Building Mobile Networks Enhanced with Infrastructure

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ABSTRACT

Networks composed of only mobile nodes typically suffer from disruption and delay. The performance of these networks can be enhanced by adding infrastructure, such as base stations connected to the Internet, wireless meshes, and untethered relays. In this paper, we examine trade-offs associated with different infrastructures using an analytical and experimental framework. We model each of these infrastructures as a system of ordinary differential equations using simplified mobility models for general epidemic routing, and we use the model to evaluate performance and resource consumption. We show that the base station, mesh, and relay hybrid networks asymptotically have similar performance. For a practically sized network, the average packet delivery delay can be reduced by a factor of two with only seven times as many relays as base stations with similar resource overhead. Given the high cost of deploying base stations our results show that in many cases enhancing a mobile network with relays or mesh nodes is more cost-effective than wired base stations. We validate results from our model through experiments in a deployed 40-node mobile network under realistic bandwidth and placement constraints. Our deployment experiments confirm the results from the model and further show that physical placement of stationary nodes is the primary determinate of performance.

1. INTRODUCTION

Mobile networks incur higher delays and more frequent disconnections than tethered networks. The high delays severely limit the number of applications supported by a mobile network. With shorter packet delivery delays, a wider range of applications can be supported: environmental monitoring can tolerate weeks or months of delay; software updates, days; media and news content, hours of delay; email, hours of delay; instant messaging, minutes; and VOIP, tens of milliseconds. Accordingly, reducing packet delay is a fundamental problem in mobile networking, and for applications that incur delays from acontemporaneous routes, it is a critical problem. Such disruption-tolerant networks (DTNs) have been proposed for interplanetary [4], underwater [10], vehicular, person-to-person [14], and wildlife monitoring [19] scenarios.

The introduction of infrastructure to mobile networks in the form of stationary resources can considerably reduce delays, under the assumption that the additional costs of such infrastructure are manageable. For example, installing wired *base stations* connected to the Internet can lower delays [11]; however, base stations require power and wired network connections, both of which impose significant costs—these costs can be as high as US$50,000 per square mile [20]. An alternative is to deploy a wireless *mesh network* [3] from short-range, high-bandwidth technologies, like WiFi, or from long-range, low-bitrate radios, like those in the 900MHz band. This saves the cost of installing wired (typically fiber) network connectivity at each drop, but it requires a minimum density to maintain a connected topology. Lastly, and perhaps most inexpensively, one can place *relays* in the network that require no connections to electrical infrastructure or to the Internet and can be placed anywhere in the network [2, 16]; such relays can only route information between mobile nodes in a disruption-tolerant fashion [17].

In light of these cost and performance tradeoffs, in this paper we examine the following question. *What is the relative performance enhancement of each of these three types of infrastructure given that each has a different cost?* To answer this question, we develop an analytical model and present results from a set of field experiments that compare the benefits of each kind of hybrid mobile network. We use simple, ordinary differential equation (ODE) models that demonstrate the benefits of hybrid mobile networks. In the analysis, we present asymptotic, closed-form expressions for the expected delay and resource consumption for simple epidemic routing. To examine these tradeoffs in a real setting we have performed experiments for the three types of infrastructure in the context of a vehicular, mobile networking testbed. While the analytical results describe many of the fundamental trade-offs in the system, they cannot fully explore the interaction of placement constraints, real-world propagation, and dynamic routing protocols. On the other hand, while the deployment demonstrates many of these practical issues, the results depend heavily on the particular system, underlying technology, and mobility patterns. By melding analysis and deployment, we strive to provide a best-of-both-worlds approach to this problem.

Our analytical and experimental analyses present the following results.

- In our analytical results, we show that for substantial delivery delay improvement in hybrid base station and hybrid relay networks, the number of stationary nodes must grow super-linearly in the number of mobile nodes. We prove that the bounds on bandwidth and energy requirements for the nodes in all hybrid mobile networks are similar.

- In a real mobile network, we show that for simple epidemic routing in networks with 20 mobile nodes, the average delay can be reduced by a factor of two using only 5–7 times as many relays as base stations. While a larger number of relays are needed, the ease and cost of deployment make relays a better choice in many circumstances.

- From the experiments in a deployed mobile network, we identify scenarios where a mesh or relay hybrid network is a better choice over a base station network. We also show differences and similarities between results obtained from the model and data gathered from a real testbed.

Our study can be used as the basis of a cost-benefit analysis in deploying a mobile network or augmenting an under-provisioned one. We don't make any exact claims on the costs of deployment, as each of the three cases — base stations, meshes, and relays — translate into different physical implementations in various scenarios. For example, underwater networks can use wireless buoys as relays in the network [27], while other underwater networks may use fully interconnected mesh networks [18]. In a vehicular network, one may use relays [2] or wireless base stations [5]. In this paper, we define the baseline as a network of mobile, wireless peers that lack added infrastructure, and our goal is to augment the network.

2. NETWORK MODEL

We begin with a network consisting exclusively of mobile nodes. As in a DTN [17], nodes transmit replicas of a packet to passing mobile nodes, which move and transmit replicas to more nodes, and eventually a copy of the packet is delivered to its destination. There are at least three options for enhancing such a mobile network through additional infrastructure, as illustrated in Figure 1. Wireless base stations provide new opportunities to propagate packets, typically via an in-network proxy with storage so that mobile nodes can pass packets without contemporaneous connections through the base stations. A wireless mesh works in the same way, but the wireless mesh nodes must be geographically placed such that a wireless backbone is connected. Lastly, disconnected store-and-forward relays route packets to any passing mobile node without connection to a mesh or the Internet. With any of these methods, and sufficient resources, one can reduce the delay of the network to arbitrarily small amounts, bounded only by transmission delays.

Intuitively, one can support much lower delays with fewer base stations than mesh nodes or relays—the wired network effectively provides a wormhole across a geographic area. However, the key questions are *how many relays are needed to lower packet delivery delay to an acceptable level, and what are the relative costs of these options?* While base stations and meshes are necessarily more effective than relays, relays avoid the constraints of mesh wireless connectivity and the costs of base station wiring.

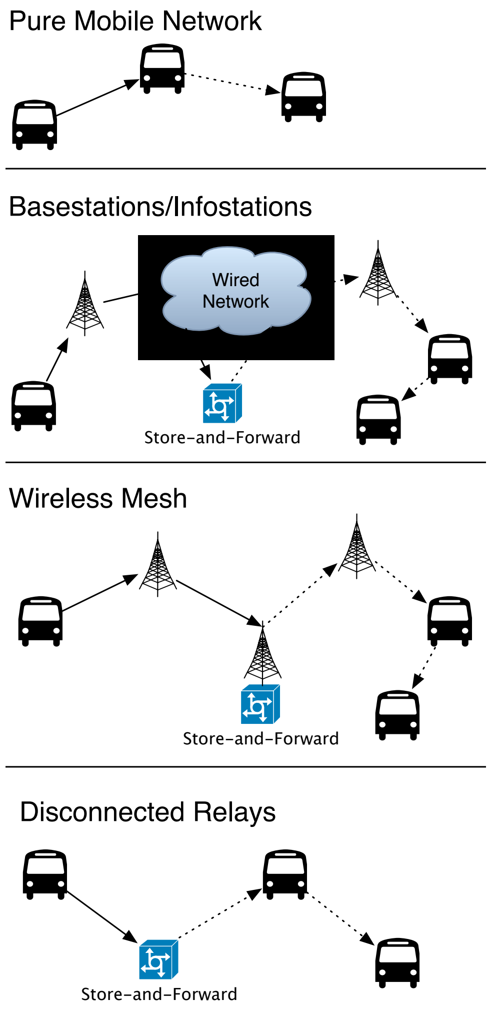

Figure 1: This figure shows three methods of augmenting a sparse mobile network with resources to reduce delay. In the first case, base stations communicate with mobile nodes storing packets on a node in the network for eventual delivery to another node. The second case, a wireless mesh, operates similarly to the base station, but the base stations must be physically proximate to transmit packets. In the third case, disconnected relays store packets, for delivery to other relays or mobile nodes, propagating information towards the final destination.

We analyze the relative benefit of adding varying numbers of base stations, mesh nodes, and relays using three methods:

- numerical solutions based on ordinary differential equations (ODE), using methods from viral worm propagation [29];
- asymptotic expressions for packet delivery delay and resource consumption derived from the ODEs;
- and a physical deployment of base stations, meshes, and relays in a network of vehicular nodes.

Through trace-driven simulations presented in Section 6, we show where there is agreement and discrepancy between a deployment and the analytical results. Here we present the framework for our analytical results.

2.1 Model and Network Parameters

We model a mobile network as $N + 1$ mobile nodes and M stationary nodes. The stationary nodes are placed uniformly at random in an area A. It is important to note that there are no constraints on the placement of the stationary nodes, even though significant and varying restrictions on placement apply in practice. For instance, base stations must be placed where there is a wired network connection. Mesh nodes need fewer wired connections but must be placed proximate to one another, and typically they must be within line-of-sight of one another. Relays can be placed fairly liberally; however, placement is still restricted. For example, in a vehicular network the best placement may be the middle of the road. This is a limitation of the model, as meshes and base stations are identical, except that the model incorporates delays in the mesh network— the delay in the base station backbone is considered negligible. We explore these real-world placement issues in our deployment evaluation (Section 6).

Mobile nodes move around within area A. We assume that the pairwise meeting times *between mobile nodes* are represented by exponentially distributed random variables with mean inter-meeting time $1/\beta_1$, and the pairwise meeting time *between mobile nodes and stationary nodes* are represented by exponentially distributed random variables with mean inter-meeting time $1/\beta_2$. The exponential assumption follows from a result by Goenevelt et al [12], which showed that pairwise inter-meeting times are nearly exponential if nodes move in A according to a common mobility models (such as random way point and random direction model) and if their transmission range d is small compared to A. The expression for the pairwise meeting rate was derived as $\beta_1 = \frac{2wdE[V]}{A}$, where w is a constant specific to the mobility model and $E[V]$ is the average relative speed among nodes. Moreover, analysis on real data has also shown that inter-meeting rate between mobile nodes can be closely approximated by an exponential distribution [7].

2.2 Routing Protocol and Traffic Model

We assume a very general traffic model: *(i)* traffic in the network is unicast between pairs of mobile nodes; *(ii)* traffic sources and destinations are uniformly random; and *(iii)* stationary nodes only route data and do not serve as sources or sinks. Below, we define cases where base stations and mesh access points, or one of the relays, is connected to the Internet, which can then act as a sink for data.

Our analytical model evaluates a general epidemic routing protocol where every node forwards packets to every other node it meets. Two nodes meet when they are within transmission range of each other. Every node has an infinite buffer and every transfer opportunity has infinite bandwidth, therefore, every packet can be considered independent of all other packets.

3. ANALYTICAL MODEL

We model the spread of a packet and its replicas as an *epidemic infection* among nodes in the network. When nodes meet one another they exchange packets, infecting one another with the packets they possess, until the packet infects the eventual destination. Similar models have been used in the analysis of worm propagation [29] purely mobile networks [28] and relay mobile networks [16].

This packet infection model is a system of non-linear differential equations with two variables, $x(t)$ and $y(t)$. The number of mobile nodes infected with a particular packet at time t is $x(t)$, and the number of infected stationary nodes at time t is $y(t)$. The network delivers a packet once the destination is infected with the packet, and our goal is to determine $P(t) = Pr[T < t]$, the probability that the time to deliver a packet is less than t. The expected delivery delay of a packet is given by $\int_0^\infty (1 - P(t))dt$.

One of our goals is to estimate the amount of resources used in the network, including bandwidth, storage, and transmission. All are strongly correlated with the number of copies the network generates by the time the packet is delivered. The number of copies of a packet is given by $\int_0^\infty (x(t) + y(t))dP(t)$. We assume in our analysis that all replicas of a packet are removed once the packet is delivered to its destination. In this section, we describe the set of differential equations and their approximate asymptotic solutions for each of three cases: relays, base stations, and meshes.

3.1 Mobile Network with Untethered Relays

The differential equations that govern the dynamics of a network of $N+1$ mobile nodes and M stationary untethered relays are:

$$\begin{aligned} x'(t) &= (\beta_1 x + \beta_2 y)(N - x), \\ y'(t) &= \beta_2 x(M - y), \\ x(0) &= 1, \; y(0) = 0. \end{aligned}$$

The change in $P(t)$ is given by the following differential equation:

$$\begin{aligned} P'(t) &= (1 - P)(\beta_1 x + \beta_2 y), \\ P(0) &= 0. \end{aligned}$$

Here $x'(t)$ is the rate at which mobile nodes in the network are infected by the packet. It is the sum of the rate of a mobile node's meeting other infected mobile nodes and the rate of mobile node's meeting infected stationary nodes. $y'(t)$ is the rate at which stationary nodes are infected in the network. This is the rate at which infected mobile nodes meet uninfected stationary nodes. $P'(t)$ is given as the product of the probability that the packet is not delivered at time less than t and the rate of the destination meeting an infected mobile node or an infected relay. The last set of equations describe the initial conditions for the system. Initially, only one mobile node and no stationary node is infected with the packet.

We first show that there exists an unique solution to the above set of differential equations, and then derive an approximate asymptotic closed-form expression for the expected delivery delay of a packet.

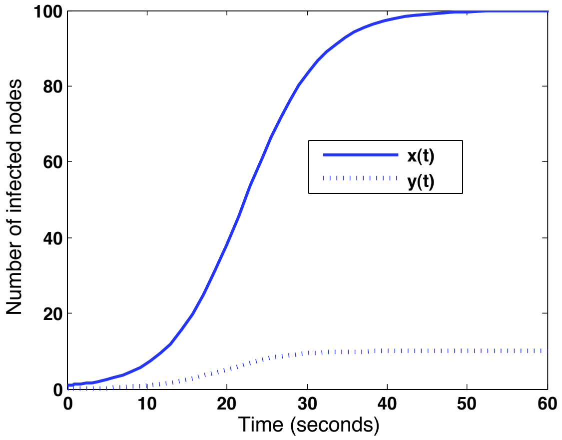

Figure 2: The infection of a packet in a hybrid mobile network with 10 relays and 100 mobile nodes.

LEMMA 1. *The above set of differential equations has a solution which is unique.*

PROOF. Writing the differential equations in matrix notation gives the following.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} f(x,y) \\ g(x,y) \end{pmatrix} = \begin{pmatrix} \beta_1 N x - \beta_1 x^2 + \beta_2 y N - \beta_2 y x \\ \beta_2 x M - \beta_2 x y \end{pmatrix}$$

Here $f(x,y)$ and $g(x,y)$ are continuous functions and are Libschitz continuous for x and y in the intervals $[1, N]$ and $[0, M]$, respectively. Therefore, by the Picard-Lindelöf theorem, the set of differential equations has a solution that is unique [13]. Unfortunately, deriving an exact closed-form analytical solution for the above set of differential equations is difficult.

The numerical solution for the number of relays and mobile nodes infected as a function of time for inter-meeting rates of $\beta_1 = (1/600)$ seconds and $\beta_2 = (1/300)$ seconds is shown in Figure 2. The total number of relays is fixed at 10 and the number of mobile nodes is fixed at 100. From the figure, it is clear that $x(t)$ and $y(t)$ exhibit three distinct regions of behavior: around the fixed points $\{0, 0\}$ and $\{M, N\}$ where derivatives are zero, as well as the region in between these fixed points. At the beginning only a few nodes are infected, therefore the infection rate is low. Similarly the infection rate is slow when the system reaches the point of diminishing returns around $\{M, N\}$. The dynamics of packet delivery is affected maximally by the behavior of x and y between $\{0, 1\}$ and $\{M, N\}$. Hence we derive an approximate closed form analytical solution for the above differential equations around $\{\frac{M}{2}, \frac{N}{2}\}$ and bound the approximation error. The solutions provide us with intuition of how the expected packet delivery delay varies with the number of relays and mobile nodes.

We linearize the derivatives for x and y by evaluating the Jacobian for the matrix in Lemma 1. We then solve for the set of linear differential equations to derive approximate solutions for the original equations around $\{\frac{M}{2}, \frac{N}{2}\}$.

$$A(x,y) = \begin{pmatrix} f_x & f_y \\ g_x & g_y \end{pmatrix} = \begin{pmatrix} \beta_1 N - \beta_2 y - 2\beta_1 x & \beta_2 N - \beta_2 x \\ \beta_2 M - \beta_2 y & -\beta_2 x \end{pmatrix}$$

The above linear set of differential equations can be solved around $\{\frac{M}{2}, \frac{N}{2}\}$ using the principle of eigenvalues.

$$A\left(\frac{M}{2}, \frac{N}{2}\right) = \frac{1}{2} \begin{pmatrix} -\beta_2 M & \beta_2 N \\ \beta_2 M & -\beta_2 N \end{pmatrix}$$

The eigenvalues for the above matrix can be obtained from $|A - \lambda I| = 0$. They are derived as:

$$\lambda = 0, \quad \lambda = -\frac{\beta_2(M+N)}{2}.$$

The eigenvectors are given by:

$$\begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = \begin{pmatrix} N \\ M \end{pmatrix}$$

$$\begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}.$$

Using the initial and final conditions for x and y, $x(0) = 1$ and $y(0) = 0$, and the conditions at the stable points $x(\infty) = N$ and $y(\infty) = M$, we obtain the following solutions for $x(t)$ and $y(t)$.

$$\begin{aligned} x(t) &= (1 - N) \cdot e^{-\frac{\beta_2(M+N)t}{2}} + N + O(d_1^2) \\ y(t) &= -Me^{-\frac{\beta_2(M+N)t}{2}} + M + O(d_2^2) \end{aligned}$$

The error terms $O(d_1^2)$ and $O(d^2)$ are outcomes of linearizing the differential equations around $\{\frac{M}{2}, \frac{N}{2}\}$. The error d_1 is determined by the distance of x from $\frac{N}{2}$ and d_2 is determined by the distance of y from $\frac{M}{2}$. Quite simply, the approximation ignores the initial, exponential, spread of the packet, and the region of diminishing returns as the delay is largely determined by the more linear spread of the packet.

THEOREM 1. *The expected delivery delay of a packet in a hybrid mobile network with relays is approximately* $\sqrt{\frac{4\pi}{(\beta_1 N + \beta_2 M - \beta_1) \cdot (\beta_2 \cdot (M+N))}}$.

PROOF. Given this model of infection, we can calculate the packet delay. Recall that the probability that a packet is delivered at time t is the product of the packet not being delivered before time t and the rate of the destination coming in contact with an infected mobile node or relay. The probability of packet delivery at time t is given by the following.

$$\frac{dP}{dt} = (1 - P)(\beta_1 x(t) + \beta_2 y(t))$$

We then substitute the value of x and y into the above equation and solve for the differential equations. Applying the initial condition to $P(0)$ yields the following expression for $(1 - P)$:

$$\begin{aligned} \ln(1 - P) = -(\beta_1 N + \beta_2 M - \beta_1)/(\beta_2(M + N)) \cdot \\ (e^{\beta_2(M+N)t/2} - 1) + (M\beta_2 + N\beta_1)t. \end{aligned}$$

The expected delay for delivery of a packet is given by $\int_0^\infty (1 - P(t))dt$. Application of the Saddle point approximation [8] yields

$$\sqrt{\frac{4\pi}{(\beta_1 N + \beta_2 M - \beta_1) \cdot (\beta_2 \cdot (M+N))}}$$

It follows from the above theorem that if the number of relays added to the network grows less than linearly in the number of mobile nodes ($M = o(N)$), then the expected delay of delivery of a packet is given by $(1/N) \cdot (\sqrt{(4\pi)/(\beta_1 \cdot \beta_2)})$. If $M = \omega(N)$, the expected delay of delivery of a packet is given by $\sqrt{(4\pi)/(M \cdot (\beta_2 M - \beta_1) \cdot \beta_2)}$.

The expected packet delivery delay is proportional to the number of relays alone if the number of relays grows super-linearly in the number of mobile nodes. The above result also shows that asymptotically (as N tends to be very large) the relay nodes do not affect the delivery delay of packets if they grows less than linear in the number of mobile nodes. The result seems to contradict previous observations where a small number of relays provided a substantial decrease in packet delivery delay [2]. However, in the analysis, we assume that relays are placed uniformly at random in the network. The performance of the network could be substantially better if the relays are placed intelligently in the network — a hypothesis we test in our evaluation in Section 6.

The overall performance and utility of a mobile network is also determined by the resources consumed by nodes in delivering packets. Various resources that can become bottlenecks are bandwidth, storage, and energy. From the perspective of packet delivery, these metrics are proportional to the number of copies of a packet in the network.

THEOREM 2. *The expected number of copies per packet in the network is given by* $E[c] \leq \frac{N-1}{2} + \frac{\beta_2(M)}{\beta_2+\beta_1}$.

PROOF. The detailed proof of the above theorem is given in the Appendix. □

The number of copies of a packet in the relay mobile network is proportional to the number of relays and mobile nodes. The expected delay of delivered packets is also proportional to the number of relays. Therefore, with an increase in the number of relay nodes, the performance as well as resource consumption of the network increases. Hence, if a network designer desires low packet delivery delay the number of relays in the network has to be large and if he desires low resource overhead (e.g., energy consumption), the number of relays to be placed in the networks needs to be small.

3.2 Mobile Networks with Base Stations

The key advantage of relays is that mobile nodes do not need to be in the same place at the same time to exchange packets, they only have to meet the same relay at different times. However, relays still depend on mobility to deliver packets. If the network is augmented with wired base stations, packets can be propagated over large geographical distances with minimal latency. In terms of the infection model, this means that once a single base station is infected by a packet, all other base stations can be considered infected by the packet. Packets may reach their destinations through any combination of mobile nodes and base stations.

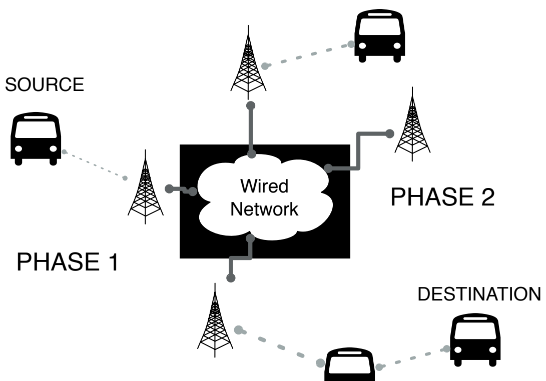

Figure 3: The figure depicts the two phases in the analysis of the base station network.

Intuitively, we can draw two conclusions. First, in a sufficiently large mobile network with enough base stations, the shortest path to the destination likely involves the wired base station network. Second, this path consists of two segments: the path from the mobile node to *any* base station, and the path from any base station to the destination mobile node, as illustrated in Figure 3. Next, we establish these conclusions more rigorously.

We model the spread of a packet in a hybrid mobile network for epidemic routing using the following heuristic. Let $t = T$ be the time at which the first base station is infected by a packet. Since no base station is infected before time T the differential equations governing the spread of packet at $t < T$ is given by:

$$\begin{aligned} x'(t) &= (\beta_1 x) \cdot (N - x), \\ P'(t) &= (1 - P) \cdot (\beta_2 x(M)). \end{aligned}$$

We solve for $P(t)$ using the system of ODEs above. We show that the expected delay of infecting the first base station, given by $\int_0^\infty (1-P(t))dt)$, lies in the interval $[\frac{\ln N}{\beta_1(N-1)}, \frac{\ln N}{\beta_2 M(N-1)}]$

The differential equations governing the dynamics of the network after time $t = T$ are given below.

$$\begin{aligned} x'(t) &= (\beta_1 x + \beta_2 M) \cdot (N - x) \\ P'(t) &= (1 - P) \cdot (\beta_1 x + \beta_2 M) \end{aligned}$$

Since every base station is considered infected at $t > T$, the rate of spread of packets among mobile nodes $x'(t)$ is proportional to the meeting rate of the non-infected mobile nodes with the infected mobile nodes and base stations. Similarly, the probability of packet delivery at time t is given by the product of the probability that a packet is not delivered by time t and the rate of an infected mobile or a stationary node meeting the destination.

THEOREM 3. *The expected delay for delivery of a packet in a hybrid network with base stations lies in the interval* $[\frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})(M\beta_2+N\beta_1)}{(\beta_2+\beta_1 N)\beta_1(N-1)} + \frac{\ln N}{\beta_1(N-1)}, \frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})}{\beta_1(N-1)} + \frac{\ln N}{\beta_2 M(N-1)}]$

PROOF. Solving the above differential equations yields

$$x(t) = \left[\frac{\frac{N}{N-1}(\beta_2 M + \beta_1) \cdot e^{t(\beta_1 N+\beta_2 M)}}{\beta_1 + \frac{\beta_2 M+\beta_1}{N-1} \cdot e^{t(\beta_1 N+\beta_2 M)}} \right].$$

$(1 - P(t))$ is the probability that a packet is delivered to the destination at time greater than t. The expression for $(1 - P(t))$ is given below.

$$(1-P(t)) = \left[\frac{N\beta_1 + M\beta_2}{(N-1)\beta_1 + (\beta_2 M + \beta_1)e^{t(\beta_1 N + \beta_2 M)}}\right]^{\frac{\beta_2+\beta_1 N}{\beta_1 N+\beta_2 M}}$$

The expression can be upper and lower bounded by the following inequality.

$$\begin{aligned}\frac{M\beta_2 + N\beta_1}{(N-1)\beta_1 + (\beta_2 M + \beta_1)\cdot e^{(\beta_2 M+\beta_1 N)t}} &\leq (1 - P(t)) \\ &\leq \frac{M\beta_2 + N\beta_1}{(N-1)\beta_1 + (\beta_2 M + \beta_1)\cdot e^{t(\beta_2+\beta_1 N)}}\end{aligned}$$

Integrating both sides of the inequality over the interval $[0, \infty]$ yields the following.

$$\begin{aligned}\frac{\ln(\frac{\beta_2 M+\beta_1 N}{\beta_1+\beta_2 M})(M\beta_2 + N\beta_1)}{(\beta_2 + \beta_1 N)\beta_1(N-1)} &\leq E[t_d] \\ &\leq \frac{\ln(\frac{\beta_2 M+\beta_1 M}{\beta_2 M+\beta_1})}{\beta_1(N-1)}\end{aligned}$$

Summing the above with the expected time to infect the first base station yields the bound in the theorem. □

Corollary 1. *If $M = o(N)$, then the expected delivery delay lies in the interval $[1/(\beta_1 \cdot (N), 1/(\beta_1 \cdot (N-1))]$. If $M = \omega(N)$, then the expected delivery delay of a packet lies in the interval $[0, \frac{1}{\beta_2} \ln \frac{M\beta_2+\beta_1}{M\beta_2}]$.*

Proof. We refer the reader to the Appendix. □

Therefore, asymptotically if the number of base stations grows less than linear in the number of mobile nodes, the expected packet delivery delay is not affected by the base stations. However, if the number of base stations grows super-linearly in the number of mobile nodes, the average packet delivery delay lies between zero and a value close to a constant. This result is similar to that obtained for untethered relays in the previous section.

Theorem 4. *The expected number copies of a packet stored in a base station mobile network is $\frac{N+M-1}{2}$.*

Proof. We refer the reader to the Appendix. □

The number of copies of a packet for the base station hybrid network is linear in the number of mobile and stationary nodes. This is also similar to the results obtained for untethered relays. Therefore, asymptotically (as the number of stationary and mobile nodes grow large) the performance enhancement and resource consumption of a base station hybrid network is similar to that of a relay hybrid network. Since laying down base stations is much more expensive than relays, it is often more cost-effective to build relay hybrid networks than base station networks.

3.3 Mobile Network with a Mesh

An alternative to building the network using wired base stations is to build a mesh network. A mesh network has the advantage that it does not require wired connectivity at every node, although it often requires line-of-sight links between the nodes and incurs higher delays. The mesh can be built over a high-bandwidth, short-range radio, such as 802.11 or CC2420 [23] or a long-range, low-bandwidth radio, such as XTend Maxstream [24]. A wireless mesh is a special case of a base station network. The difference between a base station network and a mesh network is that once a mesh node is infected by the packet, it takes some time before all nodes in a mesh become infected by a packet due to processing delays, wireless packet loss and interference, and power management at the nodes. This rate of infection, denoted by β_3, also depends on the bit rate of the mesh radio and the number of packets transfered simultaneously transmitted over the mesh. We model the spread of a packet in the mesh as an infection process — similar to viral propagation in the Internet [29].

The dynamics of the network is determined by two phases. The first phase continues till time T when all of the mesh nodes are infected with the packet either by a mobile node or by another mesh node. In the second phase, the network behaves like a base station hybrid network where all the stationary nodes have already been infected with the packet. The system of non-linear differential equations governing the infection spread in the network for the first phase is given below.

$$\begin{aligned} x'(t) &= (\beta_1 x + \beta_2 y)(N - x) \qquad (1) \\ y'(t) &= (\beta_2 x + \beta_3 y)(M - y) \\ x(0) &= 1 \\ y(0) &= 0 \end{aligned}$$

The differential equations governing the dynamics of the network in the second phase are the same as for hybrid base station mobile networks, as stated above. The first phase above can be solved using the same scheme as the relay hybrid networks by calculating the eigenvalues of the Jacobian for the ODEs around $[0, 0]$. However, the eigenvalue expressions are solutions of quadratic equations in M and N. Although closed form asymptotic expressions for the average delay are difficult to calculate for the mesh hybrid network, we can reason about the asymptotic behavior of the network.

The first phase of the network behaves similar to the relay network and the second phase is same as the base station network, hence we conjecture that the mesh network would show asymptotic behavior in between a relay and base station network. How close this behavior is to either network depends on the infection rate among nodes in the mesh network (β_3). If β_3 is large (a high bandwidth radio like 802.11), the network behaves like a base station network, while a small β_3 (low bandwidth radio) yields behavior closer to the relay network.

3.4 Traffic Model

Our discussions above evaluate only uniform peer-to-peer traffic. However, in many cases, such as data gathering applications, a large fraction of the traffic is destined to a particular sink-node, such as a gateway to the Internet or an in-network storage server. In the case of base stations, we assume that all of the wired nodes are connected to a common network, and thus all of them can reach the sink. In the case of relays and meshes, we assume that exactly one of the nodes is either connected to the Internet or serves as the final data sink. To study a general traffic model, we designate a fraction f of the packets to be destined towards the sink and the remaining fraction is peer-to-peer traffic.

In the case of relays, we can make a straightforward modification to the differential equation governing $P(t) = Pr[T < t]$ to accommodate for traffic directed towards a sink. The differential equation governing $P(t)$ is given by $P'(t) = (1 - P)(\beta_2 x(t))$. This implies that a packet is considered delivered if an infected mobile node comes in contact with the stationary sink. Using the technique of Theorem 1, the expected delivery delay of a packet destined towards the sink is given by $\sqrt{\frac{4\pi}{2\beta_2(M+N)(N-1)}}$. Therefore, the expected delay of delivery of a packet (denoted by T) is given by

$$\begin{aligned} T &= f \cdot \sqrt{\frac{4\pi}{2\beta_2(M+N)(N-1)}} \\ &\quad + (1-f) \cdot \sqrt{\frac{4\pi}{(\beta_1 N + \beta_2 M - \beta_1)\cdot(\beta_2 \cdot (M+N))}}. \end{aligned}$$

For the base station case, the delay of delivery of a packet destined to the sink is determined by the time when the first base station is infected given by the interval $[\frac{\ln N}{\beta_1(N-1)}, \frac{\ln N}{\beta_2 M(N-1)}]$. Therefore, the expected delivery delay of packets is in the interval

$$\begin{aligned} &[(1-f)\cdot\frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})(M\beta_2+N\beta_1)}{(\beta_2+\beta_1 N)\beta_1(N-1)} + \frac{\ln N}{\beta_1(N-1)}, \\ &\qquad (1-f)\cdot\frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})}{\beta_1(N-1)} + \frac{\ln N}{\beta_2 M(N-1)}] \end{aligned}$$

4. NUMERICAL RESULTS

Thus far, we have used the infection model to compare the asymptotic behavior of untethered relays and base station networks for epidemic routing. However, we also want to examine the performance of the network for a finite number of stationary and mobile nodes. In particular, we focus on the following questions: *what kind, and how many resources should we add to the network in order to achieve a particular delay?* For instance, if we need to lower the delay by a certain factor, should we add relays or base stations, and how many? We want to know the resource overhead for each network in terms of the number of copies of a packet in the network. We are also interested in these trade-offs as different fractions of traffic is destined for sinks and peer-to-peer traffic.

4.1 Traffic Model

Using our ODE model, we can evaluate the packet delivery delay in a hybrid network under general epidemic routing. We have chosen a medium-sized mobile network of 20 nodes (the average number of buses running per day in our vehicular deployment) and vary the number of stationary nodes from 0 to 100. We set the *pairwise* inter-meeting times between mobile and stationary nodes to be 149 minutes and the *pairwise* mobile-mobile inter-meeting times to be 167 minutes. These parameters are taken from measurements of our test deployment, described in Section 5. In Figure 4, we vary the fraction of sink-bound traffic as $f = 0.5$. We have experimented with other values of f and found similar results. The packet size was fixed at 10KB. From our test deployment, we calculated the infection rate among mesh nodes (β_3) to be $1/80$. We also show the number of copies of a packet in the network in Figure 5 for $f = 0.5$.

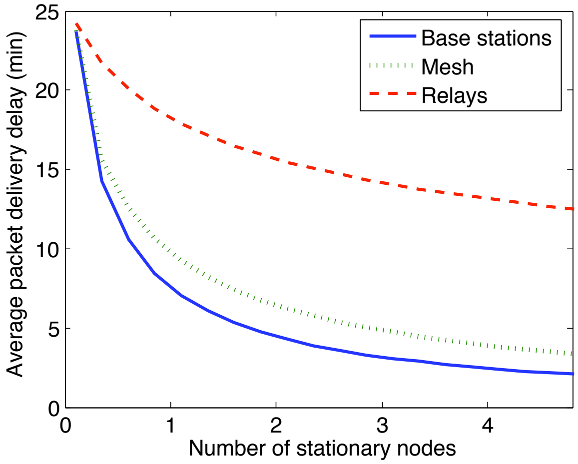

Figure 4: Average delivery delay for $\beta_1 = 1/167$ and $\beta_2 = 1/149$ for $N = 20$ and $f = 0.5$ for general epidemic routing.

From the results in those figures we make four observations. First, we can obtain very small average packet delivery delays by using a large number of base stations. However, there are values of average packet delivery delay that cannot be achieved except with an extremely large number number of untethered relays.

Second, if we want to reduce the delivery delay by 30% the network requires an average of 5-7 times the number of relays as base stations. For smaller delay reduction, this factor is less than 7. The ratio of relays to base stations is small because of the small mobile-mobile and mobile-stationary inter-meeting rates which masks the benefit of packet spread among base stations. The mesh behaves similar to a base station network since it incurs only the additional overhead of spreading the packet over the wireless link. Considering that the cost of deployment of base stations (includes power and wiring) is much more than seven times the cost of deploying relays, for a wide range of applications relays and meshes are a better choice than wired base stations.

Third, if the traffic is predominantly directed towards a sink—for example data gathering— it is better to use base stations.

Fourth, for the same number of stationary nodes (see Figure 5) the resources consumed by the relays and the mesh is less than the base stations. Moreover, for the same performance in terms of packet delivery delay, the relay and base station networks exhibit similar resource consumption and the mesh network has lower resource consumption. For

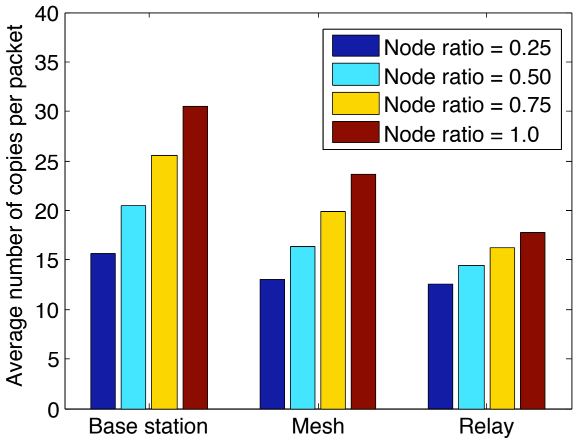

Figure 5: Average number of copies of a packet in the network for a relay, base station and mesh hybrid networks. We show the number of packet copies for different ratio of stationary to mobile nodes for $f = 0.5$.

example, to reduce the delivery delay by 25% (see Figure 4), the ratio of the number of base stations to mobile nodes is 0.25 while it is 1.0 for a relay network. However, for the two cases the number of copies of a packet is similar. Moreover, the mesh network exhibits similar performance with smaller resource consumption. This implies, that for a smaller cost, we can build a relay or mesh network which consumes similar resources (energy, storage) as a base station network and has similar performance.

4.2 Network Sparseness

Our mathematical model provides a general tool to answer questions about the performance of different types of hybrid mobile networks — for example, *how does a hybrid network perform when the inter-meeting rate between mobile nodes changes?* The inter-meeting rate between mobile nodes maps to the node density of the network; in a dense mobile network, such as a MANET, inter-meeting times between nodes are small, while in a sparse mobile network, such as a vehicular or mobile wildlife network, the inter-meeting times between nodes is large.

We use our model to evaluate the average packet delivery delay for two different inter-meeting rates: *(i)* once every 2.5 hours, representing our vehicular disruption tolerant network; *(ii)* once every 12 hours, representing a very sparse mobile network — for example buses running on reduced schedule or a wildlife tracking network [25, 19]. We assume that we have placed a sufficient number of stationary nodes such that the inter-meeting rates between mobile and stationary nodes remain unchanged.

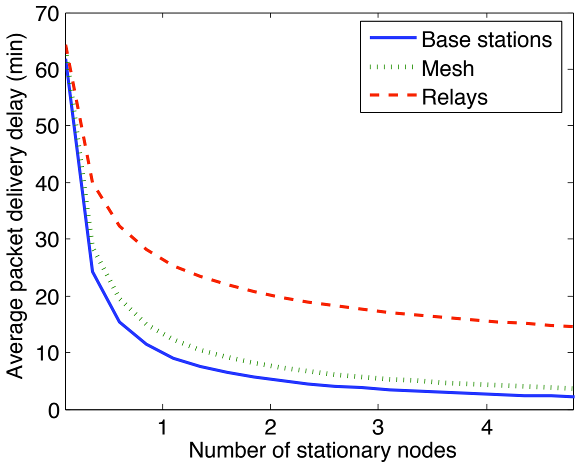

Figure 6: The figure shows the delay for a very sparse mobile network for which β_1 =1/1250 and β_2=1/149 minutes .

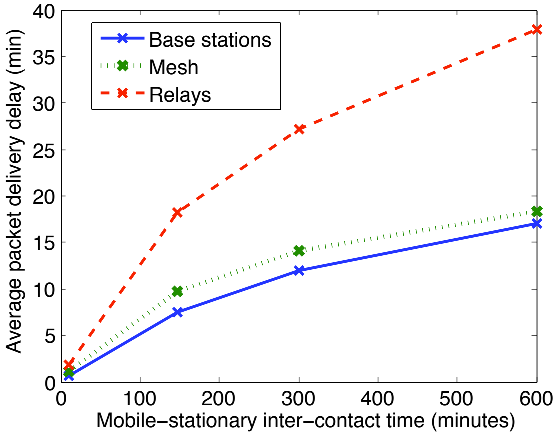

Figure 7: The figure shows the delay for a 20 node mobile network with 20 stationary nodes as β_2 is varied.

Figure 6 shows the packet delivery delay for a very sparse mobile network. We find, as we increase the network sparseness (compare with Figure 4) the difference between the three hybrid networks becomes smaller. Although a packet spreads quickly in the mesh and base station networks, there is a large constant added to the delivery delay due to scant meetings between mobile nodes that bridges the gap between the three networks. We performed another experiment in which we varied the rate at which stationary nodes meet with mobile nodes. Figure 7 shows the results for this experiment. When the inter-meeting rate is high all networks behave similarly. However, as the inter-meeting rate between stationary and mobile nodes grows, the difference between the three networks increases. Therefore, if we place the relays intelligently and consequently reduce the inter-meeting rate between mobile and stationary nodes, we can build relay networks whose performance is comparable to mesh or base station networks.

We validated the accuracy of the model described in Section 2 using simulations. We ran simulations where the average inter-meeting time of mobile nodes and stationary nodes was set to 4 hours, while the average inter-meeting time between mobile nodes is set to 4.7 hours, and packets were generated at a fixed rate. We ran the simulations until

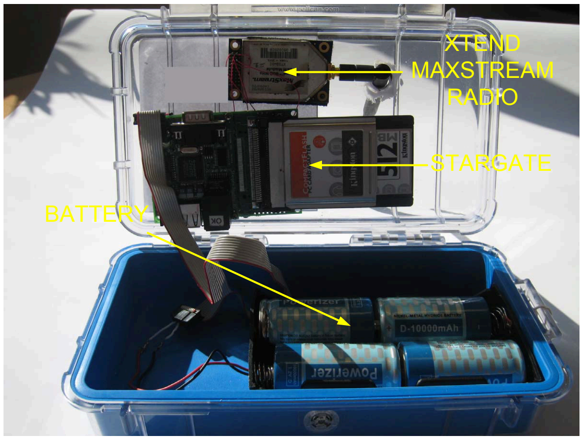

Figure 8: Prototype for the mesh node and untethered relay

a large number of packets were delivered to the destination. We fixed the number of mobile nodes in the simulations to be 20 while the number of stationary nodes was varied from $2-50$. We found that the difference in the average delay predicted by the model and simulation was less than 10%, quantitatively validating the model.

5. VEHICULAR NETWORK DEPLOYMENT

Our analytical framework relies on a number of simplifying assumptions. For example, the inter-meeting time between nodes is taken from an exponential distribution, and transfer opportunities have infinite bandwidth. Moreover, we ignore packet loss due to wireless interference issues, and consider infinite storage at mobile and stationary nodes. Although some of the assumptions like exponential inter-meeting rates may be realistic [7], other assumptions like ideal lossless wireless medium and infinite bandwidth for contact opportunities do not hold for sparse mobile networks. Hence, it is important to investigate the claims made in our analysis through a deployment study in a real mobile network.

Therefore, we study the performance of add-on stationary networks through a deployment of mesh nodes, relays, and base stations in a bus-based vehicular testbed. The mobile network consists of 40 buses moving in an area of about 140 square miles. The buses are equipped with an Linux box, a WiFi access point (AP), a USB WiFi dongle, a GPS unit and a long-range, low-bandwidth Maxstream XTend radio. We deployed six nodes at different places in the network to act as both untethered relays and as mesh nodes. The stationary nodes consist of PDA-class Stargate devices equipped with WiFi CF cards and long-range, low-bandwidth XTend radios (see Figure 8). The nodes are capable of forming a mesh over the XTend radio. Whenever, a node comes within WiFi range of a bus, it establishes a TCP connection with the AP on the bus. The node logs the amount of data transfered, the duration of the contact and the time of contact and later stores it in a central repository. The stationary nodes and the mobile nodes also communicate with each other using the low bandwidth radio. For base stations, we use the open access points around town. The buses associate with these APs and log the duration of time they were in contact with the AP. The buses transfer data over a TCP connection with a server running on the Internet. The buses encountered more than 600 APs. However, we selected six APs which have maximum number of contacts with the buses in order to compare with the six relay/mesh nodes placed in the network. The location of the mesh/relay nodes and access points can be seen from the anonymised map in Figure 9.

Figure 9: The map shows the location of the relay/mesh nodes and base stations. The colored spots represent the base stations and the white spots depict the relay/mesh nodes. For double blind reviewing, we removed the underlying map features.

To gain a better understanding of the mobility patterns of the nodes in our testbed we first look at the differences and similarities between the data collected in the deployment and the assumptions made in the model. Figure 10 shows the complementary cumulative distribution function of the *pairwise* inter-contact time between mobile-mobile and stationary-mobile contacts. Figure 11 shows the scatter plot and mean bandwidth for the mobile-mobile and mobile-stationary contact opportunities. From Figure 10 we observe that for more than 90% of the contacts, the inter-contact times follow an exponential distribution—parts of the curves for mobile-mobile and mobile-stationary contacts can be approximated by a straight line on a semi-log scale. However, each distribution exhibits a knee after which the decay is faster. Hence, our model based on exponential inter-meeting rate is not far from reality. However, the bandwidth for contacts is highly variable. Figure 11 shows that the bandwidth for connection events. The high variability in contact bandwidth could be due to variety of factors such as interference, multipath effects, TCP congestion control, DHCP, and variable association times [15]. Moreover, we observe that the bandwidth for mobile-stationary contacts

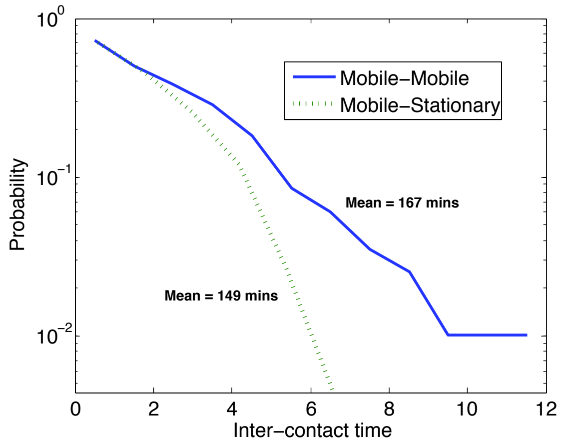

Figure 10: The figure shows the CCDF of the pairwise inter-contact times between mobile-mobile and mobile-stationary nodes.

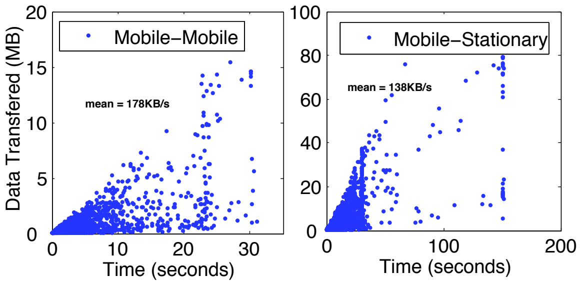

Figure 11: The figure shows the scatter plot and mean bandwidth for the mobile-mobile and mobile-stationary data transfer.

is larger than mobile-mobile contacts as the relative velocity of a mobile and stationary node is often smaller than two mobile nodes.

6. EVALUATION OF DEPLOYMENT

Our analysis in Section 4 shows a trade-off between relay, base station and mesh hybrid mobile networks. However, it is crucial to validate the results from the model under more realistic conditions using a large scale mobile testbed. For our experiments, we collected connectivity data for two weeks using our testbed.

First, we study the delivery delay performance when different fraction of traffic is destined to a sink. We use RAPID as our routing protocol, which has been shown to perform better than most contemporary routing schemes for mobile networks [1]. We fed the connectivity traces collected from our deployment into a trace-driven simulator and evaluate the performance of the routing algorithm for different hybrid networks. Packets in the trace-driven simulation are generated at a fixed rate of 5 per hour per node. The source and destination of peer-to-peer traffic is generated uniformly at random. We use a packet size of 10KB and a buffer of 4GB at each node. Figure 12 shows the performance for stationary networks when the amount of traffic destined towards a sink is 50%. We vary the number of stationary nodes from one to six. Comparing the results with those from the model (see Figure 4) we observe the following differences: (1) the absolute numbers for delivery delay are higher than those obtained from the model; (2) the performance of the mesh is close to the relays although in our model the mesh performs close to the base station network. However, the general trend of performance is similar. For example, to bring down the delay by 30% the number of relays required is five times the number of base stations and there are certain delays that cannot be achieved by relays — similar to the observation made in our model.

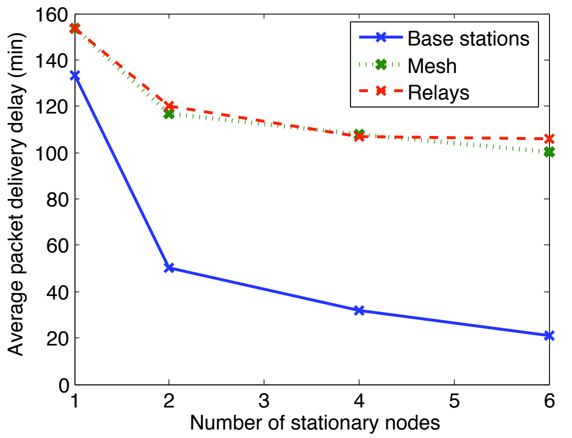

Figure 12: The figure shows the average packet delivery delay when 50% of the packet is destined for a particular sink.

We have considered a number of factors that may explain the absolute differences between the model and the deployment including dynamic routing protocols, network load, or node placement. To determine the most significant contributions we carried out experiments with different routing protocols, a varied range of network loads and different node placement.

First, we perform experiments with different network loads. We observe that if we increase the packet generation rate in the network by 600%, the change in delivery delay is less than 20% for all hybrid networks. Hence, network load is not the chief contributor to the difference between the model and the deployment. Moreover, different routing schemes show similar performance. We use three routing schemes — RAPID [1], Spray and Wait [26] and Epidemic routing. The results show that the relative performance of base stations, mesh and relays is largely independent of the routing scheme used. However, we observe that epidemic routing performs slightly better than Spray and Wait and RAPID for mesh and base stations. Note that Spray and Wait allows only a fixed number of packet copies, and the utility of a packet in RAPID goes down with the number of copies. Therefore, due to a large number of copies of a packet in the mobile network for base stations and meshes packet replication stops after a certain time leading to higher delays.

Next, we study the effect of physical node placement on

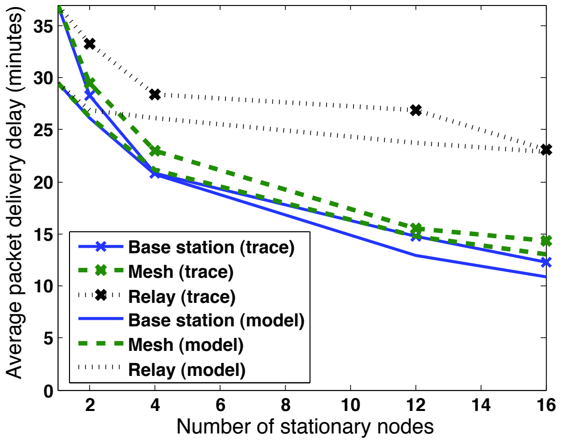

Figure 13: The figure shows the average packet delivery delay when the stationary nodes where uniformly placed in the network and 50% of the packets were destined towards a sink.

performance. Our hypothesis is that the difference between the deployment and the model is an artifact of the closely clustered placement of the mesh and relay nodes in the deployment. This brings out a constraint inherent to meshes that the model does not capture. Due to the limited range of radios, the nodes have to be placed in close proximity to each other — in many cases within line of sight of each other. Hence, the mesh does not spread packets across as wide a geographic area as a base station network. The base stations are not restricted in their placement — leading to better delay performance. However, this results in higher deployment costs.

To understand the effect of placement on performance, we carried out an experiment with 16 nodes uniformly placed throughout the vehicular network. Since, we did not physically deploy the nodes, the connection events for the stationary nodes with the mobile nodes were generated as follows. We used the GPS traces from the buses to figure out when and for how long a bus would be in WiFi range with the stationary nodes. The mobile-mobile connection events were taken from our collected traces. We carried out the same experiment as in Figure 12, and the results are shown in Figure 13. We plot the model results on the graph to show the differences between the deployment and the model.

We observe that the performance number are very close to those obtained from the model. The difference in delay between the model and the deployment is less than 10% in most cases. Moreover, we found that the number of copies per packet was also similar to those calculated from the model.

We conclude from this experiment that the most important factor that influences the performance of hybrid networks is the physical placement of the stationary nodes. The nodes should not only cover a large geographic area but should be placed where there is minimal interference from other sources. Given such a placement, network performance could be substantially improved, showing good confirmation with a simple idealized ODE model.

7. RELATED WORK

There is a large body of research on analyzing hybrid networks. These include studies on the effect of placing a sparse set of well connected base stations in an ad hoc wireless network [22], improving performance of sparse mobile networks using autonomous agents [9], and adding relays in a purely mobile network [2]. Measurement studies on throughput capacity of vehicular networks show the feasibility of Internet-based applications from mobile nodes [5]. Similarly, a system of base stations, called Infostations have been designed to provide intermittent coverage and connectivity in mobile networks [6]. Although, augmenting a mobile network with stationary nodes is a well studied area, there is little or no work that analyzes different hybrid network configurations under one unified framework. Our study offers a general analytical model and a more constrained real-world deployment study comparing the performance of different hybrid networks.

The analytical model in the paper derives from a large body of work on using Markov chains to model mobile networks. The ODE model as a fluid limit of Markov chains was first introduced to study epidemic routing in sparse mobile networks [28]. Markovian models have been used to study various routing protocols—epidemic routing, 2-hop routing [12], and Spray and Wait [26]. More fundamental work on modeling inter-meeting time between nodes following common mobility models was performed by Kurtz [21].

A more recent work by Ibrahim et al. [16] uses the Markov model to analyze hybrid mobile networks consisting of untethered relays and relays connected through a wired infrastructure. The paper derives asymptotic expressions using the fluid limit of Markov chains for a simple MTR routing protocol. Though the paper presents the differential equations for epidemic routing, it does not derive asymptotic expressions for delay and resource consumption. Our work builds on that analysis for epidemic routing. We argue that asymptotic expressions for epidemic routing are more general since most routing protocols for sparse mobile networks are variants of epidemic routing. While Ibrahim et al. concentrate on using the Markov model, our paper uses a simpler yet accurate infection model for the analysis of different hybrid mobile networks. Further, we have found that it is crucial to examine differences between the model and a real deployment for practical applicability of the model. Hence, our paper further studies the effect of several practical issues like dynamic routing protocols, node placement and network load through a deployment in a mobile testbed.

8. CONCLUSION

We have performed an experimental and analytical study of mobile network enhanced with relays, meshes and wired base stations. We used an ODE model to understand the behavior of hybrid mobile networks for simple mobility models. We further carried out a deployment study of stationary nodes in a small, bus-based mobile network.

Our study draws three main conclusions. (1) Asymptotically, base station, relay, and mesh hybrid mobile networks are similar in average packet delivery delay and resource consumption in terms of storage, energy, and bandwidth. (2) For epidemic routing protocols and uniformly random deployment, the ratio of the number of relays to base stations or to mesh nodes that bring down the delivery delay by a given factor is small — usually of the order of 5–7. Considering the high cost of deploying base stations, it is often a better choice to deploy untethered relays over base stations or mesh nodes. However, when extremely small delays are sought, such as required for a VoIP application, base stations are required. (3) Our deployment experiments in a real mobile network show that placement of stationary nodes has the largest impact on the performance of hybrid mobile networks—stationary nodes should be intelligently placed across the network for maximal performance.

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Appendix

Proof of Theorem 2

The expected number of copies of a packet in the network is given by the following

$$C_d = \int_0^\infty (x(t) + y(t))P'(t)dt - 1$$

We can write the above integral as $\int_0^\infty (x(t)+y(t))d(P(t)) - 1$. We evaluate the integral by parts and apply the initial and final conditions on $x(t), y(t)$, and $P(t)$ (i.e., $x(0) = 1, y(0) = 0, y(\infty) = M, x(\infty) = N, P(0) = 0, P(1) = 1$). Now, $C_d = \int_0^\infty (x'(t)+y'(t))Q(t)dt$ where $Q(t) = (1-P(t))$. The above integral can be broken down into two integrals, $C_d^N = \int_0^\infty x'(t)Q(t)dt$ and $C_d^M = \int_0^\infty y'(t)Q(t)dt$. We evaluate both integral separately. C_d^N is shown to be equal to $\frac{N-1}{2}$ and C_d^M is upper bounded by $\frac{\beta_2 M}{\beta_1+\beta_2}$. Combining the expressions for C_d^M and C_d^N yields the inequality in the theorem. □

Proof of Corollary 1

The expected delay of delivery of a packet lies in the interval $[\frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})(M\beta_2+N\beta_1)}{(\beta_2+\beta_1 N)\beta_1(N-1)} + \frac{\ln N}{\beta_1(N-1)}, \frac{\ln(\frac{M\beta_2+N\beta_1}{\beta_2 M+\beta_1})}{\beta_1(N-1)} + \frac{\ln N}{\beta_2 M(N-1)}]$. The first phase tends to 0 as $N \to \infty$. The bounds on the second phase can be written as

$$[\frac{\ln(\frac{M\beta_2+N\beta_1}{M\beta_2+\beta_1})}{(N-1)\beta_1}, \frac{\ln(\frac{M\beta_2+N\beta_1}{M\beta_2+\beta_1})}{\frac{(\beta_1 N+\beta_2)(N-1)\beta_1}{M\beta_2+N\beta_1}}]$$

Both functions are of the form $\frac{f(N)}{g(N)}$, where $\lim_{N\to\infty} f(N)$ tends to ∞ and $\lim_{N\to\infty} g(N)$ tends to ∞. Therefore, applying L'Hospital's rule we get the bound in the corollary.

When $M = \omega(N)$, we apply $\lim_{N\to\infty} \frac{N}{M} = 0$, and evaluate the following limit $\frac{\ln \lim_{N\to\infty}(\frac{M\beta_2+N\beta_1}{\beta_2+\beta_1 N})}{\lim_{N\to\infty} \frac{(\beta_2+\beta_1 N)(\beta_1)(N-1)}{M\beta_2+N\beta_1}}$. Applying the limit, yields the bounds in the corollary. □

Proof of Theorem 4

The number of packets in the network is given by $C_d = \int_0^\infty (\beta_1 x(t) + \beta_2 M)(N - x(t))Q(t)dt$. The integral can be shown to be equal to $N + M - (C_d + 1)$. Therefore, $C_d = \frac{N+M-1}{2}$. □