FansyRoute: Adaptive Fan-Out for Variably Intermittent Challenged Networks *

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ABSTRACT

We consider the problem of routing in a highly and variably intermittent wireless network to support delay-intolerant as well as delay tolerant applications. Specifically, the links in such a network are too volatile to maintain a consistent topology, rendering most MANET protocols ineffective. At the same time, store-and-forward (DTN) techniques are not an option due to the need for delay intolerance, and may be unnecessary due to the likely availability of contemporaneous, albeit rapidly changing, paths.

We present a novel routing mechanism called *FansyRoute*, aimed at this challenged region between MANETs and DTNs. FansyRoute adaptively adjusts the number of replications (fan-out) on a per-node basis, taking into account the level of intermittency along the path to the destination and a user-specified tradeoff between delivery expectation and the cost of replication. We study the performance of two FansyRoute schemes on a prime example of such variably intermittently connected networks, namely asynchronously duty-cycled sensor networks. Using ns-3, we compare FansyRoute to OLSR, AODV and Flooding. The results show that in an intermittent network, FansyRoute can deliver 50% more packets than the single path protocols, with less than 5% of the replication incurred by flooding. FansyRoute replicates *only* when needed and the replication is restricted to the challenged regions of the network.

Categories and Subject Descriptors

C.2.2 [**Network Protocols**]: Routing Protocols

General Terms

Algorithms

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Keywords

Routing, challenged networks, delay intolerant, adaptive, multipath, fan-out

1. INTRODUCTION

Routing mechanisms for multi-hop networks have evolved along two broad lines – for networks that largely remain connected while experiencing a moderate amount of link dynamics, and for challenged networks that largely remain disconnected with occasional links between nodes. The former *connected routing* class includes traditional routing protocols such as AODV [15] and OLSR [2], and the latter *opportunistic* or *disruption-tolerant (DTN)* class includes Epidemic and a variety of contact-prediction based store-and-forward mechanisms [4, 10]. Neglected, however, is the "twilight zone" of network connectivities in the middle for which link intermittency is high enough that connected routing is insufficient, and opportunistic routing is an overkill. Highly intermittent networks are challenged in the sense that connectivity can change faster than up-to-date topology information can be propagated, rendering *connected routing* protocols ineffective.

A prime example of such an variably intermittent network, and one that we use as our chief application for this paper, is a wireless sensor network with (asynchronous and variable) duty cycling of nodes to conserve power. Sensor nodes in such networks double as multi-hop relays and therefore we need a routing mechanism to convey sensed information. For sparse sensor networks with a low duty cycle, the probability of having an end-to-end path is prohibitively low. This not only results in inadequate delivery ratios when single-path traditional connected routing protocols and their variants are used, but also handicaps the dissemination of control information in such protocols (e.g. link state updates and route discovery messages), resulting in routing loops or failures. On the other hand when the sensor network is dense, or if the duty cycle is sufficiently high, connected routing may be sufficient and fixed-replication multi-path routing may be detrimentally wasteful of bandwidth. Other examples of variably intermittent networks include MANETs with highly mobile nodes, vehicular networks on a highway etc.

While multi-path routing [11, 12, 14] is an obvious approach, such intermittency could be highly variable across network regions, time and instantiations, and therefore such "one size fits all" multi-path routing schemes will just not suffice. Accordingly, a solution needs be *adaptive* to the level of disruption over time and across the network, and be able to support *delay bounded* routing.

There are a multitude of applications that require delay intolerant communication under the challenging conditions of variably intermittent networks. The quality of any interactive communication e.g. voice, video or telepresence can be made unbearable with the smallest of delays. For military networks, delays in battle awareness information can make the difference between mission success or failure and the unnecessary loss of life. Up-to-date traffic information in vehicular networks can shorten travel time and reduce the risks of vehicular accidents. Under these challenging conditions, delay intolerant communications may be necessary and is certainly possible.

In this paper, we present *FansyRoute* – a protocol with a "fan out" of paths that is adaptive to the level of connectivity present and/or desired by the user. When the network is well-connected with a low to moderate level of link dynamics, FansyRoute performs similar to a traditional connected routing protocol. With increasing link intermittency, FansyRoute increases packet replication commensurately till in the other extreme it resembles a "flooding" protocol. FansyRoute does not require link or contact prediction and seeks to provide the best possible delivery commensurate with the presented connectivity profile. FansyRoute, does not use "store and forward" techniques, and is not a "DTN protocol" in the sense that it cannot route over paths that are non-contemporaneous (e.g. a data mule). Consequently, FansyRoute is suitable for delay-intolerant applications as well as delay-tolerant ones. Certainly, store-and-forward capabilities can be used to extend FansyRoute to operate in the DTN realm, but we argue that delay-intolerant routing is more challenging in this "twilight zone" of connectivity.

FansyRoute operates on a generic metric called *average availability* which captures the expectation that a given link will be available when a packet needs to be sent over it, and is instantiated depending upon the application context. In a duty cycled sensor network, for instance, the average availability could be the probability that both nodes comprising a link are simultaneously "on". Unlike MANET routing protocols, FansyRoute does not attempt to construct graphs of the instantaneous connectivity of the network, nor does it rely on up-to-date topology information. Instead, average availability is measured over a longer timescale using an exponentially weighted moving average.

Previous work on routing in low duty-cycled networks have focused on scheduling the up-times of nodes [3, 6, 18, 7]. In [3], nodes perform topology discovery and redundant nodes are put to sleep. In [6], nodes do not require topology information, instead they monitor network capacity and activity to determine their own sleep schedule. The required coordination may become impractical and unnecessary as the number of flows increases. The use of multipath routing has been extensively explored, and these protocols can be can generally be classified as edge disjoint [19], node disjoint [9] or overlapping [8, 16]. Overlapping paths provide greater resilience to link failures [13] as the number of paths is not bounded by the minimum cut of the graph, and is the approach taken in this paper. Packets can be forwarded along one path at a time [8, 16] or multiple paths simultaneously [5, 11]. Adaptive redundancy has been considered in [1] in the context of backpressure routing in a mostly connected network.

We describe two adaptive fan-out variants of FansyRoute, called *Locally Constrained (FansyRoute LX)*, and *Globally Constrained (FansyRoute GX)*[1]. In the FansyRoute LX protocol, nodes make a completely local decision while FansyRoute GX factors in the existence of alternate paths. FansyRoute is not merely a multipath routing protocol, it is adaptive to *local* conditions of the network. Packets are replicated *only* where and when it is beneficial rather than using a fixed number of paths. Within the same network FansyRoute can detect challenged regions and fan-out, while using single path routing within the stable regions. The number of paths is not pre-fixed, but instead distributively determined by the current level of uncertainty at each node.

We study the performance of FansyRoute on a specific application, namely asynchronously and variably duty cycled wireless sensor networks. In other words, nodes are turned off and on independently and the duty cycle can be different for different nodes. In particular, we show that in an intermittent network, FansyRoute can deliver 50% more packets than single path protocols with less than 5% of the replications from flooding. Packets are sparingly replicated, and those few replications have a significant impact on performance. Relative to the baseline protocol, FansyRoute can be used to either increase the delivery ratio with approximately the same amount of energy consumption, or provide the same delivery ratio with reduced energy consumption

2. FANSYROUTE ALGORITHM

FansyRoute is designed to provide efficient, robust, delay-intolerant routing in highly and variably intermittent challenged networks. Robustness is achieved through the simultaneous use of multiple paths and efficiency is achieved by restricting packet replication to the challenged regions of the network. Unlike previous multipath protocols [8, 16, 5, 11] the number of paths is adaptively determined, at each node, based on the degree of intermittency in the network and is particular to the local conditions of the network. FansyRoute attempts to satisfy an application-specified delivery probability using minimal replication. In a stable network, with high connectivity, nodes will have stable paths (see Definition 1) and FansyRoute resembles single-path proactive routing protocols (e.g. OLSR). In a challenged environment, with highly volatile links (e.g. a sensor network with low duty cycle), FansyRoute can resemble flooding as there is no stable path. If the network is variably intermittent, the protocol will be combination of single and multipath routing, depending on the level of intermittentcy at each hop.

In this section, we describe two variants of FansyRoute: the LX and GX versions. In both cases, packets are routed on a hop-by-hop basis, and fan out *only* in the face of uncertainty. The two algorithms differ in the manner and degree to which they fan out. The approach to multipath routing taken in this paper is neither node disjoint [9, 12] nor link disjoint [19]. Nodes record the packet identifiers and duplicate packets are dropped silently. We reiterate that FansyRoute is targeted to accommodate delay intolerant routing (e.g. live audio or video), and if a node has no current path to the destination, the packets are dropped.

2.1 Estimating Intermittency

FansyRoute measures the intermittency of the network in order to determine when, where and to what degree to fan-out. We define the average availability of a link from A to

[1]Inspired by the way car trim levels are named. ☺

B, denoted $p(A \to B)$, to be the average up-time of B as *observed* by A using an exponentially weighted moving average (EWMA). Periodic hello messages are used as the basis for average availability measurements. Every time a node sends a hello message it updates the average availability of all other nodes. If A received a hello message from B within the last hello interval, A updates $p(A \to B)$, at time time t, according to Equation 1. Otherwise the average availability is updated according to Equation 2. Average availability can be asymmetric for a link.

$$p(A \to B)_t = \alpha + (1 - \alpha) \cdot p(A \to B)_{t-1} \qquad (1)$$

$$p(A \to B)_t = (1 - \alpha) \cdot p(A \to B)_{t-1} \qquad (2)$$

In simulation, we use a value of 0.1 for α, the EWMA coefficient. Intuitively, average availability translates into the conditional probability that A will be able to forward a packet through B, given that the packet arrives at A. By extension, we define the average availability of a path to be the product of the average availabilities of its constituent links. The average availability of a path corresponds to the probability of successfully delivering a packet along the path *without* store and forward techniques.

Unlike distance vector and link state protocols, FansyRoute does not attempt to determine the instantaneous connectivity of the network. On-demand distance vector protocols, such as AODV, take a snapshot of the network by flooding route request (RREQ) packets. In a highly intermittent challenged network, AODV will have to perform route discovery each time a path breaks. Link-state routing protocols, such as OLSR, propagate current link state information throughout the network. In OLSR, it becomes difficult for all nodes to maintain up-to-date routing tables, resulting in routing loops. Average availability, on the other hand, is an average over a longer timescale and does not change as rapidly as link state. In the underlying network, there is no guarantee that links in a path currently exist. We demonstrate that this approach yields better results in highly intermittent networks than using stale instantaneous connectivity information.

2.2 Signaling, State and Path computation

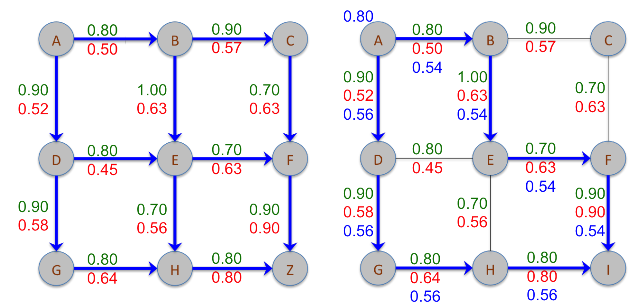
Nodes transmit hello messages with a period of one second and topology control (TC) messages with a period of five seconds. TC messages are similar to those of OLSR except nodes advertise average availability rather than link state.

We modify Dijkstra's shortest path algorithm to compute paths with maximum average availability. Each node uses this algorithm to compute a path through each of its neighbors to every other node in the network. Let $G = \{V, E\}$ be the network with vertices V and edges E. The weights of the edges in G corresponds to the average availability of that link in the network. When a node S is computing paths through a neighbor A, it removes all its other one-hop neighbors from consideration in the computation. It runs Dijkstra on the remaining nodes, except paths with higher average availability are favored instead of shortest distance.

Definition 1 : Stable Path
A path is considered *stable* if its average availability is greater than some probabilistic delivery threshold, λ. The value of λ should be application specific. Replication is not needed along stable paths.

Definition 2 : Successor Relationship
Suppose node B received a packet from node C for destination D. Node B can forward the packet to node A if and only if $p(A \to D) > p(C \to D)$ or ($p(A \to D) = p(C \to D)$ and $distance(AD) < distance(CD)$), where $distance(XY)$ is the number of hops between X and Y. In this case, we say A is a *successor* of B or that B is a *predecessor* of A.

The level of replication in FansyRoute can approach flooding in a highly intermittent network. However, *Definition 2* imposes a constraint on the average availability of successors. With the exception of the source node, all neighbors cannot be successors.



(a) FansyRoute LX (b) FansyRoute GX

Figure 1: FancyRoute GX incurs less replication than FancyRoute LX

2.3 FansyRoute LX

In FansyRoute LX nodes make local decisions based solely on the average availability of their best path to the destination. If the best path is stable, according to Definition 1, the packet is forwarded along that path. On the other hand, if there are no stable paths, packets are replicated and sent along the fewest paths such that the cumulative average availability at each node is greater than the delivery threshold (λ in Definition 1). If multiple replicas of a packet arrive at a single node only the first is forwarded, effectively reducing the number of paths (fan-in) within stable regions..

For example, consider Figure 1(a) where node A is the source of a packet to be delivered to node Z. Suppose the delivery threshold is $\lambda = 0.8$. Each link in Figure 1(a) is associated with two values. The first value, denoted in green font, is the average availability of the link in the direction shown. The average availability of the best path to Z starting with the link is shown in red (second value). Node A runs the modified Dijkstra's algorithm to determine the best path through each neighbor. Its best path is $ABEFZ$ with $p(ADGHG) = 0.52 < \lambda$, therefore node A must fan out (replicate) the packet. A has 2 possible successors, and uses both of them. Node B receives the packet from A and does not have a single path that satisfies the threshold. It replicates the packet and sends it to C and E. Node E may receive the packet from either B or D. E will forward the first packet and drop the second. Node E has three paths, but the best two will achieve a delivery probability, as $(1 - (1 - 0.63) \cdot (1 - 0.56)) = 0.84 > \lambda$. When node H or F receive the packet, they can satisfy the threshold with a single path and therefore do not fan-out. In this example, FansyRoute LX is equivalent to flooding the packet. Some nodes may be offline, but as long as one path is available the packet will arrive at the destination.

2.4 FansyRoute GX

FansyRoute GX improves on FansyRoute LX by considering upstream replication, and is therefore more efficient. Additional information is necessary and is conveyed by a dynamic delivery threshold, δ, carried in data packets and is updated by each node before forwarding the packet. Each node should use as few paths as possible to achieve the delivery threshold δ. At the source of the flow, $\delta = \lambda$, but each time a packet is fanned out, a new, lower value of δ is indicated so that the cumulative probability is at least λ.

An important observation is that fan-out is subject to diminishing marginal returns. As the delivery probability approaches 1, the incremental benefit of additional paths is smaller and after some number of replications, the benefit (increased probability of delivery) is not worth the overhead incurred. Figure 2, illustrates the decision process involved in packet forwarding in FansyRoute GX. Suppose a node, call it A, receives a packet for destination Z with constraint δ. Node A uses the modified Dijkstra's algorithm to calculate the best average availability through each neighbor. Node A then calculates the cumulative delivery probability through all successors, denoted τ, in Equation 3.

$$\tau = 1 - \prod_{x \in Successors} (1 - p(A \to x \to D)) \tag{3}$$

$$\Delta = \max(\delta_{in} - \tau, 0) \tag{4}$$

$$\delta = \frac{\delta - p(x \to D)}{1 - p(x \to D)} \tag{5}$$

Before forwarding a data packet, nodes calculate τ and Δ, according to Equation 3 and Equation 4 respectively. If $\tau \leq \delta_{in}$, the packets requires a greater delivery probably than the link allows and this extra probability, Δ is added. Packets will be forwarded along one or more paths, starting with the paths with the highest average availability to the lowest. Each packet will carry a new value of $\delta = \min(\delta, p(x \to D)) + \Delta$. After forwarding the packet, the value of δ is updated, according to Equation 5. Equation 5 is derived such that the cumulative delivery probability of all replications is at least that specified in the input packet.

For example, consider Figure 1(b), where A is sending packets to Z. Links are denoted with two or three values. The first value, in green, is the average availability of the link in the direction shown. The second value, in red, is the average availability of the best path through that link. And the third value, in blue, is the value of δ_{out} used in outgoing packets.

Assume we set $\lambda = 0.8$. Node A is the source of the packet and has a delivery constraint of $\lambda = 0.8$. The cumulative average availability through all paths is: $(1-(1-0.5)\cdot(1-0.52)) = 0.76$, which is less than $\delta = \lambda$. Both of node A's successors must be used with a value of $\Delta = 0.8 - 0.76 = 0.04$. A forwards the packet to B and specifies a threshold $\delta = p(B \to Z) + \Delta = 0.54$. Likewise, A forwards the packet to D and specifies $\delta = 0.56$. Node B can satisfy the threshold with a single path and replication is not needed. The value of δ is not changed at node B.

3. SIMULATION RESULTS

We compare FansyRoute to AODV, OLSR and flooding. AODV and OLSR are well known protocols and indicate the performance of single path routing in intermittently connected challenged networks. Flooding indicates the upper bound performance, in terms of delivery, of any multipath routing protocol, albeit at the cost of maximum replication. Since we target delay intolerant as well as delay tolerant application, we focus on comparisons with MANET rather than DTN protocols. We present results in a sensor network setting with 49 nodes and static placement. We vary the intermittency by adjusting the duty cycle, with a lower duty cycle creating a more challenged network. Each node randomly chooses an average duty cycle centered around some mean, m, such that $\max(m-0.20, 0) \leq p \leq \min(m+0.20, 1)$.

We monitor the fraction of *unique* packets that are successfully delivered to the destination and the total number of replicas created during each experiment. We expect to see a tradeoff between the number of replicas created and the number of unique packets successfully delivered to the destination. Table 1 presents a summary of the parameters used in the experiments.

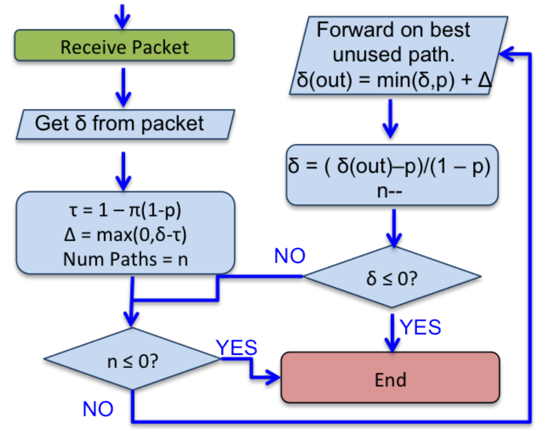


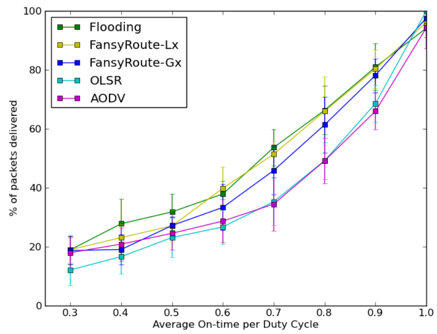
Figure 2: Flowchart for FansyRoute GX

Parameter	Value
Simulation time	150 s
Node Placement	Grid or Uniform
Mobility Model	Stationary
Physical layer	802.11
Antenna model	Omnidirectional
MAC Protocol	802.11 DCF
Data Source	constant bit rate (CBR)
Number of flows	15
Number of sinks	5
Packet rate	1 packets per second
Number of repetitions	10

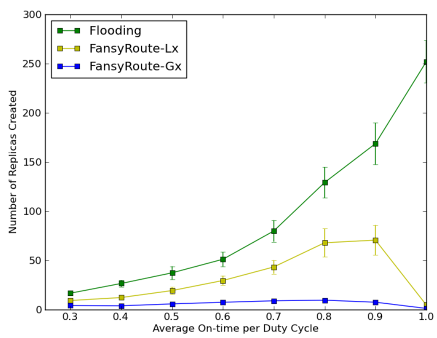
Table 1: Simulation Parameters

3.1 Random Node Placement

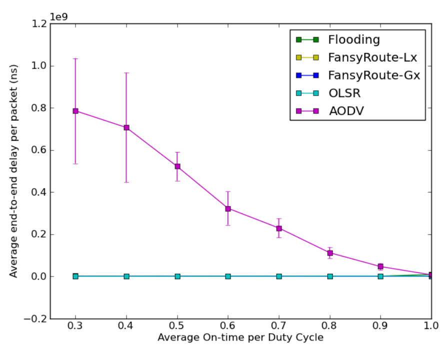
In this experiment 49 nodes are randomly distributed within a square area with side of 500 m with a radio range of 100 m. The other experimental parameters of Table 1. Fifteen nodes are randomly selected to be data sources and they randomly assigned to one of five data sinks. Each source node generates 1 packet per second, of size 1 KB. and transmits at a rate of 8000 bps for the duration of the experiment (120 s). We use a delivery threshold of $\lambda = 0.8$ i.e. the packet is not replicated if a node has a path of average availability of 0.8 or higher. The experiment was repeated 10 times using different random seeds and we present the mean values and a 95% confidence interval.



(a) Delivery



(b) Replication



(c) Delay

Figure 3: FansyRoute performs comparably to Flooding with less than half the replication in intermittent networks and no replications in connected networks.

In this setting, nodes have an average of 7 neighbors, allowing ample opportunities for multipath routing. The duty cycle of nodes is uniformly distributed around a specified mean and the results are shown in Figure 3. Based on the duty-cycle, the network can be roughly categorized as *connected* if the duty-cycle is greater than 90%, *disconnected* if the duty cycle is less than 50% and otherwise *intermittent*.

For the *disconnected* region, delay intolerant routing is near impossible over multiple hops. Store and forward techniques (e.g. epidemic, spray and wait, etc) are necessary and applications must tolerate delay. We focus our analysis on the *intermittent* region since this is the less studied "twilight zone" of network connectivity.

Without replication a single dropped packet results in failure. If average availability of the links is less than 1, there is some probability that the successor will be offline and the packet will be dropped. With FansyRoute however, the packet must be dropped along each path for delivery failure.

In terms of delivery, shown in Figure 3(a), we observe that the multipath protocols far outperform the single-path protocols. In fact, with an 80% duty cycle FansyRoute GX delivers almost 50% more packets than the single path routing protocols! As the number of replications increase, the probability of a packet arriving at the destination increases, thus flooding achieves the highest delivery rate.

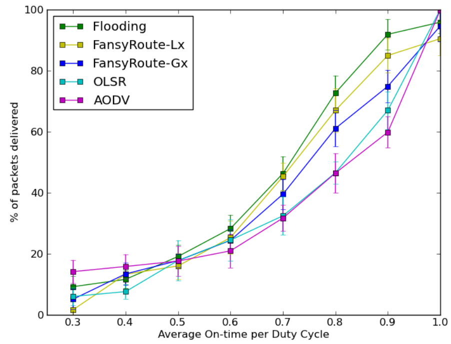
It is critical to note that this performance increase comes with a relatively small replication factor. From Figure 3(b) we see that, with an 80% duty cycle, FansyRoute GX incurs about 5% the number of replications as flooding and about 10% that of FansyRoute LX. As the network becomes more stable, FansyRoute replicates less and eventually does not replicate as it is adaptive to the current network conditions. In contrast, the number of replicas increases with flooding as there are more nodes participating in the flooding. FansyRoute GX replicates sparingly and the few replicas it does create are created only when necessary.

The rate at which route discovery must be performed in on-demand routing protocols (e.g. AODV) is related to the stability of the paths. Route discovery increases delay and overhead due to the search process. The lower the average on-time of nodes, the shorter the lifetime of paths. Proactive protocols, such as FansyRoute and OLSR, do not need to wait and packets experience an almost constant delay as shown in Figure 3(c). The overhead of the protocols is not shown, but in FansyRoute, the overhead is fixed and equal to that of OLSR.

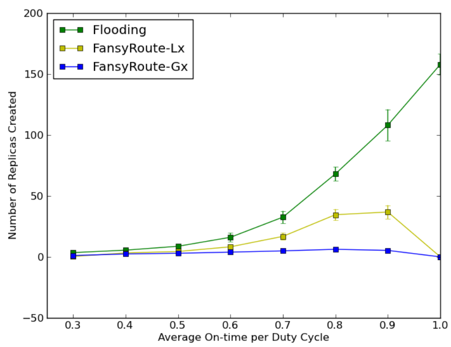
3.2 Routing in a grid

We consider routing performance in a 7x7 Manhattan grid, as a case of sparse connectivity. For a $n \cdot n$ grid, the average path length is $\frac{2}{3}n$ [17], which means packets will have to travel close to 4 hops on average to reach the destination. In our experiments, the average availability of links is determined by the period (T) and duty cycle (d) of links. Then the average lifetime of path is given by $d^{\frac{2n}{3}} \cdot T$. For example, the average lifetime of an end-to-end path in a 7x7 grid where nodes operate at an 80% duty cycle with a period of 9 seconds is: $0.8^{\frac{2}{3} \cdot n} \cdot 9 = 3.18$ seconds. The constant churn in paths constitutes a challenged network and traditional MANET routing protocols will perform poorly. On-demand routing protocol will have to perform route discovery every 3.18 seconds on average. Proactive routing protocols will make routing decisions based on stale information, resulting in transient routing loops.

The performance, as shown in Figure 4, is similar to that with random placement. However, nodes have fewer neighbors resulting in fewer total replications, as shown in Figure 4(b). Also, the difference in terms of packet delivery between FansyRoute and flooding is more pronounced in the grid (Figure 4(a)). Replication is restricted to *successors* in FansyRoute but is unrestricted in flooding. Therefore, packets can take more circuitous paths with flooding but ultimately arrive at the destination.



(a) Delivery



(b) Replication

Figure 4: FancyRoute GX incurs significantly less replication than FancyRoute LX while out performing the single path protocols

4. CONCLUSION

We have presented a new routing protocol, called FansyRoute, for variably intermittent challenged networks. FansyRoute is an adaptive routing protocol where the fan-out of packets at each node is commensurate with the perceived level of link disruption in the network – more the disruption, the more the replication. FansyRoute does not store packets, and hence provides tight delay bounds required by many applications. We have studied the performance of two variants of FansyRoute (locally constrained LX and globally constrained GX) in the context of duty cycled wireless sensor networks which typically presents a wide spectrum of connectivities. Using simulations, we have shown that FansyRoute can improve over a baseline routing protocol such as OLSR by up to 50% in intermittent networks.

In future work, FansyRoute can be modified and studied at either ends of the connectivity spectrum. Given store and forward capabilities, it can theoretically support *delay-bounded* routing with adaptive replication. Likewise, it would be interesting to investigate its performance in a mobile network rather than duty-cycled networks.

5. ACKNOWLEDGEMENTS

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