereby increasing the likelihood of probable connectivity.

C. Message Ferry Model

The message-ferry mobility model is commonly deployed across DTNs [4]. In this model, sensor nodes are distributed across a space in a pattern such that it maximizes the coverage of the sensor network. Message ferries are mobile nodes which move between these sensor nodes in order to collect and deliver data by providing a relay opportunity to static nodes. In such scenarios, mobile nodes normally follow a deterministic path which maximizes the connection opportunities for static nodes.

The route taken by the ferry is deployment dependent. In our case we chose to develop a message ferry model that maximizes the possibilities of connection, in case the static nodes are randomly distributed. As such, the message ferry topology was based on the Manhattan model's grid structure, as shown Figure 4. The static nodes were distributed randomly across the field, while the mobile ferry nodes were restricted to traveling on paths similar to the Manhattan model. Here, just as with the Manhattan model, the maximum and minimum velocity of mobile nodes are restricted along with the maximum acceleration.

D. Orlando Model

Simulated and mathematical mobility models can provide traces which are good to obtain an idea about the performance of a system. However, since real world fluctuations can lead to unanticipated results, it is essential to evaluate the effects real world mobility can have on the performance of any networking scheme. As such, in our study we chose to use real-world traces from human and animal mobility patterns.

The Orlando mobility model [10] is based on the human mobility traces collected at Disney World, Orlando, Florida. The Disney World traces were obtained from four volunteers, each day for 70 days, who spent their thanksgiving or Christmas holidays in Disney World. Only the track logs from the inside of the theme parks are used for the study; the participants mainly walked in the parks and occasionally rode trolleys. Each participant was provided with GPS receivers that take reading of their current positions every 10 seconds and record them into a daily track log. Since GPS signals cannot be recorded indoors, such holes in the data are treated as the participant not having moved between two locations for an extended period, and then moving at a rapid pace.

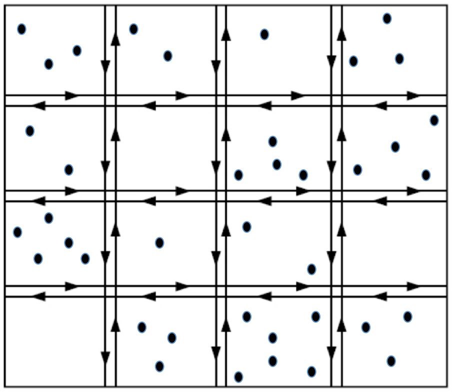


Figure 4. The message ferry mobility model; each line represents a single-lane in which the mobile nodes may move. The arrows represent the direction in which a mobile node is allowed to move. The static nodes, represented by the black dots, are distributed randomly across the field.

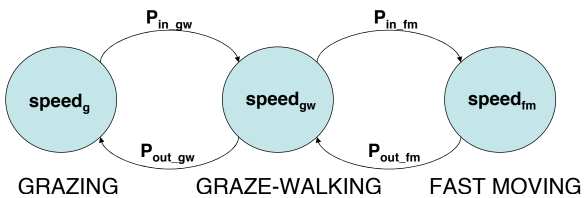


Figure 5. The Zebra mobility model, inspired from the ZebraNet [15] experiment. The three different modes that each zebra follows.

The Orlando model provides an insight into human mobility in a structured environment and as such is a good basis to study the effects of human mobility on the performance of a DTN with an active multi-radio energy saving scheme.

E. Zebra Model

The zebra mobility model is based upon the observed mobility habits of zebras [15]. This model is used to obtain an understanding of the impact of a mobility model, which may have multiple mobility characteristics, as a result of multiple operating modes.

As shown in Figure 5, a Zebra normally has three modes, namely *grazing*, *graze-walking* and *fast moving*. Each zebra in the model moves independently in a landscape composed of rectangular grazing areas and watering holes. A zebra's general movement pattern is a random waypoint search for a grazing area, interspersed with periodic trips to a watering hole. In searching for a grazing area, zebras use the *fast moving* mode, in which they move faster and across longer distances following the random waypoint model. Once a zebra finds a grazing area, it enters the *grazing* mode, not moving at all or the *graze-walking* mode, moving slower and across shorter distances between each movement. After each movement in a grazing area, the zebra randomly decides to continue grazing or return to the *fast moving* mode, selecting a random position among the landscape as the next destination. Each zebra also regularly visits a watering hole, i.e., a pre-determined fixed position using the *fast moving* mode.

V. SIMULATION SETUP

Since the purpose of this study was to obtain a better understanding of the effects of mobility on the performance of a DTN with energy saving schemes, it was thought appropriate to use ns2, one of the popular mobile wireless networking simulators available. However, ns2 only supports single radio interface simulations in it's current release and as such, it had to be intended to support multi-radio communication.

In this section, a brief discussion regarding the extensions made to ns2 is provided along with details on the simulation scenarios and mobility model dataset used for evaluation purposes.

A. ns2 Extensions

Since the existing ns2 implementation was unsuitable for evaluation a multi-radio energy conservation scheme, a number of modifications were made to ns2 to support multi-radio communications. Rather than multiplexing every interface on a single object, multiple instances of the wireless channel were created at the *Tcl* level. This approach allows greater flexibility and reduces the complexity of the changes that are required within the C++ code. Furthermore, this approach allows any existing routing protocol to continue functioning without any modifications.

The `node-config` was modified to take channels as an argument after they have been created, rather than creating them while the procedure is called. New procedures were implemented to set the number of interfaces, create multiple channels by taking the channel index and type as inputs and retrieve the number of interfaces. Once the multiple interface structures have been created within *Tcl*, it is necessary to associate them with the appropriate channel in the C++ code. In order to manage multiple channels, the variables governing the channel lists were modified to arrays. However, a functional limit of a maximum of 2 channels using a `MAX_CHANNELS` variable was imposed so as to keep the array size static and relevant to our study. The MAC layer code also needed modification in order to successfully identify the interface through which a message is received.

Normally, a routing protocol must either be designed or modified to successfully utilize multiple link layers and interface queues, however, this was not necessary in our case since each interface was being used independent of the other, i.e., the routing decisions were taken by the low-power interface and the high-power only performed data transfers based on this information.

B. Simulation Scenarios

In order to evaluate the impact of mobility on DTN performance, with the multi-radio energy conservation, the random waypoint, Manhattan, message ferry, Orlando and zebra mobility models discussed in Section IV were used for the simulations. Each simulation was performed with a total of 40 nodes distributed over a space of 1000 x 1000 m^2, 1150 x 1150 m^2, 1400 x 1400 m^2, 2000 x 2000 m^2 and 3000 x 3000 m^2, as per the mobility scenario's requirements

Table I
ENERGY CONSUMPTION CHARACTERISTICS OF DIFFERENT RADIO TYPES (IN WATT)[7], [3]

Radio	Tx/Rx	Idle	Sleep
WaveLan (2 Mbps)	1.3272/0.9670	0.8437	0.0664
XTend (115.2 Kbps)	1/0.36	0.36	0.01

Table II
PARAMETER VALUES

Packet rate	Node density	Sleeping pattern (W,C,K)
3pkt/s	1000 x 1000-40	(0.024, 1.67, 3)
	1150 x 1150-40	(0.024, 1.67, 3)
	1400 x 1400-40	(0.017, 1.46, 3)
	2000 x 2000-40	(0.01, 1,25, 4)
	3000 x 3000-40	(0.01, 1,6, 3)
0.25pkt/s	1000 x 1000-40	(0.04, 0.4, 12)
	1150 x 1150-40	(0.04, 0.4, 12)
	1400 x 1400-40	(0.04, 0.4, 12)
	2000 x 2000-40	(0.01, 0.4, 12)
	3000 x 3000-40	(0.01, 0.4, 12)

explained below, in order to obtain results from sparse and dense deployments. As such, in our evaluation node density is defined as the number of nodes divided by the area. We use constant bit rate traffic with 10 CBR flows and a packet size of 512 bytes. The traffic generation for each flow varied from 0.25 pkts/s to 3 pkts/s, for obtaining results from low to high loads. The sources and destinations of the CBR flows are randomly selected before each run amongst the 40 nodes, however, only a maximum of 10 connections are allowed during each run. In order to minimize the possibility of only a corner case being encountered, five different mobility scenarios for each field size, with every mobility model, were tested and every reported result is an average taken over these 5 runs. Using five runs we noticed that the variance in results was not very high, and as such, this choice was deemed appropriate.

Trace data for the random waypoint model was obtained by using the ns2 mobility generators [2]. Each node was restricted to move at a constant velocity of 5 $\mathrm{m/s}$. The Manhattan traces were obtained from trace generator tools provided by the original authors [5]. The mobile nodes were setup to move on a fixed grid like path with vertical and horizontal lanes. The 1000 x 1000 m^2 scenario consisted of 4 vertical and horizontal lanes each. Similarly, the 1150 x 1150 m^2, 1400 x 1400 m^2, 2000 x 2000 m^2 and 3000 x 3000 m^2 scenarios had 5, 6, 8 and 12 vertical and horizontal lanes each respectively. Each of the 40 nodes was restricted to move at a maximum velocity 5 m/s, minimum velocity of 2 m/s and a maximum acceleration of 2 m/s^2.

Since the message ferry model, as discussed in Section IV-E, is an extension of the Manhattan model, the trace generator tools for the Manhattan model were modified to create static as well as mobile nodes in the ns2 traces. The Message Ferry model had 25 randomly distributed stationary nodes with 15 message ferries. The test field configurations and mobile node characteristics were modelled with the same parameters as those used in the Manhattan model.

The Orlando model ns2 traces were obtained from the GPS data collected at Disney World and made available at the CRAWDAD repository [10]. Since the GPS traces were actually spread out across a large area, a tool was written to scale the available GPS traces into the five different target field sizes used for this simulation study. Another tool was then written to convert GPS position data into ns2 traces. The zebra mobility traces were generated using the data and tools provided by the original investigators of the ZebraNet [13]. The availability of both these models makes it possible to test the impact of real-world mobility patterns on the performance of a DTN with energy conservation.

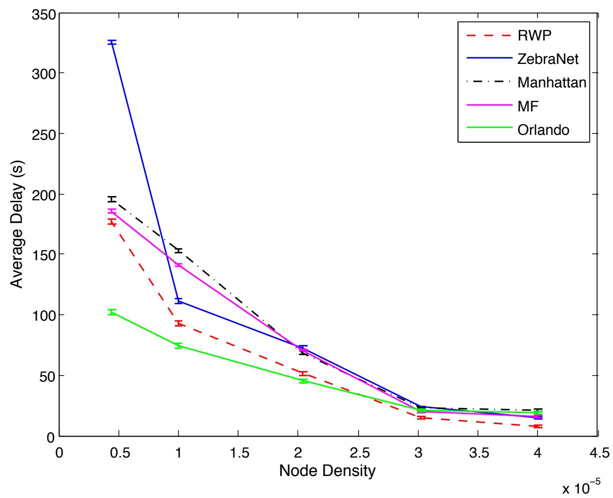
It is extremely important that the low-power radio is chosen with great care because if the transmission range of this radio is greater than the high-power radio then there might be many delivery failures as nodes discovered by the low-power radio would not always be reachable by the high-power radio. Furthermore, there must be some frequency band independence between the two radios in order to avoid signal interference that may degrade network performance. As such, the XTend low-power radio was chosen since its range and power consumption values are such that the chosen WaveLan high-power radio could still deliver data in every discovery scenario with energy savings. The energy consumption models for these two radios are shown in Table I, and these properties are used for all the simulations.

Since varying the chosen values for the (W, C, K) tuple can also have a pronounced impact on the performance of the network, we chose optimized values in accordance with the detailed discussion provided by the authors of the CAPM scheme on these parameters [14]. The chosen optimal values for these parameters can be seen in Table II. The PRoPHET protocol's transitivity and historical features are also configurable, as such, the optimal values, as derived by the authors of PRoPHET, were chosen for this study [8]. Each individual simulation was configured to run for 2000 seconds, with 1000 seconds being utilized as a warm-up period to allow for the network to reach a stable simulation state [14] and the performance data being recorded only for the last 1000 seconds of the simulation.

VI. PERFORMANCE EVALUATION

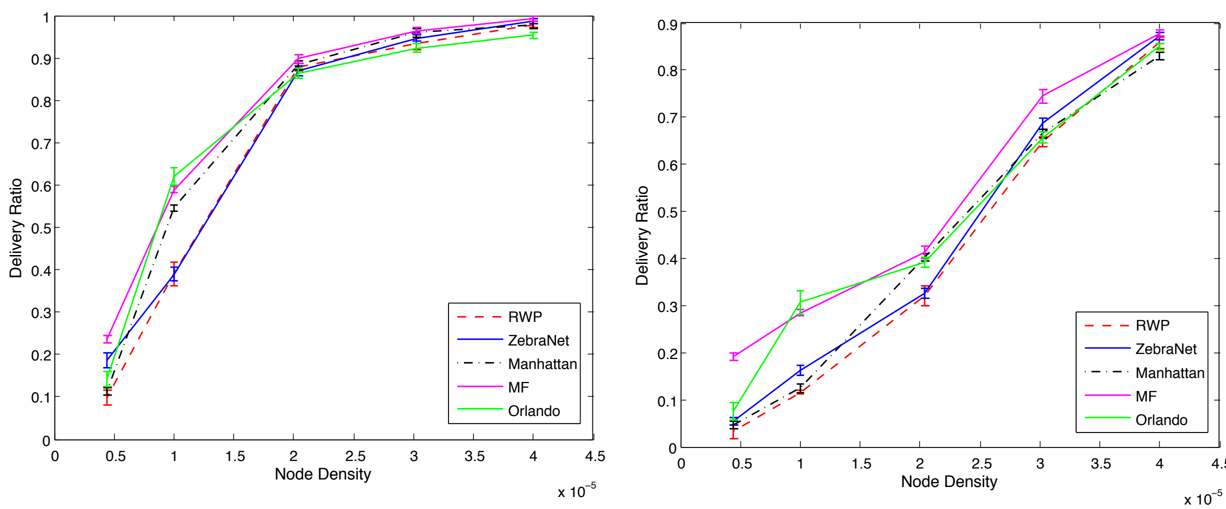
In order to understand the impact of node mobility, it is important to first identify the potential characteristics of a network that might be effected. As such, the following three metrics are used in order to evaluate the performance of the DTN because they stand the greatest chance of being hindered by different mobility patterns:

1) Average End-to-End Delay: The average delay it takes to deliver a data packet from the source to the destination.
2) Delivery Ratio: The ratio of the number of the successfully received data packets divided by the number of the data packets sent.
3) Normalized Energy Consumption: The ratio of the energy consumption when the multi-radio scheme is applied divided by the energy consumption in the absence of energy conservation.



(a) (b)

Figure 6. Impact of mobility patterns on the average delay in DTNs, deployed across various node densities, with multi-radio energy savings under (a) low traffic load; 0.25 pkts/s (b) high traffic load; 3 pkts/s. Variance for each data-point also shown.

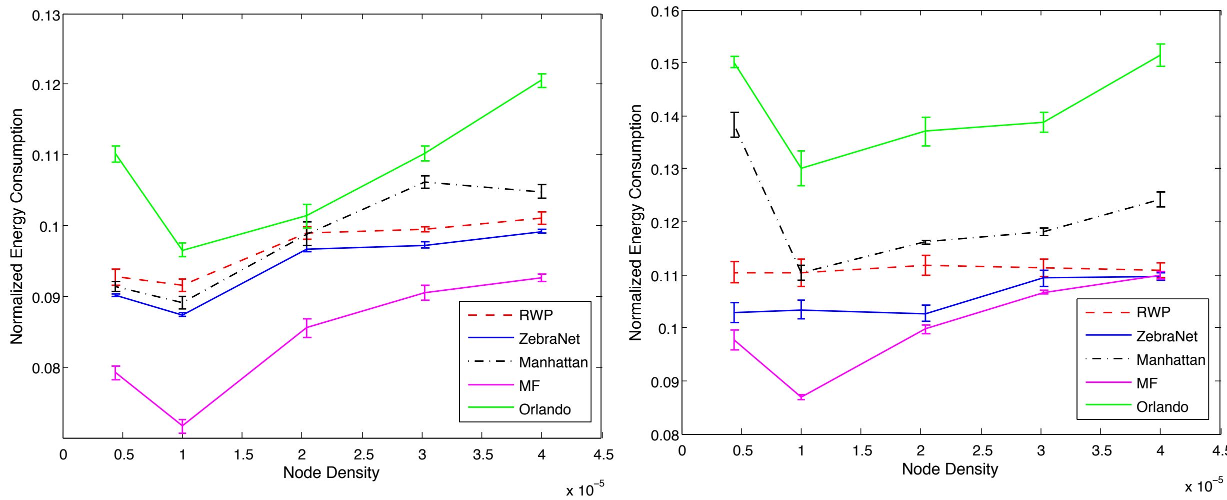


(a) (b)

Figure 7. Impact of mobility patterns on the delivery ratio in DTNs, deployed across various node densities, with multi-radio energy savings under (a) low traffic load; 0.25 pkts/s (b) high traffic load; 3 pkts/s. Variance for each data-point also shown.

Our performance evaluation experiments were carried out with evaluations of the effects of different node densities and traffic-loads. Figure 6 shows the the average delay over different traffic loads and node densities using the various mobility models. It is clear from these plots that the variance in the results, even across multiple runs, was minor and as such the results are dependable. Under low-traffic load and high node density the impact of mobility pattern is not high, however, the situation becomes different in sparse deployments. It is interesting to note that human mobility patterns, as gathered from the Orlando model, seem to have the lowest average delay and the random waypoint model outperforms the others, even though both models are not designed to increase connection opportunities. The similarity in the average delay between the Manhattan and message ferry models can be easily explained by the similar structure of the topologies. The zebra model has the worst average delay performance of all models, most likely due to the fact that zebras only congregate periodically at the watering hole and at all other times smaller groups of individuals follow an absolutely random movement pattern within regions separated from other sub-groups. The average delay experienced under high loads also shows similar behavior, except that the impact of mobility patterns becomes more apparent even at high densities.

Figure 7 shows the delivery ratio that can be achieved under low and high traffic loads when different mobility patterns are used along with energy conservation. It is easy to ascertain that under low traffic load and high node density the delivery ratios are quite high, as such, it can safely be said that under higher node densities mobility patterns do not have an impact on the delivery ratio if the traffic load is low. Under heavy traffic



(a) (b)

Figure 8. Impact of mobility patterns on the normalized energy consumption in DTNs, deployed across various node densities, with multi-radio energy savings under (a) low traffic load; 0.25 pkts/s (b) high traffic load; 3 pkts/s. Variance for each data-point also shown. Normalization is performed against no energy conservation.

load the difference even in higher node densities are a bit more pronounced. However, it is absolutely clear that at low node densities mobility patterns have clear effects on the delivery ratio. As expected, the delivery ratio of the random waypoint model is the worst and the zebra model also closely mimics similar results. The message ferry model outperforms all other mobility patterns in general, as this can be generally attributed to the high number of connection opportunities message ferries provide to static nodes in the network. The Manhattan model results closely resemble those of the message ferry model. However, the Orlando model performs unexpectedly better than other models. While this behavior could be attributed to the fact that most human might have predictable patterns behind it, it is also interesting to note that the variance in results exhibited by the human and zebra mobility patterns is higher than the others. This would seem to indicate that more studies involving collection of GPS traces from humans and animals are necessary to obtain a concrete picture.

Since we are especially interested in the behavior of the network with respect to energy consumption, it becomes imperative to also analyze the effects that different mobility patterns would have upon energy consumption in a network. Figure 8 shows the impact of different mobility models on normalized energy consumption in case of low and high traffic loads with varying node densities. The results are normalized against the case when no energy conservation scheme is utilized and depict the energy consumed by the entire network during, both, the neighbor discovery and data transfer modes of the multi-radio scheme.

From Figure 8 it is clear that generally higher node densities consume more energy than low node densities. This behavior is to be expected because at higher node densities there are more opportunities for packet collisions, which can lead to many re-transmissions and as such higher energy consumption. Furthermore, the higher connection opportunities lead to a much higher delivery ratio, which obviously consumes more energy as well because of a total higher number of transmissions. However, the reasons behind the generally high energy consumption at 3000 x 3000 m^2 compared to 2000 x 2000 m^2 is not immediately clear. It is possible that this behavior emerges as a result of the radio characteristics, and since a similar behavior is also exhibited under high traffic load.

Under low traffic load conditions it is clear from Figure 8(a) that the message ferry model consumes significantly less energy compared to the other models, because this model is highly structured and the likelihood of mobility pattern repetitions in this model are high, thereby increasing the connection opportunities. The zebra model closely mimics the performance of the random waypoint model and this is to be expected since most of the time is spent by the zebras in the grazing mode, which is random movement. However, the improvement in energy consumption is due to the deterministic nature of the watering hole position and the zebras' need to visit it's location at a regular interval. It is most interesting to note that the Orlando model based on human mobility patterns performs the worst in terms of energy consumption under low traffic load, but an explanation for this behavior is forthcoming in the fact that the mobility of each node in this model is based upon the speeds obtained from real GPS data. As such, the recorded and simulated speeds of the mobile nodes following the human mobility pattern is considerably lower than the other models. This could potentially lead to higher energy consumption as the velocity is likely to provide higher opportunities for data delivery to successfully complete and also a higher number of total data packets transmitted, since the connection reliability is now higher.

The message ferry model, once again, outperforms other mobility patterns in energy consumption even under high traffic load, as can be seen from Figure 8(b). Due to the partly predictable nature of zebra mobility, it performs better than random waypoint. But it is interesting here to note that

Manhattan mobility consumes more energy even though it is highly structured. This is likely because of the high velocity of mobile nodes and the restriction imposed on them to move within lanes in a particular direction until they reach an intersection. The Orlando human mobility model once again performs poorly, however, this can be attributed to the very slow movement of nodes.

VII. Conclusion

The effects of different mobility patterns on the performance of a DTN with multi-radio energy conservation have been investigated in this study. The random waypoint, Manhattan, message ferry, Orlando human and zebra mobility models were used to perform the investigation. Effects on average delay, delivery ratio and energy consumption were analyzed under high and low traffic load condition, while also varying the node density from sparse to dense distribution.

It emerges that a message ferry model tends to provide the best performance in a DTN scenario, in terms of energy consumption and delivery ratio. It can also be said that generally, using structured mobility with high predictability of future positions tends to significantly improve the performance of a DTN with wake-up schedule energy conservation. Furthermore, while the impact of mobility on average delay and delivery ratio is not high in dense networks with low traffic load, this becomes quite pronounced in sparse node distributions. On the other hand, node mobility patterns have an immediate impact upon average delay and delivery ratio in case of high traffic load, even with dense networks. The absolute difference in terms of normalized energy consumption under different mobility patterns is rather small, in fact the worst case impact of mobility on energy consumption is limited to an approximate 25% increase.

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