Delay, Cost and Infrastructure Tradeoff of Epidemic Routing in Mobile Sensor Networks

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ABSTRACT

This paper studies the delay, cost and infrastructure tradeoff of epidemic routing in mobile sensor networks. We consider a mobile sensor network with M mobiles and B static base stations. The mobile sensors collect information when moving around and need to report the information to the base stations. Three different epidemic routing schemes — target epidemic routing, uncontrolled epidemic routing and controlled epidemic routing — are analyzed in this paper. For each of the three schemes, we characterize the scaling behaviors of the delay, which is defined to be the average number of time slots required to deliver a message, and the cost, which is defined to be the average number of transmissions required to deliver a message, in terms of the number of mobiles (M) and the number of base stations (B). These scaling results reveal the fundamental tradeoff among delay, cost and infrastructure in mobile sensor networks.

Categories and Subject Descriptors

H.1 [**Models and Principles**]: Miscellaneous

General Terms

Theory, Performance

Keywords

Epidemic routing, scaling law, mobile sensor networks

1. INTRODUCTION

Wireless technology has provided an infrastructure-free and fast-deployable method to establish communication, and has inspired many emerging applications. One of these applications is mobile sensor network where mobile sensors collect information when moving around and then report the collected information to base stations. For example, ZebraNet [7] is a mobile sensor network used to monitor and study animal migrations and inter-species interactions, where each zebra is equipped with an wireless antenna and pairwise communication is used to transmit data when two zebras are close to each other. The CarTel project at MIT [4] is another example, where cars equipped with WiFi, Bluetooth and cellular devices collect traffic information and cooperatively deliver the information to a public web site.

While mobile sensor networks have many important applications in practice, designing a high performance mobile sensor network is a very challenging task. In mobile sensor networks, the network topology constantly changes over time due to node mobility, so there is no fixed route from a mobile to the base stations. One approach to deliver data to base stations is to use the *epidemic routing,* i.e., mobile sensors exchange their messages whenever they meet to eventually deliver the messages to the base stations [6]. Under the epidemic routing, a packet in the network can be viewed as a type of infectious disease. A mobile node is said to be *infected* if it carries the packet in its buffer. An infected mobile may encounter other susceptible mobiles who do not have the packet and further, pass the packet to them, leading to more and more infected mobiles. Due to the similarities between the dissemination of the messages under the epidemic routing and the spread of an infectious disease, Markovian models and ordinary differential equations (ODEs) [2,3,5,8] are adopted from infectious disease spread model [1] to study the characteristics of the epidemic routing. Although ODE is a useful method to analyze the behavior of epidemic routing, it is an fluid-like approximation. In this paper, we propose a Markov chain model which describes the discrete stochastic process of the epidemic routing and study the behavior of epidemic routing based on the discrete Markov chain. We consider a mobile network with M mobile wireless nodes and B base stations. We are interested in characterizing three important performance metrics of epidemic routing in mobile sensor networks:

- **Delay:** The time required to deliver a message from a mobile to the base stations.
- **Cost:** The number of transmissions required to deliver a message to the base stations. Note that the number of transmissions is directly related to the energy consumed to deliver a message.
- **Infrastructure:** The number of base stations required for guaranteeing certain delay and cost requirements.

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It is easy to see that the most cost-efficient strategy is to let the mobiles directly transmit their messages to the base stations, while the most delay-efficient strategy is to allow uncontrolled epidemic routing (i.e., two mobiles exchange their messages whenever they meet). Clearly, there is a tension between delay and cost. More specially, more duplications (transmissions) reduce the delay but increase the cost. So it is imperative to understand the cost and delay tradeoff of epidemic routing so that the algorithm can provide a desired delay performance with a minimum cost. On the other hand, more base stations can reduce both delay and cost. So it is also very important to quantify the benefit of adding more stations to guide the deployment of infrastructure. Motivated by these observations, we are interested in characterizing the delay, cost and infrastructure tradeoff in mobile sensor networks.

We note that this paper is different from previous work on epidemic routing by including the infrastructure in the analysis. In practice, many mobile sensor networks include not only mobile sensors but also static base stations (e.g., the CarTel network) to assist data collection process. The infrastructure therefore plays an critical role in many mobile sensor networks. This motivates us to study the three-dimensional tradeoff (delay, cost and infrastructure). In the paper, we study three epidemic routing schemes: target epidemic routing, uncontrolled epidemic routing and controlled epidemic routing (these schemes will be defined in a detail in Section 2). We first model the epidemic routing processes as Markov chains and then characterize the scaling behaviors of the three performance metrics based on the Markov chains.

2. BASIC MODEL AND MAIN RESULTS

In this section, we first introduce the basic model and then summarize the main results of this paper. We consider a mobile network with M mobile and B static base stations. The mobiles collect information when moving around and report the collected information to the base stations. We assume that the base stations are connected by high-speed wires so that all base stations obtain a message once one of them receives the message. Furthermore, we assume that the number of base stations is less than the number of mobiles by an order of magnitude, i.e., $B = o(M)$. Since a base station in general is more expensive than a mobile sensor, this assumption is expected to hold in many practical systems.

The mobiles are equipped with wireless antennas and can communicate with each other and with the base stations. In this paper, we adopt a gossiping-like model such that at each time slot, one mobile is uniformly and randomly selected as the transmitter (with probability $1/M$), and then one mobile or one base station is uniformly randomly selected as the receiver (with probability $1/(M+B)$). The transmitter (mobile) then sends the messages it has to the receiver. This is a simplified mobility model which ignores the temporal and spatial correlations of node mobilities. We assume this simplified mobility model for two reasons: *(i)* this model enables us to analytically compute the expected delay and cost based on the corresponding Markov chains; and *(ii)* according to our simulations, the results obtained based on this simple model hold under the random walk model. The simulations results are presented in Section 6. Therefore, while this simple model is unlikely to hold in practice, the results obtained from this model can provide insightful guidance for analyzing and designing mobile sensor networks.

We consider the epidemic routing in this paper. Under the epidemic routing, duplication is allowed. So a message may have multiple copies carried by different mobiles. To distinguish these duplications, we use X_{ij} to denote the copy of message i carried by mobile j. In this paper, we assume that a mobile has at most one message to deliver to the base stations, and message i is originated from mobile i. We consider three different routing schemes in this paper:

(i) **Target epidemic routing:** Mobiles do not communicate with each other. Message i is delivered to the base stations when mobile i communicates with one of the base stations.

(ii) **Uncontrolled epidemic routing:** At each time slot, the selected transmitter sends all messages it has to the receiver. Note that the receiver can be a mobile or a base station.

(iii) **Controlled epidemic routing:** Assume each mobile has the global information about the number of mobiles carrying each message. If the receiver is a mobile, the transmitter sends the messages which are carried by less than N mobiles to the receiver. In other words, once there are N copies of a message in the network, the message will not be duplicated anymore. If the receiver is a base station, the transmitter transmits all the messages that have not been delivered to the base stations to the selected base station. [1]

	Uncontrolled epidemic routing	Controlled epidemic routing	Target epidemic routing
Expected delay	$\Theta(M \log M)$	$\Theta\left(M \log M + \frac{M^2}{BN}\right)$	$\Theta(M^2)$
Expected cost	$\Theta\left(\frac{M}{B}\right)$	$\Theta(N)$	1

Table 1: Delay and cost of the three schemes

We characterize the cost and delay under these three different policies. The main results are summarized in Table 1. From the results above, we can reach the following conclusions:

- The minimum expected delay is $\Theta(M \log M)$. The uncontrolled epidemic routing results in the minimum expected delay, but it requires $\Theta\left(\frac{M}{B}\right)$ transmissions on

[1] In practice, the global information is hard to maintain. The controlled epidemic routing can be implemented in the following fashion: Each message X_{ij} contains a counter C_{ij}. The initial value of the counter (C_{ii}) is set to be $\log N$. At a given time slot, if the receiver is a mobile, the transmitter (say mobile j) selects the message X_{ij} such that $C_{ij} \neq 0$, reduces the value of the counter by one (i.e., $C_{ij} \leftarrow C_{ij} - 1$), and then transmits the messages to the receiver. It is easy to verify that each message can be carried by at most N mobiles under this controlled epidemic routing. If the receiver is a base station, the transmitter (mobile) transmits all the messages that have not been delivered to the base stations to the selected base station.

average to deliver a message. Under the controlled epidemic routing, it requires only $\Theta\left(\frac{M}{B\log M}\right)$ transmissions on average to deliver a message. Therefore, the controlled epidemic routing leads to an order of $\log M$ cost reduction compared to the uncontrolled epidemic routing.

- Under the controlled epidemic routing, increasing the number of duplications (N) can reduce the expected delay when $N = O\left(\frac{M}{B\log M}\right)$. The order of the expected delay cannot be further reduced by increasing N when $N = \Omega\left(\frac{M}{B\log M}\right)$. This result states that there exists a certain threshold on N such that beyond the threshold, the gain of duplication becomes negligible.

- Assume that $N = O\left(\frac{M}{B\log M}\right)$, we have

$$M^2 = \Theta(BDN) \tag{1}$$

where D is the expected delay. This equation describes the fundamental tradeoff among the delay (D), cost (N) and infrastructure (B). For example, to guarantee a smaller delay D, we can either increase the number of duplications per message (N) or the number of base stations (B). They have similar impact on the expected delay. We note that the cost of increasing duplications depends on the frequency the messages are generated while the cost of adding more base stations is independent of that.

Therefore, depending on how "busy" the network is, we may want to select different N and B. For example, assume that on average, F new messages are generated in each time slot and each transmission incurs a unit cost. Further, assume that the maintenance cost of each base-station is Z units per base-station per time slot. We then can formulate the following minimum cost problem:

$$\begin{aligned} &\min\nolimits_{N,B} FN + ZB \\ \text{subject to:} \quad & BDN = M^2, \end{aligned}$$

and obtain that

$$\begin{aligned} B^* &= M\sqrt{\frac{F}{ZD}} \\ N^* &= M\sqrt{\frac{Z}{FD}}. \end{aligned}$$

So our results can provide some basic guideline of designing a cost-efficient mobile sensor network.

3. TARGET EPIDEMIC ROUTING

We first consider the target epidemic routing, where no duplication is allowed and a message needs to be directly transmitted from the source to the base stations. The Markov chain model is depicted in Figure 1. In this case, a message is carried by only one mobile (the source). The message is delivered if the source is selected as the sender and one of the base stations is selected as a receiver. In each time slot, the probability this event happens is:

$$\Pr(\text{A message is delivered at time slot } t) = \frac{1}{M}\frac{B}{M+B}.$$

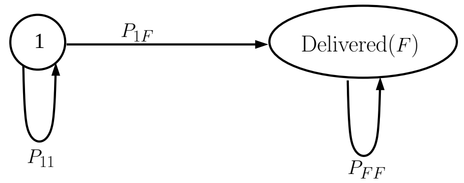

Figure 1: Markov chain model under target epidemic routing

Therefore, the expected delay is

$$D = M\frac{M+B}{B} = \Theta\left(\frac{M^2}{B}\right) \tag{2}$$

Since no duplication is allowed, the expected cost is 1. We therefore have the following theorem.

THEOREM 1. *Under the target epidemic routing, the expected delay is* $\Theta\left(\frac{M^2}{B}\right)$ *and the expected cost is* $\Theta(1)$.

4. UNCONTROLLED EPIDEMIC ROUTING

Under the uncontrolled flooding policy, a message is duplicated whenever possible. Therefore, the delay is minimized under the uncontrolled epidemic routing, while the cost is maximized.

4.1 The Markov chain model

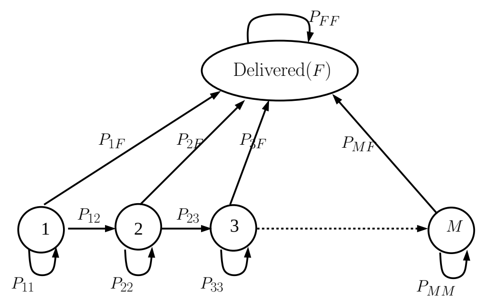

Figure 2: Markov chain model under uncontrolled epidemic routing

At each time slot, a mobile is selected to be the transmitter with probability $1/M$, and a mobile or a base station is selected as the receiver with probability $1/(M+B)$. The duplication process can be modeled as a Markov chain as shown in Figure 2, where state k is the state that k mobiles carry the message and the message has not been delivered to the base stations, and state F is the state that the message has been delivered to the base stations. It is easy to see that from state k, the Markov chain can stay at state k, go to state $k+1$ or go to state F. Defining p_{kh} to be the transition probability from state k to state h, we have

$$\begin{aligned} p_{kF} &= \Pr(\text{A mobile carrying the message is selected as Tx}) \\ &\times \Pr(\text{A base station is selected as Rx}) \\ p_{k(k+1)} &= \Pr(\text{A mobile carrying the message is selected as Tx}) \\ &\times \Pr(\text{A mobile without the message is selected as Rx}). \end{aligned}$$

Therefore, the transition probabilities are

$$\begin{aligned} p_{kF} &= \frac{k}{M}\frac{B}{M+B} \\ p_{k(k+1)} &= \frac{k}{M}\frac{M-k}{M+B} \\ p_{kk} &= 1 - p_{kF} - p_{k(k+1)} \\ &= 1 - \frac{k}{M}\frac{B}{M+B} - \frac{k}{M}\frac{M-k}{M+B} \\ p_{FF} &= 1, \end{aligned}$$

where $k = 1, 2, \ldots, M$.

4.2 The expected delay and expected cost

Let T_k denote the delivery time of a message with k copies in the network initially, i.e., the time to reach state F starting from state k. In other words,

$$T_k = \min\{n \geq 1 | X_n = F, X_0 = k\},$$

where X_n is the state of the Markov chain at time slot n. We further let D_k denote the expected delay of delivering a message which has k copies in the network initially, i.e.,

$$D_k = E[T_k].$$

Note that the expected delay we are interested is D_1.

From the Markov chain model, we can derive the following recursive equation of D_k, $k = 1, 2, \ldots, M-1$.

$$\begin{aligned} D_k &= p_{kF} + (1 + D_k)p_{kk} + (1 + D_{k+1})p_{k(k+1)} \\ &= 1 + D_k p_{kk} + D_{k+1} p_{k(k+1)}. \end{aligned} \tag{3}$$

Substituting p_{kF}, $p_{k(k+1)}$, and p_{kk} in Equality (3), we obtain the following recursive equation:

$$D_k = M\left(\frac{1}{k} + \frac{1}{M+B-k}\right) + D_{k+1}\frac{M-k}{M+B-k}, \tag{4}$$

where $k = 1, 2, \ldots, M-1$ and

$$D_M = \frac{1}{p_{MF}} = \frac{M+B}{B}.$$

Based on the recursive equation (4), we derive the upper bound and lower bound on the expected delay and show that the upper bound and lower bound are actually of the same order. The detail analysis can be found in [9].

Theorem 2. *Under the uncontrolled epidemic routing, the expected delay is $\Theta(M \log M)$ and the expected cost is $\Theta\left(\frac{M}{B}\right)$.*

5. CONTROLLED EPIDEMIC ROUTING

In this section, we study the expected delay given that the maximum number of copies of a message is N.

5.1 The Markov chain model

We first assume that each mobile has the global information about the number of copies of a message in the network. In this scenario, a message is not allowed to be duplicated if there are already N copies in the network. The Markov chain represented the controlled epidemic routing is as shown in Figure 3.

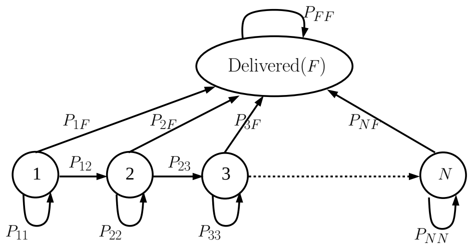

Figure 3: Markov chain model under controlled epidemic routing

5.2 The expected delay and expected cost

Let $D_k(N)$ denote the expected delay of delivering a message which has k copies in the network initially. We derive the expected delay $D_1(N)$ under the controlled epidemic routing following the similar steps as the uncontrolled epidemic routing. First, we develop a recursive equation of the expected delay $D_k(N)$. Then we derive the upper bound and lower bound on the expected delay. Finally, by showing that the upper bound and lower bound are actually of the same order, we obtain the order of the $D_1(N)$. The detail analysis can be found in our technical report [9].

Theorem 3. *Assume that for each message, only N duplications are allowed in the network. Then the expected delay is $D_1(N) = \Theta\left(M \log M + \frac{M^2}{BN}\right)$ and the expected number of copies of this message is $\Theta(N)$.*

6. SIMULATION

In this section, we use simulations to show that the results obtained under the gossiping-like model also hold under the random walk model. We consider a mobile network with M mobiles and B static base stations. The mobiles and the base stations are located on an $L \times L$ grid. The base stations are uniformly and randomly positioned on the grid. The initial locations of the mobiles are also uniformly and randomly selected. At each time slot, the mobile moves according to the following random walk model: At the beginning of each time slot, a mobile moves from its current point to one of its eight neighboring points or stays at the current point. Each of the actions occurs with probability 1/9.

At each time slot, a mobile transmits all the messages in its buffer to the mobiles and the base stations at the same location.

6.1 Different numbers of mobiles under the uncontrolled epidemic routing

In this simulation, the number of mobiles in the network (M) varies from 100 to 1000 with a step size of 100. The side length of the grid is set to be $L = M$. The number of static base stations (B) is chosen to be a constant 10. For each M, we ran the simulation 50 times and then computed the average delay and the average cost. Figure 4 and 5 depict the average delay and cost under uncontrolled epidemic routing. The values of the coefficients are $\alpha = 2.7990$ and $\beta = 1.1692$. From the figures, we can see that the average cost and delay under the random walk model follow the same scaling laws as those obtained under the gossiping-like model.

6.2 Different N's under the controlled epidemic routing

In this simulation, we varied N from 10 to 35 with step size 5. We fixed $M = 1000$, the side length of the grid $L = 1000$, and the number of base stations $B = 10$. For each N, we ran the simulation 10 times and computed the average delay

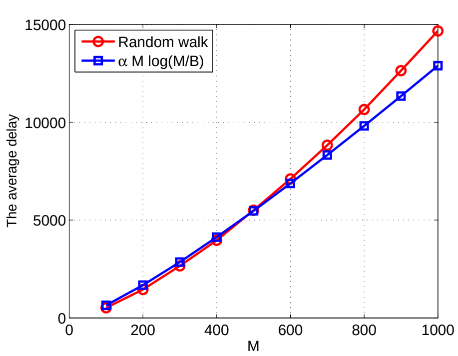

Figure 4: Average delay under the uncontrolled epidemic routing with different M's

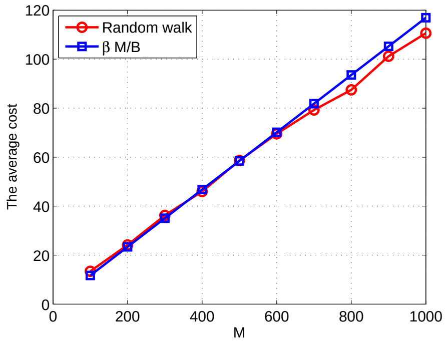

Figure 5: Average cost under the uncontrolled epidemic routing with different M's

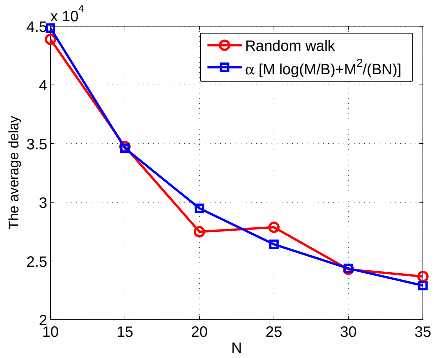

Figure 6: Average delay under the controlled epidemic routing with different N's

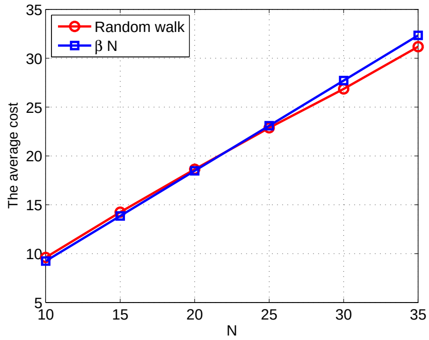

Figure 7: Average cost under the controlled epidemic routing with different N's

and cost. The results are illustrated in Figure 6 and 7. The values of the coefficients are $\alpha = 3.0700$ and $\beta = 0.9238$. From the figures, we can see that the average cost and delay under the random walk model follow the same scaling laws as those obtained under the gossiping-like model.

7. CONCLUSION

In this paper, we studied a mobile sensor network with M mobiles and B base stations. We modeled the epidemic routing as a Markov chain and characterized the delay-cost-infrastructure tradeoff. Our simulations result confirmed the scaling laws obtained hold under a random walk model.

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8. REFERENCES

[1] F. Brauer and C. Castillo-Chavez. *Mathematical models in population biology and epidemiology.* Springer Verlag, 2001.

[2] R. Groenevelt, P. Nain, and G. Koole. The message delay in mobile ad hoc networks. *Performance Evaluation*, 62(1-4):210–228, 2005.

[3] Z. J. Haas and T. Small. A new networking model for biological applications of ad hoc sensor networks. *IEEE/ACM Transactions on Networking*, 14(1):40, 2006.

[4] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. Miu, E. Shih, H. Balakrishnan, and S. Madden. CarTel: a distributed mobile sensor computing system. In *Proceedings of the 4th international conference on Embedded networked sensor systems*, page 138, 2006.

[5] T. Small and Z. J. Haas. The shared wireless infostation model: a new ad hoc networking paradigm. In *MobiHoc*, 2003.

[6] A. Vahdat and D. Becker. Epidemic routing for partially connected ad hoc networks. Technical Report CS-2000-06, Department of Computer Science, Duke University, April 2000.

[7] P. Zhang, C. M. Sadler, S. A. Lyon, and M. Martonosi. Hardware design experiences in zebranet. In *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 227–238, New York, NY, USA, 2004. ACM.

[8] X. Zhang, G. Neglia, J. Kurose, and D. Towsley. Performance modeling of epidemic routing. *Computer Networks*, 51(10):2867–2891, 2007.

[9] S. Zhou, L. Ying, and S. Tirthapura. On delay, cost and infrastructure tradeoff in mobile sensor networks. 2010. Technical Report, available at `http://inl.ece.iastate.edu/Publications/ZhoYinTir10.pdf`.