Understanding the Wireless and Mobile Network Space: A Routing-Centered Classification

Vincent Borrel*
Lab. d'Informatique de Paris 6
University Pierre & Marie
Curie – Paris VI
Paris, France
vincent.borrel@lip6.fr

Mostafa H. Ammar
School of Computer Science
Georgia Institute of
Technology
Atlanta, GA
ammar@cc.gatech.edu

Ellen W. Zegura
School of Computer Science
Georgia Institute of
Technology
Atlanta, GA
ewz@cc.gatech.edu

ABSTRACT

Research into wireless data networks with mobile nodes has mostly considered Mobile Ad Hoc Networks (or MANETs). In such networks, it is generally assumed that end-to-end, possibly multi-hop paths between node pairs exist most of the time. Routing protocols designed to operate in MANETs assume that these paths are formed by a set of wireless links that exist contemporaneously. Disruption or delay tolerant networks (DTNs) have received significant attention recently. Their primary distinction from MANETs is that in DTNs links on an end-to-end path may not exist contemporaneously and intermediate nodes may need to store data waiting for opportunities to transfer data towards its destination. We call such DTN paths *space-time paths* to distinguish them from contemporaneous *space paths* used in MANETs. We argue in this paper that MANETs are actually a special case of DTNs. Furthermore, DTNs are, in turn, a special case of disconnected networks where even space-time paths do not exist. In this paper we consider the question of how to classify mobile and wireless networks with the goal of understanding what form of routing is most suitable for which network. We first develop a formal graph-theoretic classification of networks based on the theory of evolving graphs. We next develop a routing-aware classification that recognizes that the boundaries between network classes are not hard and are dependent on routing protocol parameters. This is followed by the development of algorithms that can be used to classify a network based on information regarding node contacts. Lastly, we apply these algorithms to a selected set of mobility models in order to illustrate how our classification approach can be used to provide insight into wireless and mobile network design and operation.

Categories and Subject Descriptors

C.2.2 [**Computer Communication Networks**]: Network Protocols—*Routing Protocols*

General Terms

Design, Theory

1. INTRODUCTION

Wireless data networks with mobile nodes have been the subject of extensive research for at least three decades now. Research into such networks has mostly considered networks called Mobile Ad Hoc Networks (or MANETs)[3, 1]. While the nodes in such networks are mobile, it is generally assumed that end-to-end, possibly multi-hop paths between node pairs exist most of the time. Routing protocols designed to operate in MANETs assume that these paths are formed by a set of wireless links that exist contemporaneously [1, 15, 7, 14]. It is also assumed that if these paths are disrupted because of node mobility, then this disruption is only temporary and the same or alternate paths are restored relatively quickly.

Disruption or delay tolerant networks (DTNs) are a form of wireless and mobile networks that has received significant attention recently [17, 5, 16, 11]. Their primary distinction from MANETs is the fact that in DTNs links on an end-to-end path may not exist contemporaneously and intermediate nodes may need to store data waiting for opportunities to transfer data towards its destination. We call such paths *space-time paths* to distinguish them from contemporaneous *space paths* used in MANETs [13]. Figure 1 illustrates the concept of a space-time path. To deliver data in DTNs new routing protocols that are quite different from those used in MANETs have been developed [17, 5, 16].

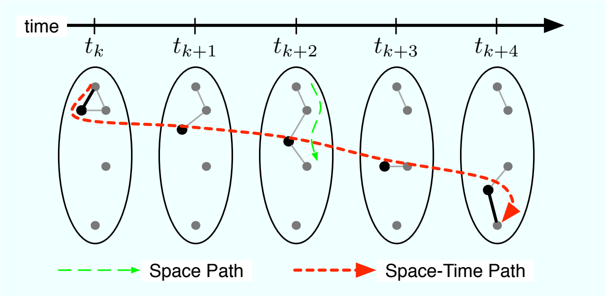


Figure 1: Example of a space-time path. The links in the path appear at different points in time.

---

[*] Work done while this author was visiting the School of Computer Science at Georgia Tech.

This work is supported in part by NSF Grants ITR-0313062 and NETS-0519784 and by the RNRT project SVP under contract 01504.

CHANTS'07, September 14, 2007, Montréal, Québec, Canada.

For any particular network, the question of whether the network is a MANET or a DTN is important to answer as it will influence its design and operation. In reality such a question is hard to formulate and even harder to answer as many networks will not fit neatly within a simple classification scheme. How a network is classified depends on several factors. Most important are the size of the network, the geographical area covered by the network, the node mobility pattern, and the range of wireless radios. Except for some extreme cases, it is in general not obvious, given these network parameters, as to which class a particular network belongs to. This paper is concerned with developing a formal classification of mobile and wireless networks. The goal is to have the classification be usable to determine the most appropriate routing strategy for a network. We call this a *routing-centered classification.* We also aim to develop a methodology that allows us to perform this classification given network characteristics. Note that our objective is to have the network classification provide guidance regarding which *class* of routing protocol (e.g., MANET,or DTN) is feasible. Further specification of the routing protocol would be needed within the specific class indicated but beyond what our classification informs. This will typically require additional information that is beyond the scope of our classification such as traffic and reliability requirements.

The rest of the paper is structured as follows. Section 2 provides an informal overview of our classification. Section 3 develops a formal graph-theoretic classification of networks based on the theory of evolving graphs [4]. We next develop in Section 4 a routing-aware classification that recognizes that the boundaries between network classes is not hard and is dependent on routing protocol parameters. This is followed in Section 5 by the development of algorithms that can be used to classify a network based on information regarding node contacts, which can, in turn, be derived from mobility and radio range information. Lastly, we apply these algorithms in Section 6 to a selected set of mobility models in order to demonstrate how our classification approach can be used to provide insight into wireless and mobile network design and operation.

2. AN INFORMAL CLASSIFICATION

We already mentioned two main classes of wireless and mobile networks, namely MANETs and DTNs. MANETs are characterized by the availability of space paths and DTNs by the availability of space-time paths. Space paths are actually a special case of space-time paths in which all the links exist simultaneously. Because of this, it can be argued that MANETs are actually a special case of DTNs. In fact, it is easy to see that DTN routing protocols (e.g., [17, 12]) are perfectly usable in MANETs[1].

DTNs are, in turn, actually a special case of a more general class of networks in which space-time paths may not exist [2]. For example, a network with nodes that are sparsely deployed and move in limited regions does not provide end-to-end space-time paths. In such networks data delivery is simply not possible between node pairs. Networks of this type require additional *assistance* in order to enable paths (space or space-time) for data delivery. Proposals for the use of message ferries [19] or throwboxes [20] are motivated by this type of network. It should be noted, however, that message ferrying and throwboxes while initially motivated by this type of sparse network are perfectly usable in regular DTNs or MANETs. See, for example, the work in [8] where a ferry is used to improve the energy efficiency in a MANET.

To describe the network classes above we will first of all use the term *Space-Path Networks (SPNs)* to denote what we have been calling MANETs so far. We do this because the term “MANET” is currently overloaded in the literature to indicate both a network path characterization as well as the type of routing protocols used. Our terminology emphasizes the path behavior of MANETs that we are interested in without implying the use of any particular routing protocol. We use the term *unassisted DTN or U-DTN* to describe networks which provide space-time paths between all node pairs. Note that the U-DTN class includes the SPN class. We use the term *strict U-DTN* to describe networks in the U-DTN class but not in the SPN class. Networks that do not provide space-time paths between some or all the nodes (or alternatively whose space-time paths take an infinite amount of time to complete) are called *assistance-needed DTNs or A-DTNs.* The A-DTN class includes the U-DTN class. Here again we use the term *strict A-DTN* to describe networks in the A-DTN class that are not in the U-DTN class. Figure 2 illustrates our network classification.

Note that while the network classification above is based on path properties it also is intended to inform routing protocol design. Traditional MANET protocols are usable in networks belonging to the SPN class and perform poorly for networks outside the class. Of course, exactly which MANET protocol is best cannot be specified with this type of classification. DTN routing protocols like epidemic routing are usable in the entire U-DTN class (including the SPN-class. Assistance (like Message Ferrying) is required in the strict A-DTN class but is usable and sometimes beneficial in the entire A-DTN class (including networks in U-DTN and SPN classes). Again exactly which form of assistance or how it should designed (e.g., how a ferry route should be designed) is not informed by our classification and requires additional information beyond what we use in our classification.

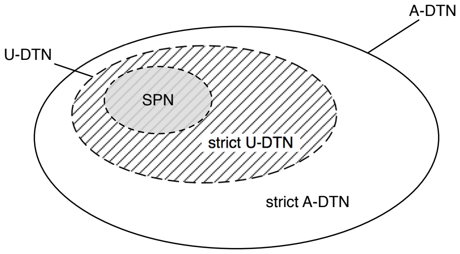


Figure 2: Classification of Wireless and Mobile Networks

We note that with this classification in mind, one can talk about *transformations* that can move a particular network from one class to another. For example, an “upgrade” transformation (like the addition of throwboxes or message ferries) can change a strict A-DTN into a U-DTN. Node failure or power depletion can result in the “downgrading” of an SPN to a strict U-DTN or a strict A-DTN. Changing network characteristics like node speed, the number of nodes,

---

[1] Traditional MANET routing protocols like DSR [7] and AODV [15]) are, of course, not in general usable in DTNs.

[2] A space-time path can be considered a special case of no path when it takes an infinite amount of time to complete.

or radio range, can also have transformative effects. Our classification framework enables us to also formally describe network transformation. We relegate this topic to future research.

Our network classification focuses on the properties of paths between node pairs. As such a network can appear to be of one class for some node pairs but of another class for other node pairs. This can complicate the classification quite a bit. So for the purposes of this paper, we consider a network to be of the SPN class if space paths exist between all node pairs. If a network is not in the SPN class but all node pairs are connected by space-time paths it belongs to the strict U-DTN class, otherwise it belong to the strict A-DTN class.

Another complication in formulating the classification arises from the question of the *time window* over which we consider a particular network. This is important because space-time paths take time to complete and if one considers a network over shorter periods, the network may appear to be in the strict A-DTN class, while over a longer period, the network appears to be in the U-DTN class. The notion of time window will be part of our formalism.

3. A FORMAL CLASSIFICATION BASED ON EVOLVING GRAPHS

In this section we formalize the classification presented above starting with formalisms developed for *evolving graphs* in [4]. We start from the basic evolving graph definitions and then augment them with features necessary to complete the formulation of our classification.

3.1 Basic Evolving Graph Definitions

An evolving graph is a graph whose links can change over time. This is formalized in the following definition.

DEFINITION 1. *EVOLVING GRAPH [4]: An evolving graph* $\mathcal{G} = (G, S_G, S_T)$ *is comprised of* $G = (V, E)$ *the graph representing existing nodes and existing paths, the sequence of its* $\mathcal{T}$ *subgraphs* $S_G = G_1, G_2, ..., G_\mathcal{T}$ *and the sequence of its* $\mathcal{T}+1$ *time instants* $S_T = t_0, t_1, t_2, ...t_\mathcal{T}$. *We have* $\bigcup_{i=1}^{\mathcal{T}} G_i = G$ *and each* G_i *is the subgraph in place during* $[t_{i-1}, t_i)$.

Informally, an evolving graph progresses in *epochs*. Epoch i lasts for the period $[t_{i-1}, t_i)$, during which the evolving graph is described by G_i.

It is relatively straightforward to see how a wireless and mobile network can be described as an evolving graph. As nodes move they potentially acquire and shed neighbors, changing the shape of a graph. The exact nature of these neighbor changes is a function of the node mobility and can be captured by the specifics of graph evolution. To describe this relationship we say that an evolving graph *maps onto* a wireless mobile network if the evolving graph provides an accurate representation of the node-contact evolution over time. With this mapping we are then able to formally define the classes of network described previously using a formal characterization of the corresponding evolving graph.

As mentioned earlier, it is important for our purpose to be explicit about the time over which we consider a graph. We therefore introduce the following new definition.

DEFINITION 2. *SUB-EVOLVING GRAPH: Given an evolving graph* $\mathcal{G} = (G, S_G, S_T)$, $1 \leq i \leq j \leq \mathcal{T}$, *a* (t_i, t_j)-windowed sub-evolving graph *of* $\mathcal{G}$ *is the graph* $\mathcal{G}' = (G, S'_G, S'_T)$ *where* $S'_G = G_i, G_{i+1}, ..., G_j$ *and* $S_T = t_i, t_{i+1}, ..., t_j$. $\mathcal{G}'$ *is generally called a* sub-evolving- graph *of* $\mathcal{G}$.

In some cases it will be useful for us to talk about an infinitely long time window. For this we make the following definition of an evolving graph being considered over an infinitely long period of time.

DEFINITION 3. *INFINITE EVOLVING GRAPH: An* infinite evolving graph $\mathcal{G} = (G, S_G)$ *is comprised of* $G = (V, E)$ *the graph representing existing nodes and existing paths, and* $S_G = \{G_t, t \in \mathbb{R}\}$ *the infinite sequence of its time-discrete subgraphs. Given two successive subgraphs* G_{t1} *and* G_{t2} *in* S_G, G_{t2} *is the subgraph in place during* $[t1, t2)$.

Our notion of space-time paths is captured by the definition of journeys as follows:

DEFINITION 4. *JOURNEY [4]: A journey* $\mathcal{J} = (R, R_\delta)$ *in an evolving graph* $\mathcal{G}$ *is comprised of* $R = e_1, e_2, ..., e_k$ *the sequence of edges it traverses, and* $R_\delta = \delta_1, \delta_2, ..., \delta_k$ *the corresponding time instants of node traversal.* R_δ *must be in accordance with* R *and* $\mathcal{G}$.

Ferreira *et al* [4] also define three kinds of journeys[3] that start at an origin node i at time t_0 to a destination node j:

- A *foremost journey* has the earliest arrival time to j.
- A *min-hop journey* has the minimum number of hops to j.
- A *fastest journey* has the minimum delay between leaving i and arriving to j.

The notion of connected graph is also extended to evolving graphs as follows:

DEFINITION 5. *TIME-CONNECTION [4]: An evolving graph is said to be time-connected if there exists journeys in* $\mathcal{G}$ *between any two vertices in* $V_\mathcal{G}$.

3.2 SPNs, U-DTNs and A-DTNs as Evolving Graphs: An idealized classification

We now formally define our network classes described previously by mapping them onto evolving graphs of certain properties. The mapping we describe here is *idealized* in the sense that we consider infinite evolving graphs and our classification is strictly dependent on the network contact properties and completely unaware of any routing protocol parameters or timing. We consider a more complex form of classification in the next section.

SPN:

Determining the evolving graph properties for an SPN is simple. Because an SPN provides strict space paths, an evolving graph will map onto an SPN if each of the graphs representing its evolution is connected.

DEFINITION 6. *IDEAL SPN: An infinite evolving graph* $\mathcal{G} = (G, S_G)$ *maps onto an SPN if each subgraph* G_t *in* S_G *is connected.*

Note that this classification is rather harsh because even if the evolving graph is disconnected during a single epoch, it cannot be classified as an SPN. This may be overkill since it would depend on how long the graph stays in this state.

---

[3] Note that although these journeys start from t_0, they can be made to start from a given time instant t_i by being applied to the sub- evolving graph containing all time instants later or equal to t_i.

These issues are the motivation for the more practical classifications described in the next section.

Strict U-DTN:
The principle behind U-DTN is that any source node can expect to reach any destination node in the future, and this at any time. This property holds for SPNs as well since they are a special case of U-DTNs. An infinite evolving graph maps onto a strict U-DTN if for any given time, and any pair of source and destination nodes, there exist a journey between these nodes, and if this evolving graph does not map onto an SPN.

Definition 7. *IDEAL STRICT U-DTN: An infinite evolving graph* $\mathcal{G} = (G, S_G)$ *maps onto a strict U-DTN if:*
- $\forall t \in \mathbb{R}, \forall (i,j) \in V \times V$*, there is a journey in* $\mathcal{G}$ *from* i *to* j *starting after* t*, and*
- $\mathcal{G}$ *does not map onto an SPN.*

Strict A-DTN:
Assistance is needed as soon as there exist a time and pair of nodes such that one cannot reach the other by a space-time path after this time.

Definition 8. *IDEAL STRICT A-DTN: An infinite evolving graph* $\mathcal{G} = (G, S_G)$ *maps onto a strict A-DTN if* $\exists t \in \mathbb{R}, \exists (i,j) \in V \times V$*, there is no journey in* $\mathcal{G}$ *from* i *to* j *starting after* t*.*

While this ideal classification gives us a base to build upon, most real-life scenarios are finite in time. On finite evolving graphs, the strict U-DTN classification cannot apply, since any evolving graph not finishing by a connected subgraph will have a time and a pair of nodes such that there is no journey relating them past this time. Moreover, we wish to account for simple real-life constraints, that might influence the usability of a routing approach. In the next section we devise such a classification.

4. A PRACTICAL CLASSIFICATION

The previous section provides a graph-theoretic classification of a mobile network that lasts for an infinitely long time into a single class. In reality of course, networks typically operate over finite durations. Even if a network operates for a long time, it is possible that its character may change over time. The classification is idealized in that it ignores details of the routing protocols. For example, a network that gets disconnected even for a short period of time is not classified as an SPN, even though, in practice, such temporary disconnection does not affect the operation of most MANET routing protocols.

In this section we extend the baseline idealized classification into a more practical one. We are interested in providing a classification that tells us something about how one should operate the network. The first difference from the idealized classification is the fact that we consider classifying finite duration evolving graphs. Our goal is to produce a single classification for the entire duration of each graph. As will be shown in Section 5, we then use this finite-duration classification to decompose a network into *time phases* with a single classification per phase.

The second difference is that we include practical aspects of the network operation into the classification. There are possibly many approaches to this depending on which aspects of a network's operation one wants to highlight. A full exploration of this issue is relegated to future research. We focus here on routing-related concerns in the classification. But even in that regard, we do not attempt to exhaust all routing concerns, but rather we aim to illustrate how they may be incorporated into network classification through simple parameters.

4.1 Practical SPN classification

In our idealized classification we have said that a network is an SPN if its corresponding evolving graph is always connected. This type of classification, however, does not tell us a lot about whether this class of networks is suitable for the deployment of MANET routing protocols. For example, consider an evolving graph where the graph changes significantly from one time epoch to the other while maintaining a connected graph at all epochs. While this qualifies as an SPN according to our classification above, it is clearly not a suitable environment for the deployment of a MANET routing protocol. Another important aspect of MANET routing protocols is that they require time to settle down, so an SPN that is defined over a short period of time may not be suitable for MANET routing.

In order to capture the above effects we first define a *link persistence* metric as follows:

Definition 9. *LINK PERSISTENCE: Let* $\mathcal{G}$ *be an evolving graph.*
We define $P(\mathcal{G}) = \frac{Q(\mathcal{G})}{\sum_{k=1}^{k \leq \mathcal{T}} l_{t_k}/2}$*, called* link persistence*, which is the average duration a link spends from its inception to its outage in the evolving graph.*
$Q(\mathcal{G}) = \sum_{1 \leq k \leq \mathcal{T}} ((t_k - t_{k-1}) \times |E_k|)$*, called the link-time quantity, is the amount of existence time cumulated by all links in the evolving graph.*
l_{t_k}*, called the link variation at time* t_k*, is the number of links added or removed from the evolving graph at time* t_k*.*

Using this definition, we obtain our practical SPN classification. This classification will be influenced by two parameters, which have to be provided from the point of view of a MANET routing protocol: the minimum acceptable duration of an SPN, η, and the minimal edge persistence that is acceptable by the network, δ.

Definition 10. *PRACTICAL (*η*,* δ*)-SPN: Given a minimum duration* η *and a minimal persistence* δ*, an evolving graph* $\mathcal{G} = (G, S_G, S_T)$ *maps onto an SPN if:*
- each subgraph in S_G *is connected, and*
- $t_\mathcal{T} - t_0 > \eta$*, and*
- $P(\mathcal{G}) > \delta$*.*

4.2 Practical strict U-DTN, strict A-DTN classification

For networks that do not belong to the practical SPN class we defined above, we now consider how to classify them as either U-DTNs or A-DTNs. Again we are interested in a practical classification that takes into account routing concerns. In U-DTNs we typically have to wait for links in a journey to appear for the data to be effectively transferred to destination. This waiting time, related to node motion, can be very large in relation to typical network delays. Thus, it becomes a predominant factor. Even though delays can be tolerated in such networks, it is often the case that one would like to bound this delay in order to, for example, set data expiry times. In the very least we are interested to know that the journey delay is not infinite.

Thus, when deciding if a DTN needs assistance or not, we choose to consider the worst delay of journeys in the evolving graph. We use foremost journeys to estimate the minimal delay to reach a destination from a given source. Thus, the we define a measure called "Longest Foremost Journey" as follows.

Definition 11. *LONGEST FOREMOST JOURNEY: Given an evolving graph $\mathcal{G}$ and a time instant $t_i \in S_T$, we define $L(\mathcal{G}, t_i)$, called* longest foremost journey *of $\mathcal{G}$ at instant t_i, the maximal duration that a foremost journey will take from any origin node to any destination node in $\mathcal{G}$.*

Our practical U-DTN classification is expressed as follows:

Definition 12. *PRACTICAL γ-U-DTN: Given a maximal journey delay γ, an evolving graph $\mathcal{G} = (G, S_G, S_T)$ maps onto a strict U-DTN if:*
- $\mathcal{G}$ is time-connected, and
- $L(\mathcal{G}, t) < \gamma, \forall t < t_{\mathcal{T}} - \gamma$
- $\mathcal{G}$ does not map onto an SPN.

5. CLASSIFYING NETWORKS FROM MOBILITY TRACES

We are now interested in the problem of classifying a certain wireless and mobile network given its mobility model or trace and given desired routing protocols. The mobility model (in conjunction with wireless range and propagation data) allows us to model the network as an evolving graph. The desired routing protocols give us the parameters η, δ, and γ used in our practical classification. In this section we develop an approach that allows us to take this input and produce a network classification. Recall that our classification framework is designed to help us with determining appropriate routing protocols for the network.

The evolving graph produced from the network characteristics is necessarily of a finite duration. Within this time duration we are interested in determining how a network classification changes over time, resulting in a time decomposition of the duration of network operation in time phases with a different classification in each.

Our approach to providing network classification is based on extracting certain metrics from the evolving graph. These metrics are derived from our formal classification. We then develop algorithms that consider the time-evolution of these metrics to produce the desired classification outcome.

5.1 Metrics of Interest

Our classification algorithm is based on the following metrics:

- NCC_i: The number of connected graph components in the evolving graph at epoch $[t_{i-1}, t_i)$.
- L_i: is the accumulated link departures up to and including time t_i. Note that $L_i = \sum_{t_0}^{t_i} l_{t_i}$ (see definition 9).
- Q_i: link-time quantity at time t_i (as defined in definition 9).
- $LFJ_i(j,k)$: is the longest foremost journey between nodes j and k and starting at instant t_i.

For a given evolving graph, the computation of most of these metrics is simple. Computing NCC_i uses well known graph algorithms [9]. Computing L_i and Q_i requires simple accumulation of information about link changes.

LFJ_i is computed using the Foremost Journeys algorithm, as defined in [4]. In that paper, starting from the observation that, given a source, a foremost journey to any destination is recursively based on a foremost journey to the node preceding the destination, the authors propose a simple modification of Dijkstra's algorithm using time of arrival as the ordering criterion. This algorithm gives, from any source node, foremost journeys to all possible destinations, and has a complexity in $O(M \times (\log \delta_E + \log N))$, where δ_E, called *activity* of the evolving graph, is the average number of time instants where an edge is present in this evolving graph.

A slight modification of this algorithm, permitting us to specify an arbitrary initial time instant in the evolving graphs, is used to compute LFJ_i. Here, at each time instant t_i, we compute, for one arbitrary node in each of the cliques of G_i, the foremost journeys from this source to all possible destinations, recording the longest one in LFJ_i.

5.2 The classification process and its outcomes

Given η and δ for the SPN classification and γ for the U-DTN and A-DTN classifications, our goal is to decompose the time duration of the evolving graphs into time-windowed sub-evolving graphs (see Definition 2) where each subgraph maps onto a single network classification. The original evolving graph can then be characterized by the percentage of time it spends in each network class.

We first determine the sub-evolving graphs that map onto the SPN network class using the following procedure:

- Any time epoch $[t_{i-1}, t_i)$ where $NCC_i = 1$ is SPN-eligible.
- A maximal succession of SPN-eligible instants $\{a \dots b\}$ going from t_a to t_b constitutes an SPN phase, i.e., forms sub-evolving graph that maps onto the SPN class if it meets the following conditions: 1) $t_b - t_a > \eta$ and 2) $\frac{2\times(Q_b - Q_a)}{L_b - L_a} < \delta$.

To determine the sub-evolving graphs that map onto the DTN classes we follow the procedure below:

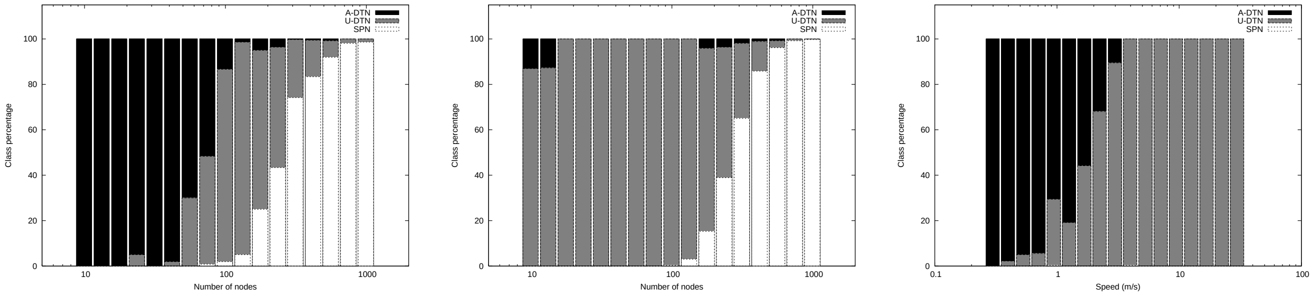
- Any epoch $[t_{i-1}, t_i)$ that is not SPN-eligible, or is SPN-eligible but not part of an SPN-phase, belongs to either a U-DTN phase or an A-DTN phase.
- The epoch belongs to a U-DTN class if it meets either one of the following two conditions: 1) ($t_i < t_{\mathcal{T}} - \gamma$ and $LFJ_i < \gamma$), or ($t_i \geq t_{\mathcal{T}} - \gamma$) and its predecessor epoch $[t_{i-2}, t_{i-1})$ maps onto the U-DTN class.
- Otherwise, the epoch is part of an A-DTN phase.

6. ILLUSTRATIVE CLASSIFICATION EXAMPLES

In this section we illustrate the use of our classification framework by applying it to two mobility models: the Random Waypoint (RWP) and Random Walk [6, 2] models. Our goal is to show how network classification is affected by the specifics of the mobility model, and its parameters, as well as the classification parameters derived from routing concerns.

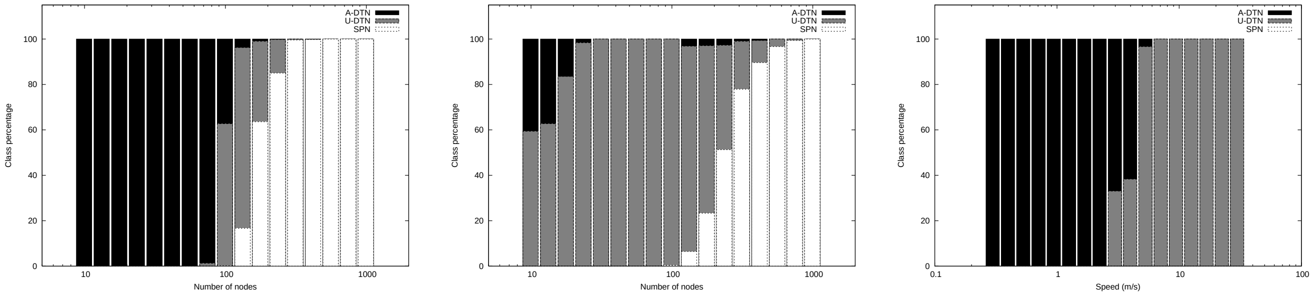
Although numerous articles [18, 10] in recent years have shown that these mobility models have clear weaknesses for a real mobility simulation, we chose them because of their simplicity. Our aim here is to highlight the interesting potential of our classification framework.

We use the mobility models to generate node-contact traces which, in turn, define an evolving graph. We then use our classification procedures described in Section 5 to classify the evolving graph. Recall that our classification results in a decomposition of the evolving graph into time phases, each with a corresponding network classification.



(a) RWP density variation: pedestrians (b) RWP density variation: vehicles (c) RWP speed variation: 60 nodes

Figure 3: Random Waypoint classification



(a) RW density variation: pedestrians (b) RW density variation: vehicles (c) RW speed variation: 60 nodes

Figure 4: Random Walk classification

In our models we move a specified number of nodes in a 2Km by 2 Km square area. We assume that radios have a 250m range. The number of nodes and the node speeds are varied. For the RWP, we assume a pause time uniformly distributed between 0 and 10 sec. The network starts with all nodes uniformly distributed within the area and runs for 3 hours.

6.1 Impact of mobility parameters

We first study the impact of the two defining parameters for RWP and RW: the number of nodes and their speeds. Before discussing our results, recall that our classification is a function of three parameters: namely η, the minimum acceptable duration for an SPN, δ, the minimum acceptable link persistence for an SPN, and γ, the bound on acceptable delay in a DTN. We set nominal values for these parameters as follows[4]: $\eta = 1$ minute, $\delta = 1$ second, and $\gamma=$ 10 minutes.

Density:

The first parameter we want to study is the influence of node density on the general classification of networks moving according to the RWP and RW mobility models. We vary the number of nodes from 5 to 500 and consider two speed ranges: pedestrian speeds, chosen uniformly between 1m/s and 2m/s and vehicular speeds, randomly chosen between 10m/s and 20m/s.

Figures 3(a), 3(b), 4(a), 4(b) show the results of these experiments in form of a stacked bar-chart with the proportion of time spent in each class. These results show that, for example, a network with 100 nodes moving at pedestrian speeds, spends about 20% of the time in the SPN class, 78% of the time in the U-DTN class and 2% of the time in the A-DTN class. A similar network moving at vehicular speeds is classified as a U-DTN 100% of the time.

This classification achieves our objectives of providing guidance on how the network should be operated. For example, the pedestrian speed example above can be operated using (unassisted) DTN routing protocols for the entire time. These protocols would not work for a small percentage of the time (when the network is in the A-DTN class. Further efficiency may be obtainable by adapting the operation of the network to use MANET routing during the 20% of the time it is classified as an SPN. This is not necessary, however, since DTN routing will work when the network is in the SPN class. Our framework insures through the setting of the values for η and δ that when a network is classified as an SPN, it is “stable-enough” for the adaptation to make sense. Although, other considerations that are outside the scope of our framework will need to be taken into account before the decision to use adaptive protocols is made.

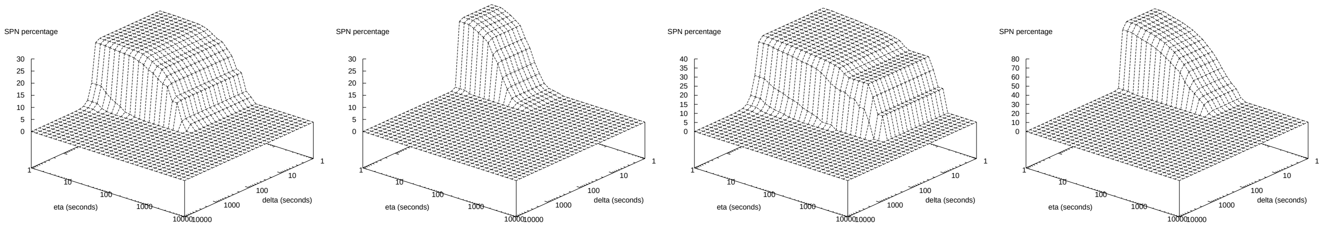
We can make several observations from these graphs. First note that for slow pedestrian speeds, the network is mostly classified as an A-DTN when the node density is low. At vehicular speeds, however, the network is mostly classified as a U-DTN, even for low node densities. Second we can see that higher speeds give more space-time connectivity to the network (less networks in the A-DTN class, it also results in lower space-path connectivity (less networks in the SPN class). Also observe that at slow pedestrian speeds the RW mobility model results in a “more disconnected” network than an RWP mobility model for the same parameters. This is a result of the more randomness imparted by the RWP model.

Speed:

Figures 3(c), and 4(c) show the effect of speed on network classification for the the RWP and RW mobility models, respectively. In both graphs we fix the number of nodes to 60. As expected, when the speed of the nodes increases the network changes from being predominantly in the A-

---

[4] Note that later results show the effect of changing these parameters on our classification.



(a) RWP pedestrians (b) RWP cars (c) RW pedestrians (d) RWP cars

Figure 5: Proportion of time spent in SPN for RWP and RW mobilities as a function of classification parameters.

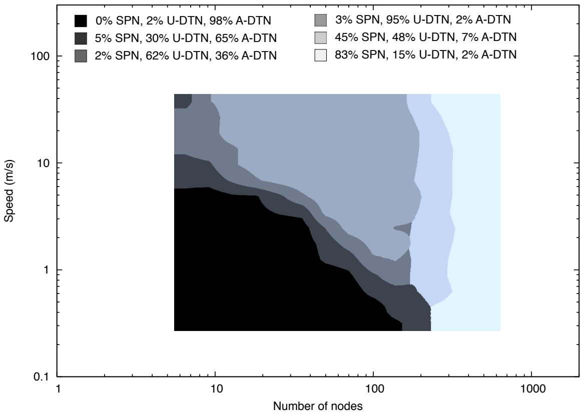


Figure 6: Joint Density/Speed Classification – RWP

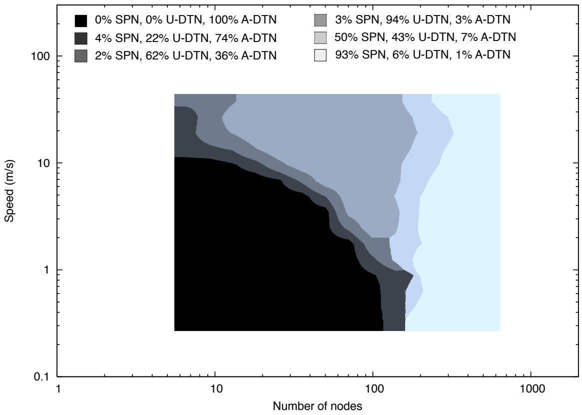


Figure 7: Joint Density/Speed Classification – RW

DTN class to being predominantly in the U-DTN class. The transition happens at lower speeds for the RWP model than for the RW model.

Join Speed/Density Classification:
The results above show that speed and density have complimentary impact on network classification. The higher the speed the more connected the network but also high speeds provide space-time paths at the expense of space paths. Increased density has the effect of increasing the percentage of SPN-class networks but more nodes were required for this at higher speeds. To be able to understand these effects better we show contour speed/density plots in figures 6 and 7 for RWP and RW, respectively. The graphs show the speed/density space subdivided into six zones. The boundaries of the zones are shown in the legend.

These kinds of graphs can again form the basis of the design of routing schemes for such networks. In cases where the networks operate in fixed regions within the space, specific routing can be designed for them. For example, networks that operate in the darker shaded region would require assistance in the form of, for example, message ferries. Networks that move widely within the space can justify the incorporation of learning mechanisms that can tell where they are operating and adapt routing to suit the region they are in at the moment.

6.2 Impact of classification parameters

We next consider the impact of parameters η, δ and γ in our classification. We will look at two aspects of this: 1) the decision separating the SPN from the rest, which relies on η and δ and 2) the decision separating strict A- DTN from the remainder, relying on γ.

SPN Decision:
We now look at how the classification of SPN versus other classes is influenced by its parameters, in the two scenarios of pedestrian and vehicular speeds. Figures 5(a), 5(b), for the RWP model, and figures 5(c) and 5(d), for the RW model, show the proportion of total time that the network spends in the SPN class as a function of our two classification parameters, η and δ. The graphs are for a network with 200 nodes. Note that for very low values of η and δ, the classification scheme is very liberal in classifying any connected portion of the network in the SPN class. This actually corresponds to an idealized classification. As the values of the parameters increases, the SPN classification applies to smaller proportions of the network duration.

A-DTN decision:
Using the simulation setup as above, we now consider at the outcome of the decision separating strict A-DTN from strict U-DTN, as a function of the parameter γ, the longest foremost journey.

Figure 8 shows the variation of the proportion of time that the network is classified in the A-DTN class as a function of γ for Random Waypoint and Random Walk, at pedestrian and vehicular speeds.

One interesting observation is that we clearly see here that for sufficiently large γ (which corresponds to maximum acceptable; message delivery delay) each mobility situation can result in a 0% time spent in the A-DTN class[5]. We can also see that higher speeds diminish the proportion of A-DTN classification for this node density (200 nodes in the area). Another observation is the fact that for small γ, the RW mobility model results in less proportion in the A-

---

[5] Of course this conclusion only applies to the RWP and RW models considered here.

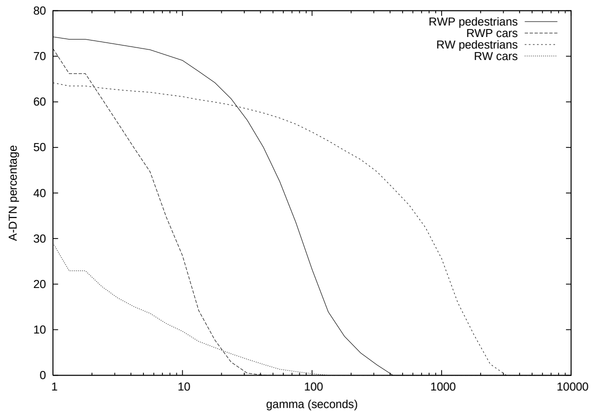


Figure 8: Proportion of time spent in A-DTN for the Random Waypoint and Random Walk as a function of γ

DTN class and the situation is reversed for higher γ. This is because RW mobility produces more area coverage. At lower speeds this is beneficial as it results in more space-time paths, while at higher speeds it is more disruptive.

7. CONCLUDING REMARKS

In this paper we have proposed a framework for classifying wireless and mobile networks, with the goal of having the classification inform the design of routing for the network. Our approach is based on the theory of evolving graphs and provides for three classes of networks (SPN, U-DTN and A-DTN), each derived from our understanding of routing approaches within such networks. We develop formal idealized and practical classifications. The former is based on infinite-duration evolving graphs, while the latter consider finite duration graphs. Our practical classification is based on parameters derived from the constraints imposed by routing protocols. We also develop a methodology that can be applied to given mobility models and traces to obtain the classification for a given network scenario. Finally, we illustrated the use of our classification approach using example network scenarios and mobility models.

We view this as the beginning of an examination of the important question of how one can classify networks with the goal of understanding their design and operation. While we believe that the work reported in this paper has touched upon most aspects of this problem, there are many important issues that require further consideration. These include:

- Further formulation of the process of network transformation that can be used to change one network class into another. This is discussed briefly in Section 2.
- Extensions of the classification formalisms to allow for *partial* classification that may for example include only a specified subset of node pairs in a classification scheme.
- A more in-depth investigation of how to devise parametric classification based on various routing protocols.
- More experience in using the classification approach for other mobility models and network scenarios with possibly a specific application to routing design exercise.

8. REFERENCES

[1] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *MobiCom '98: Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking*, pages 85–97, New York, NY, USA, 1998. ACM Press.

[2] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing*, 2(5):483–502, Aug. 2002.

[3] S. Corson and J. Macker. Mobile ad hoc networking (manet): Routing protocol performance issues and evaluation considerations, 1999.

[4] A. Ferreira. Building a reference combinatorial model for manets. *IEEE Network*, 18(5):24–29, Set 2004.

[5] K. Harras, K. Almeroth, and E. Belding-Royer. Delay tolerant mobile networks (dtmns): Controlled flooding schemes in sparse mobile networks. In *Proceedings of IFIP Netwoking*, 2005.

[6] D. B. Johnson and D. A. Maltz. Dynamic source routing in ad hoc wireless networks. In Imielinski and Korth, editors, *Mobile Computing*, volume 353. Kluwer Academic Publishers, 1996.

[7] D. B. Johnson, D. A. Maltz, and J. Broch. *DSR: the dynamic source routing protocol for multihop wireless ad hoc networks*, pages 139–172. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, December 2000.

[8] H. Jun, W. Zhao, M. H. Ammar, E. W. Zegura, and C. Lee. Trading latency for energy in wireless ad hoc networks using message ferrying. In *Proc. Third IEEE Intl Conf on Pervasive Computing and Communications Workshops (PERCOMW '05)*, pages 220–225, Washington, DC, USA, 2005. IEEE Computer Society.

[9] D. J. King and J. Launchbury. Lazy Depth-First Search and Linear Graph Algorithms in Haskell. In J. T. O. Donnell and K. Hammond, editors, *GLA*, pages 145–155, Ayr, Scotland, 93. Springer-Verlag.

[10] J.-Y. Le Boudec and M. Vojnovic. Perfect simulation and stationarity of a class of mobility models. In *IEEE INFOCOM*, Miami, FL, Mar. 2005.

[11] J. Leguay, T. Friedman, and V. Conan. Evaluating mobility pattern space routing for dtns. In *Proceedingss of IEEE INFOCOMM*, 2006.

[12] A. Lindgren, A. Doria, and O. Scheln. Probabilistic routing in intermittently connected networks. *SIGMOBILE Mob. Comput. Commun. Rev.*, 7(3):19–20, July 2003.

[13] S. Merugu, M. Ammar, and E. Zegura. Routing in space and time in networks with predictable mobility.

[14] C. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. In *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, pages 234–244, 1994.

[15] C. Perkins. Ad-hoc on-demand distance vector routing, 1997.

[16] T. Spyropoulos, K. Psounis, and C. S. Raghavendra. Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In *Proceeding of the ACM SIGCOMM workshop on Delay-tolerant networking*, pages 252–259, 2005.

[17] A. Vahdat and D. Becker. Epidemic routing for partially connected ad hoc networks. Technical Report CS-200006, Duke University, 2000.

[18] J. Yoon, M. Liu, and B. Noble. Random waypoint considered harmful. In *IEEE INFOCOM*, San Francisco, CA, Mar. 2003.

[19] W. Zhao, M. Ammar, and E. Zegura. A message ferrying approach for data delivery in sparse mobile ad hoc networks. In *Proc. 5th ACM Intl Symp on Mobile ad hoc networking and computing (MobiHoc '04)*, pages 187–198, New York, NY, USA, 2004.

[20] W. Zhao, Y. Chen, M. Ammar, M. D. Corner, B. N. Levine, and E. Zegura. Capacity Enhancement using Throwboxes in DTNs. In *Proc. IEEE Intl Conf on Mobile Ad hoc and Sensor Systems (MASS)*, pages 31–40, Oct 2006.