# Mélange: Supporting Heterogeneous QoS Requirements in Delay Tolerant Sensor Networks

Hengchang Liu, Aravind Srinivasan, Kamin Whitehouse, and John A. Stankovic
Department of Computer Science
University of Virginia
Charlottesville, Virginia 22904
Email:$\{hl4d|av3b|whitehouse|stankovic\}$@cs.virginia.edu

***Abstract*—In sparse mobile sensor networks, nodes have a small number of neighbors with intermittent connectivity. This paper presents a new networking protocol for this type of network, aimed at maximizing system performance in terms of both delay and reliability. The system is motivated by the observation that many applications on this type of network have two kinds of co-existing data packets: those with real-time constraints and those with reliability constraints. By treating these packets differently, we are able to better meet the needs of both. We show that our approach outperforms ordinary epidemic routing when packets with different types of QoS requirements exist in the network.**

***Index Terms*—Delay Tolerant Sensor Networks, QoS Heterogeneity, Optimization.**

## I. Introduction

Delay Tolerant Networking (DTN) [2] facilitates communication across unreliable, high-latency, and failure-prone networks. DTNs are particularly useful in mobile networks such as vehicular networks [5], indoor firefighter networks [4], and wildlife tracking networks [6]. *Epidemic protocols* have recently been proposed for routing information through a DTN to a base station [9]. In these protocols, mobile nodes transmit data packets with some probability $p$ to every other node that they encounter, similar to the way that humans infect each other with a virus. As nodes move around they randomly encounter and infect each other, creating an *epidemic* that eventually reaches the base station. Thus, this approach can transmit data through a network of mobile nodes, even when prior information about the velocity and direction of the nodes is not available. The value $p$ that is used affects both the speed and reliability with which each packet is delivered. A high value of $p$ causes the packet to be transmit frequently, increasing speed of delivery but also causing each node's packet buffer to fill more quickly, possibly leading to packet loss. A low value of $p$ causes the packet to be transmit infrequently, decreasing speed of delivery but also increasing reliability by decreasing the chance of buffer overflow and packet loss.

Our work is motivated by the observation that a large number of sensor network applications have two kinds of co-existing data packets: those that must be sent to the base station *quickly* and those that must be sent *reliably*. We might call these $Q$ and $R$ packets, respectively. For example, the MIT CarTel project [5] collects two types of data from a network of 9 private cars and 27 taxis. GPS data from the vehicles must be collected quickly because it is used to model traffic delays, but does not necessarily need to be sent reliably. On the other hand, data that is used to detect road-surface anomalies such as potholes requires high reliability to avoid false alarms, but does not need to be sent quickly. Another example can be seen in indoor firefighter tracking applications. Location data must be sent back to the base station as soon as possible but we do not need all data to reconstruct the route, while system maintenance data requires high reliability but not quickness. We call this property of an application *QoS heterogeneity*. To our best knowledge, Mélangepresents the first study of QoS heterogeneity in delay tolerant sensor networks.

In this paper, we propose a system that explicitly deals with QoS heterogeneity in delay tolerant sensor networks by applying different routing strategies to data packets with different quality of service requirements. The system has two parts: First, we propose an analytical framework to choose the optimal transmission probability $p$ given the QoS requirements of each packet, the mobile dynamics of the network, and the buffer capacity on the nodes. Second, we present the design of a new priority based local buffer eviction policy, which we combine with the transmission probability to produce our QoS heterogeneous epidemic protocol. In combination, the transmission probabilities and eviction policies form our DTN protocol called *Mélange*.

The remainder of this paper is organized as follows. The detailed system description including the QoS heterogeneous propagation model in Section 2.1 and a buffer management mechanism in Section 2.2. The simulation results for model validation are shown in Section 3. Finally, we conclude the paper in Section 4.

## II. Mélange

Mélange is a delay tolerant networking protocol designed to handle heterogeneous QoS requirements on the packets being relayed through the network. Mélange is designed to operate in a sparse network of $N+1$ mobile nodes. There are $N$ mobile sensor nodes that generate sensor data and one mobile gateway node or *base station* to which all sensor data must be sent. Each sensor node can generate two types of data packets: those that must be delivered *quickly*, or $Q$ packets, and those that must be delivered *reliably*, or $R$ packets. The sampling rates


Fig. 1. State Transition Graph for a man in the Epidemiological Model. States "S", "I", "H", and "IM" represent "susceptible", "Infected", "Healed", and "Immune", respectively.

of $Q$ and $R$ packets are denoted by $\lambda_Q$ and $\lambda_R$, respectively. The mobile nodes move throughout a monitored area of size $A$ and have a transmission range of $r$. All nodes have buffers of fixed size $C_0$ that can be used to store packets. We model the meeting rate with a parameter $\beta$.

### A. The Propagation Model

The goal of this section is to theoretically calculate the optimal transmission probability for the $R$ packets, denoted by $p$, for which the expected overall storage requirement does not exceed the local buffer capacity $C_0$ in the steady state.

*1) Basic Ordinary Differential Equation (ODE) Model:* We model the state of the nodes in the network based on the common *epidemiological* model, which is widely used to describe the transmission dynamics of a communicable disease [1]. This model has multiple stages: (1) a person without a disease is called *susceptible* (2) a person who has just contracted a disease is *infectious* (3) a person who is no longer infectious is *healed*, and (4) and a person who is no longer susceptible is *immune*. The state transitions for this model are shown in Figure 1. We first describe in this subsubsection the basic ODE Model used in [3], [8], [10] as the basis of our new results that calculate the optimal probability for $R$ packets, developed in Section II-A2.

If their transmission range $r$ is relatively small compared to the region area $A$, their speed is sufficiently high, and they move according to the common random way-point model [3], then the nodal meeting rate, denoted by $\beta$, can be estimated as [3]:

$$\beta \doteq (2wrE[V^\star])/A \quad (1)$$

in which $w$ is a mobility model specific constant, and $E[V^\star]$ stands for the average relative speed between the nodes.

First the analytical model for $Q$ packets is constructed. We denote $P(t)$ by the cumulative distribution function for this Poisson process, i.e., $P(t) = Prob[T_d < t]$. At the beginning of the infection, we assume $I(0) = 1$ and $P(0) = 0$. Since the infection rate is equal to the nodal meeting rate, we obtain the following first-order differential equation [8]:

$$I'(t) = \beta I(N - I)$$

This equation is separable and thus can be solved with $I(0) = 1$ to give the solution as follows [8]:

$$I(t) = N/(1 + (N - 1) \cdot e^{-\beta N t}) \quad (2)$$

By integrating this particular function together with the initial condition $P(0) = 0$, we can obtain the cumulative distribution function: $P(t) = 1 - \frac{N}{N-1+e^{\beta N t}}$. The expected number of copies when it is offloaded to the base station, denoted by $E[C_T]$, can also be calculated using the approach described in [10]:

$$E[C_T] = \int_0^\infty I(t)P'(t)\,dt - 1 = (N - 1)/2$$

*2) Calculating Optimal Probability:* We proceed to explain our new approach to calculate the optimal probability for $R$ packets. We first estimate the available space for $R$ packets and then obtain the theoretical optimal transmission probability.

The $P(T)$ curves and the numbers of infected nodes for each packet assist in the calculation of storage requirements for local buffers. We first predefine a threshold probability, denoted by $\alpha$, with which the packets are expected to be offloaded. For example, we choose probability of $\alpha = 0.99$, then find the appropriate value of $T$ from the plotted $P(T)$ curve. The $TTL$ field is therefore set to this value of T, indicating that these packets become "obsolete" after $T$ time units with a confidence level of 0.99. In steady states of the system, local buffer usage is equal to the expected number of copies of generated packets multiplied by the expected number of packets generated during the delivery time. Thus, the expected storage requirement for $Q$ packets in the steady state, $E[S_Q]$, can be calculated as:

$$E[S_Q] = (E[C_T]) \cdot (\lambda_Q P^{-1}(\alpha))(Packets)$$
$$= \frac{\lambda_Q}{2N\beta}(N - 1) \cdot \ln((N/(1 - \alpha)) - (N - 1))$$

This value of $E[S_Q]$ represents the average buffer usage for storing $Q$ packets in the steady state; as a result, the remaining available storage space for $R$ packets, $S_{limit}$, should be $C_0 - E[S_Q]$. For packets with type $R$, reliability is the major criterion and they are not limited by deadlines. Since these packets only have a "soft" latency requirement, a pure epidemic flooding is unnecessary because it leads to an inefficient buffer resource usage. Therefore, instead of a pure epidemic flooding scheme, we use a probabilistic epidemic forwarding [7], that is, when two nodes meet one another, they would exchange their data with a probability $p$. Again, $p$ can be used to tradeoff delay and storage constraints depending on the application requirements and our concern is to obtain the optimal $p$ while guaranteeing the storage constraint. The goal in this case is to somehow successfully deliver the packet to the base station and this type of packets doesn't have timing requirements.

The ordinary differential equation (ODE) model for $R$ packets is derived similarly to calculate the expected delay time and average buffer occupancy. The corresponding ODE equations for this scenario is:

$$I'(t) = \beta p I(N - I), P'(t) = \beta I(1 - P)$$

Again applying our analysis above for expecting buffer usage, the corresponding average storage requirement in the steady state for $R$ packets, $E(S_R)$, can be derived as:

$$E(S_R) = (N\lambda_R P^{-1}(\alpha)) \cdot \frac{p}{1+p}(N-1)$$
$$= \frac{p}{1+p} \cdot N \cdot (N-1) \cdot \lambda_R \cdot P^{-1}(\alpha)$$

Thus the *final* formula for storage requirement is:

$$\frac{\lambda_R}{\beta(1+p)}(N-1) \cdot \ln((N/(1-\alpha)^p) - (N-1)) \leq S_{limit} \quad (3)$$

By solving the above inequality, we can obtain the optimal probability that minimize the latency for packets in $R$ while satisfying the storage constraints of the system. As long as we have the parameters $N, \lambda_R, \lambda_Q, \alpha, C_0, r, v_{max}, v_{min}$, and $A$, we can calculate the optimal probability. The above equations illustrate the heterogeneity of our system depending on the QoS requirements which are common in many applications. Note that although the inequality in non-linear, the approximation value $p$ can still be obtained easily with the help of existing software such as Matlab.

### *B. A Prioritized Eviction Policy*

Previous work on epidemic routing assume that all packets have the same QoS requirements, which makes the eviction policy relatively straightforward. For example, the ZebraNet system evicted oldest packets and packets from other nodes first [6]. Mélange must deal with packets that have heterogeneous QoS requirements, and we modify the eviction policy appropriately. Packets are each given a priority according to their origin node, their age, whether they are known to have reached the base station, and their QoS requirements. The priorities are assigned in the following order, from highest to lowest:

1) New $R$ packets generated locally
2) Old $R$ packets generated locally
3) New $R$ packets generated by other nodes
4) Old $R$ packets generated by other nodes
5) New $Q$ packets generated locally
6) Old $Q$ packets generated locally
7) New $Q$ packets generated by other nodes
8) Old $Q$ packets generated by other nodes
9) Old $R$ or $Q$ packets that are known to have reached the base station

Thus, active $R$ packets always have higher priority than $Q$ packets, because $Q$ packets have no reliability constraints while $R$ packets do. Newer packets always have a higher priority than older packets because older packets are more likely to be stored at other nodes, or to have been relayed to the base station. Packets generated by other nodes always have lower priority than packets generated locally. This mechanism is used to introduce heterogeneity in the priorities assigned to a packet by each node, which helps ensure that a large number of packets continue to be stored as the network load approaches the storage capacity; every packet will be stored at exactly one node, minimizing redundancy in the network and therefore maximizing storage utilization. Finally, the network immunization process is used to give packets the lowest priority if they have been relayed to the base station. The eviction policy is applied on an as-needed basis and ties between packets with the same priority are broken randomly.

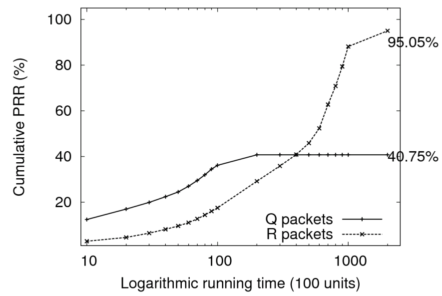


Fig. 2. Comparison of delivery time of $Q$ and $R$ packets.

## III. Evaluation

We built a DTN simulator to evaluate the performance of Mélange. The simulator provides an environment of 20 sparse mobile sensor nodes and one mobile base station, and is designed to be representative of a farm that is $500m$ x $500m$ in size. Each animal on the farm is tagged with a sensor that has a $12.4m$ transmission range, which is small compared to the total farm area. The mobility pattern of the herds follows the random way point model: they randomly pick an angle, randomly select a velocity in a predefined range with a minimum value $2m$ per timeunit to a maximum value $6m$ per timeunit, and run straight for 5 time units, and then stop and pick another angle and velocity.

Two types of packets are generated. One for the environmental data of the surrounding environments and the other for the health condition of the herds. We assume that the health data must be sent quickly, particularly during emergencies, but not reliably, and that the environmental monitoring data must be sent reliably but not quickly. One packet of each packet type is generated every $4$ time units. The $TTL$ value for packets in Q is set to $200,000$ time units. All experiments are evaluated with a confidence level $\alpha = 0.9$.

### *A. Ability to Meet Heterogeneous QoS Requirements*

First, to check how packets with different QoS constraints perform when the storage capacity is highly constrained, we set the storage capacity to be $100$ packets and the corresponding optimal probability $p$ for $R$ packets can be calculated as $0.776$ by solving Equation 3. Packets are generated as soon as the simulation starts. The buffers do not become full until approximately $200$ timeunits, so to best represent the steady state of the running system, we keep track of those packets generated in between timeunits $1,000$ and $10,000$. The simulation stops when none of these tracked packets are still in the network, because either they have been offloaded to the base station or discarded from all local buffers.

Figure 2 describes the different ways that $Q$ and $R$ packets are delivered to the base station when the Mélange protocol

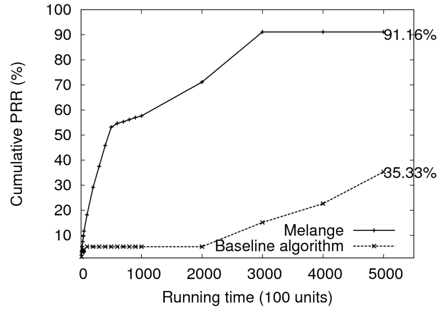


Fig. 3. Cumulative probabilistic distribution function for Performance of Mélange compared to epidemic routing approach.

is applied. Logarithmic scales are used for better readability. Points in the graph indicate the percentage of packets that are delivered to the station in a time bound, for example the first two points mean that around $12$ percent of $Q$ packets and $3$ percent of $R$ packets reach the base station in $1,000$ timeunits. These results show that both $Q$ and $R$ packets achieve their QoS requirements. The $Q$ packets arrive relatively quickly, typically before $4,738$ time units. However, they are often lost before delivery, and the overall packet delivery ratio (PDR) is as low as $40.75\%$. $R$ packets travel to the base station much more slowly, many of them not arriving until $10,000$ or even $50,000$ time units after they are generated. However, these packets are delivered with much higher reliability, and the final PDR is as high as $95.05\%$. The total PDR is less than 100% because of the extremely constraint buffer capacity, and so some $R$ packets are evicted due to high storage pressure. With larger packet buffers, the reliability of both the $R$ and the $Q$ packets would increase.

### *B. Comparison with Baseline Epidemic Routing*

In this experiment, we study the performance of Mélange compared to the baseline epidemic routing approach. To do so, we implement the baseline epidemic routing algorithm and evaluate it using the same simulation parameters that were used in Section III-A. In the baseline algorithm, all new packets are exchanged between nodes with probability $1.0$ whenever they meet. The eviction policy gives higher priority to locally generated and newer packets. Thus, the baseline algorithm is the same as Mélange except that it does not distinguish between $Q$ and $R$ packets. We compare these results to the simulation results of Mélange discussed in Section III-A.

Figure 3 shows the cumulative distribution of packets received using both algorithms over time. The final PRR is $35.33\%$ for the baseline algorithm and $91.16\%$ using Mélange system. Furthermore, Mélange delivers most of the packets within the first $50,000$ time units, whereas the baseline algorithm takes over $300,000$ time units to deliver the first half of its packets. The main reason for the bad performance of the baseline routing approach is that the $R$ packets are transmit with a higher probability, causing increased network traffic and increased demand on the packet buffers. As the buffers reach capacity, all packets are deleted from the buffers with the same probability, resulting in the lost of many packets. From these results, we conclude that Mélange produces both higher delivery rates and lower latency than the baseline epidemic routing approach.

## IV. Conclusions

In this paper, we present the Mélange protocol that can route packets through a DTN network while supporting heterogeneous QoS requirements. The key insight of Mélange is that packets that need to be sent quickly require bandwidth resources while packets that need to be sent reliably need storage resources. Algorithms that treat both types of packets equally require all packets to consume both types of resources. By treating the different packets differently, we can allocate more bandwidth for $Q$ packets and more storage for $R$ packets. Simulation results demonstrate that our QoS heterogeneous routing approach performs better than baseline epidemic routing strategy when packets with different types of QoS requirements exist in the network.

## V. Acknowledgments

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