Goodput and Delay in Networks with Controlled Mobility

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Abstract—The use of mobility has been shown to be beneficial in wireless ad hoc and sensor networks, for improving communication performance and other functionality. This paper discusses the communication throughput, goodput and delay considerations when a set of mobile nodes is used as relays to transfer data among multiple static nodes. While previous work has considered randomly mobile nodes, we consider controlled mobile agents. Randomly mobile agents are not available in many network scenarios, such as embedded sensor network deployments, and the use of controllably mobile agents has been considered for such networks. We derive results for the worst case delay, throughput and goodput with controllably mobile relays. Our analysis indicates that this scenario differs fundamentally from the random mobility case. This scenario could, however, be used in defense applications for better communications yield. Further, our results are guaranteed to be achieved in a particular topology, as opposed to previous results which are probabilistic for a particular deployment. We also discuss practical algorithms that can be used to control the routes of mobile agents.

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1. INTRODUCTION

Mobility has traditionally been considered an overhead for networks because protocol stacks had to provide additional functionality to allow mobile users [1], [2], [3], [4]. More recently, however, mobility has been found to be useful for wireless ad hoc networks for increasing their throughput capacity [5], [6], [7], [8]. These advantages are accrued by utilizing the mobility of the nodes for transferring data. Mobility provides additional capacity to the network, over and above the wireless channel amongst static nodes alone.

Mobility can be classified as follows:

1. **Random Mobility**: The nodes are assumed to move in an arbitrarily random pattern typically modelled as uniform Brownian motion for analytical convenience. Throughput has been studied for the cases when all nodes move [5], [8], [7] and when only a subset of the nodes move [6], [9].
2. **Predictable Mobility**: This model assumes that the pattern of mobility of the mobile nodes is known and this knowledge can be exploited to route data [10], [11], [12]. The mobile agents are not moving for the purpose of data transfer and hence their paths may not coincide with the routing requirements.
3. **Controlled Mobility**: Here the mobility pattern of the mobiles is completely under the control of the network. Prototypes of such networks have been considered [13], [14], [15].

We consider the third category – the network with controlled mobile agents, and characterize its delay and goodput properties. Further, attainable throughput for such a network is also discussed. Our analysis shows that there are fundamental differences in these properties when the mobility is controlled as opposed to when the mobility is random or predictable. Also note that using controlled mobility, we are able to ensure performance for any arbitrary topology. The results derived for random models only provide the expected throughput and delay considered over multiple topologies, and not what would be achieved in a particular deployment, nor what could be guaranteed in the worst case.

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The Need for Controlled Mobility

Random mobility is not a valid model in all classes of wireless ad hoc networks. In particular, sensor networks are autonomous embedded systems and do not involve user carried nodes. Most of their nodes are either static or mounted on robots which can be controlled as per application requirements. Further, the use of controlled mobility has several advantages in wireless ad hoc and sensor networks. Example of such a scenarios is Networked Infomechanical System (NIMS) as shown in Figure 1. In NIMS, the mobile sensor nodes are loaded on a trolley and hence, providing infrastructure for the mobility. These mobile sensor nodes are used to collect the data (such as environmental, habitat, etc.) from the static nodes deployed on the ground.

Figure 1. Example of Controlled Mobility: Networked Infomechanical System (NIMS).

First, the mobile nodes can help save energy in static embedded nodes. This is because if the mobile nodes are used for carrying data, then the static nodes need not relay data from other nodes over multi-hop wireless routes. The extra energy overhead of mobility is not a major concern as these nodes are mobile and can thus periodically recharge themselves. Self recharging robots have been prototyped such as the robot tortoise described in [16] and the commercially available Sony Aibo [17]. Second, mobile agents can be used to connect sparse and disjoint networks. Particular network components can get disconnected due to deterioration in channel conditions and these can be connected using mobile components. Third, the number of wireless hops travelled by a data packet is reduced and this reduces the possibility of packet error, helping enhance goodput performance, and delays due to retransmission.

There are other advantages of using mobile components for improving network sustainability. It was shown in [18] that time synchronization error increases with increasing number of hops between two nodes. Using the mobiles for time synchronization reduces the hop distance between nodes, and hence much finer time synchronization is possible than in a multi-hop case. Controlled mobility also helps improve the performance of localization systems [19]. Mobile components can support other system activities such as delivering required resources [20], [21].

Thus, the used of control mobility is helpful in several situations, and it is worthwhile to study the performance considerations for such a scenario.

The paper is organized as follows: Section 2 states the problem setup and analyzes the achievable goodput and delay. Along with the discussion on throughput, some special cases and comparisons with other mobility models are also presented. Practical methods for routing the mobile agents are discussed in section 3. The paper is concluded in section 4.

Related Work

The capacity of wireless networks was first evaluated in [22]. They assumed a network of n randomly deployed nodes in a unit area disc and found the average throughput if sources and destinations are chosen randomly across the network. The throughput per node was found to be $\Theta\left(1/\sqrt{n \log n}\right)$ [1]. For the model considered in [22], if the traffic pattern is such that the average distance between source and destination nodes remains small as the network grows, then the throughput per node was derived to be $O(1)$ in [23]. The use of mobility was considered in [5]. They assumed all nodes to be randomly mobile within a unit disc area. Data traffic pattern was assumed to be random as in [22]. Data traveled over only two wireless hops, from the source node to a mobile node which acted as relay and then from the relay to the destination. With this model the throughput was found to be $\Theta(1)$. Later, [8] showed that if the mobility was restricted to one dimension only, the constant order throughout can still be achieved. The delay for the above scenarios was found in [7]. They also discussed algorithms for improving throughput at the cost of delay and vice versa. They found the delay $D(n)$ to be related to the throughput $T(n)$ as $D(n) = \Theta(nT(n))$ for the wireless network scenario of [22]. For the model in [5] when the nodes are randomly mobile with average velocity $v(n)$, they found the delay to scale as $\Theta(\sqrt{n}/v(n))$. However, it should be noted that this is for one particular scheme.

Another scenario for a network with mobile nodes was considered in [6]. The network consisted of n static nodes which acted as sources and destinations for data. However, the network also had m randomly mobile nodes which were used as relays. For this model, using the routing scheme proposed in [6], the throughout is $O(m/n \log^3 n)$ with an average delay of $2d/v$ where d is the diameter of the network and v is the velocity of the mobile nodes. We consider a similar model,

[1] We use the usual notation: $f(n) = O(g(n))$ means that there exists a constant c and an integer N such that $f(n) \leq cg(n)$ for $n > N$; $f(n) = \Theta(g(n))$ means that $f(n) = O(g(n))$ and $g(n) = O(f(n))$.

with n static and m mobile nodes but the mobility is controlled instead of random. The problem is defined in greater detail in the next section.

2. Capacity of the Mobile Channel with Controlled mobile agents

Let us first consider the network scenario as considered in [5] where all nodes are mobile except that instead of considering the nodes to be randomly mobile, we assume their motion is controlled. For this case an obvious communication strategy is for each source to move to its destination and communicate at almost zero range. Hence interference among simultaneous transmissions is zero and each sender-receiver pair could utilize the full available bandwidth W. The per node throughput is W with constant delay. The delay here depends on the traveling time of mobile nodes to reach their destinations which is constant as network area is constant. This is significantly better than the worst case delay in [5] which is infinite. Clearly, controlled mobility has the potential to yield fundamentally different goodput, throughput and delay limits compared to those achieved with random mobility in [5], [6]. We now consider a more practical scenario wherein all nodes are not mobile but a small number of controllably mobile agents are available for routing data.

Problem Statement

Assume n nodes deployed randomly in a unit area disc. Any node in the network may have data to be sent to any other node. Further, m mobile agents are available whose paths can be controlled as per the data requirements. Here m could potentially be much smaller than n. The mobile travels close to the source location, collects its data over a wireless link, and then travels to the destination location and delivers the data to the destination node, again using a wireless link. The path from the source to destination may not be direct but may involve servicing other data transfer requests in between. This is because, using one mobile to serve only one source destination pair at one time does not necessarily yield optimal path planning for the mobiles and we allow the mobiles to collect data from multiple sources for multiple destinations, depending on the node locations. Figure 2 shows the problem scenario. The bandwidth of communication on the wireless channel is W. Note that W could potentially be very high as the mobile node can travel very close to the static node. However, we perform the analysis for any available W. The velocity of the mobile nodes is denoted by v meters/sec . For ease of exposition, we assume that each source has k bits for its destination. Some nodes may have less than k bits, however using k for all nodes suffices for evaluating worst case limits.

We consider the problem of determining the achievable goodput and delay experienced by any data packet in the above network scenario in the worst case. We later also discuss the problem of allotting the optimal paths to the mobile nodes for routing data and throughput that could be obtained from such networks.

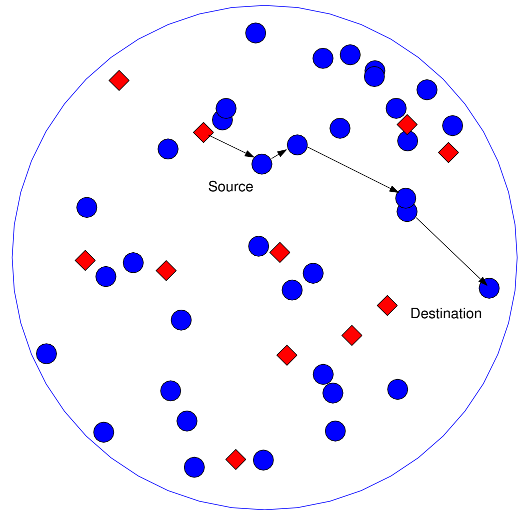

Figure 2. Network with mobile and static nodes. The diamond shaped nodes (in red) represent the mobile nodes and the circular nodes (in blue) are the static nodes.

The network model described above could be implemented for defense applications. For instance, sensors or any nodes with the controlled mobility could be used to collect the surveillance data from the deployed static nodes. This approach, as shown next, is the most efficient for delay sensitive data and providing high goodput and throughput.

Solution

Let us calculate the delay suffered by a k-bit packet in travelling from its source to destination after it is ready to be transmitted at the source. For calculating the worst case achievable delay, we assume that each mobile serves n/m sender-receiver pairs. Depending on what metric is used for optimizing the paths of the mobile nodes, the actual allocation may deviate from this equitable allotment; we consider practical methods for such allotment in Section 3. The delay and goodput derived below are definitely achievable, using the (potentially sub-optimal) equitable allotment. The sender-receiver pairs need not be addressed one after the other, rather multiple such pairs will be simultaneously served. Instead of calculating the worst case delay individually, we evaluate the delay and goodput for a group of n/m nodes served by a single mobile. Since not all packets suffer the worst case delay, this method allows us to calculate the achieved goodput for all the data, rather than just for the node which happens to get the worst case delay. This total delay in serving n/m requests is also the worst case delay suffered by a packet, since the worst case packet would be the one which is served last in the group. The delay can be calculated as follows:

1. Mobile collects data from source:- This time is the summation of following terms:

(a) Contention near source: When the mobile arrives at a source, there may be other mobiles too at this node delivering data destined for this node. Assume that the traffic pattern is such that at most γ nodes could send data to a particular node. Then, the maximum number of mobiles which can be present at a node, Γ, to deliver can be

$$\Gamma = min(\gamma, m) \quad (1)$$

Hence the time spent waiting for these transmissions becomes $d_1 \leq \Gamma k/W$, where W is the bandwidth used for communication among static and mobile nodes. This communication occurs at very small range and does not interfere with other communication in the network.

(b) Wireless data communication delay: The time taken to send k bits from the source to the mobile agent will be $d_2 = k/W$.

(c) Motion delay: The distance to a source from the previous node served can be at most $1/\pi$, the diameter of the network with unit area. Hence this delay is $d_3 \leq 1/(\pi v)$ where v is the speed of the mobile.

2. Time to travel from a served node to a destination. This can be at most $d_4 \leq 1/(\pi v)$ as explained for the travel time taken to reach a source. The delay, d_4, needs to be added in addition to d_3 since d_3 only calculates the time taken to arrive at sources, and not at destinations. Adding these will give the per request travel time.

3. Contention at destination: This is $d_5 \leq \Gamma k/W$ as was the contention at source.

4. Time to deliver at destination: The transmission time at destination is $d_6 = k/W$.

Thus, the total delay, D, for the worst case packet among the n/m sender-receiver pairs served by one mobile agent is the summation of the delays evaluated above:

$$D \leq \frac{n}{m}\left[d_1 + d_2 + d_3 + d_4 + d_5 + d_6\right] \quad (2)$$

Substituting the values of $\{d_i\}_{i=1}^{6}$ and simplifying, we obtain:

$$D \leq \frac{2n}{m}\left[\frac{k}{W}(\Gamma + 1) + \frac{1}{\pi v}\right] \quad (3)$$

The goodput per node can be defined as the bits transmitted by a node divided by the time taken for those bits. Thus, the goodput, G, for the node with the worst case delay is:

$$G = \frac{k}{D} \geq \frac{mkW\pi v}{2n[k\pi v(\Gamma + 1) + W]} \quad (4)$$

The total goodput for the group of n/m nodes is nG/m as the total data transferred within the delay, D, was nk/m. Thus, the network goodput is $m\times(nT/m)$ since there are m groups. Thus, the per node goodput and delay are $G = O(m/n)$ and $D = O(n/m)$ respectively.

Throughput Discussion

In a broad sense, network throughput consists of sum of the data rates that are available to nodes for simultaneous transmission in a network. Here, we can have m nodes in the network simultaneously transmitting at the data rate of almost W bps (considering mobile nodes travel very close to static nodes). That is, available network throughput is $f(mW)$, where $f(\cdot)$ indicates some real function. Hence, the throughput per node is $T = f(mW/n)$ bps. It can be observed that as opposed to the previous results, the network could be made scalable.

Scalability Concerns

Let us study the effect of the wireless bandwidth available among static and mobile nodes. This bandwidth can be very large as the communication range is small and fast technologies such as UWB or a contact based transfer may be used. We let $W \to \infty$ in equations (3) and (4):

$$D_{W\to\infty} \leq \frac{2n}{m\pi v} \quad (5)$$

$$T_{W\to\infty} \geq \frac{mk\pi v}{2n} \quad (6)$$

As expected, the delay and goodput are limited by the mobile velocity, v m/s, in this case. While the delay is reduced compared to the case of finite W, the scalability of the network delay is not affected and hence the investment in larger bandwidth may not be recommendable if scalability is the key concern. However, the goodput (and throughput) can be very high here, as the value of k used can be very large when $W \to \infty$.

Consider next the case when the number of mobiles used is a linear function of the number of static nodes in the network, i.e., $m = an$ where a is a positive constant, potentially much less than 1. In this case $\Gamma = \min(\gamma, m) = \gamma$ since we expect n and hence an to be much greater than γ. Here, the delay and goodput can be seen to be:

$$D_m \leq \frac{2}{a}\left(\frac{k}{W}(\gamma + 1) + \frac{1}{\pi v}\right) \quad (7)$$

$$G_m \geq \frac{akW\pi v}{2[k\pi v(\gamma + 1) + W]} \quad (8)$$

These are both independent of n and m. Hence we achieve $G = O(1)$ and $D = O(1)$ for this case. In this case, even per-node throughput would be $O(1)$. Observe that compared to the case of random mobility [5] where $O(1)$ throughput is achieved when all n nodes are mobile, using controlled mobility such throughput can be achieved with less than n mobile nodes. Also, while the worst case delay in [5] can be infinite, here the worst case delay is also $O(1)$.

Mobile and Wireless Channels

We calculated the capacity when data is transferred using only the mobile relays and multihop wireless transmission is not exploited. Let us now consider the capacity when the multihop relaying is used in addition to mobile agents. Since the mobile router is controllably mobile it can come very close to the static node it is communicating with and thus cause negligible interference to any other communication which may be simultaneously taking place. Hence, the wireless multihop relaying channel can be used simultaneously along with the mobile channel. The capacity of wireless channel has already been shown to be $\Theta\left(\sqrt{n \log n}\right)$ in [22].

The delay for the wireless multihop relaying channel was calculated in [7] while the delay for the mobile channel was shown in section 2. Thus, data traveling on the two channels experiences the respective delays.

Trade-offs in the Throughput-Delay Space

The trade-offs for throughput and delay for the models in [22], [5] are considered in [7]. The curve PRS in Figure 3 [2] depicts that trade-off. The segment PR is valid for the model in [5] where all the nodes are mobile. The segment RS holds for the model in [22] using only static nodes. The per node throughput can be varied from $O(1/n)$ to $O(1)$ by paying a penalty in delay. The use of controlled mobility introduces new possibilities, shown along the curve AB. Different points on the curve AB correspond to different values of m. As m increases delay is reduced. The point A is achieved with $m = 1$ and point B is achieved with only a small increase to $m = 0.05n$.

Now consider the point P in Figure 3. This point corresponds to the constant per node throughput achieved in [5] using the routing scheme given in [7]. However the delay is $O(n)$. The point B on the other hand shows constant per node throughput at constant delay using the controlled mobility model.

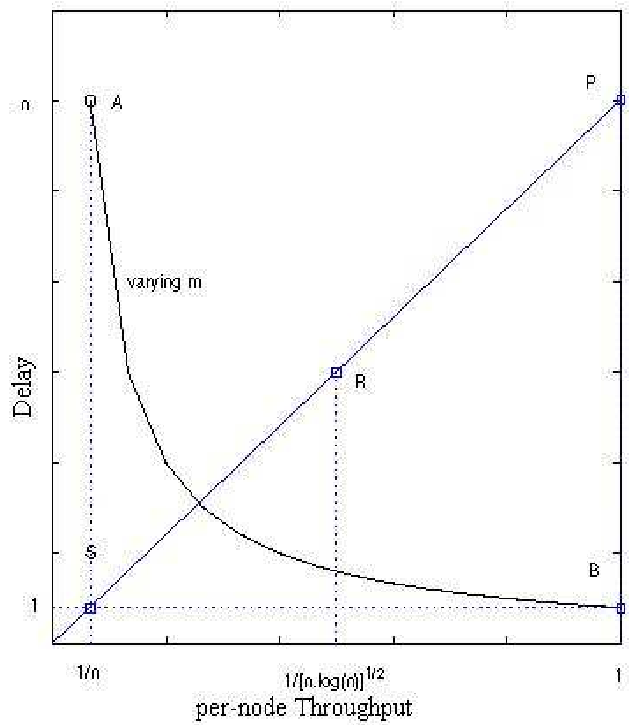

Figure 3. Comparison of throughput-delay trade-offs in controlled mobility and other models.

3. MOBILE ROUTING PROTOCOLS

We now consider practical methods to control the paths of the mobile agents. This problem can be reduced to a known optimization problem, namely, the general pickup and delivery problem (GPDP) stated in [24], [25]. We state the problem in the context of routing data for our network scenario. Define the following variables:

N: the set of all sender-receiver pairs, where the cardinality of N is n.
M: the set, with cardinality m, of all the mobiles.
N_i^+: the i^{th} data source, $i \in \{1, 2, \ldots, n\}$.
N_i^-: the i^{th} data destination, corresponding to N_i^+.
s^+: the start location of mobile s, where $s \in M$.
s^-: the end location of mobile s, where $s \in M$.
M^+: set of start locations of all the mobiles.
M^-: set of end locations of all the mobiles.
Z: $M^+ \cup M^-$.

[2] The relative magnitudes of the curves shown are valid for large n, since the results from [7], [5], [22] are valid only at large n even though our results are valid for finite m and n also.

Now, $\forall\, i, j \in \{N_i^+ \cup N_i^- \cup Z\}$, let d_{ij} and t_{ij} denote the distance and the time taken in travel, respectively, from location i to j.

Definition 3.1 (Mobile Path) A path R_s for mobile s is an ordered subset $Z_s \in Z$ such that the following constraints are satisfied:

1. **Docking Constraint:** R_s starts at s^+ and ends at s^-.

2. **Pairing Constraint:** $(N_i^+ \cup N_i^-) \cap Z_s = \emptyset$ or $(N_i^+ \cup N_i^-) \cap Z_s = N_i^+ \cup N_i^-$. (This implies that if mobile s visits a data source, then it must also visit the corresponding destination.)

3. **Precedence Constraint:** If $N_i^+ \cup N_i^- \subseteq Z_s$, then N_i^+ is visited before N_i^-.

Definition 3.2 (Routing Plan for Mobile Relays) A routing plan is a set of routes $\mathcal{R} = \{\mathcal{R}_{\int} | \int \in \mathcal{M}\}$ such that:

1. R_s is a valid path for mobile s, for each $s \in M$.

2. $\{Z_s | s \in M\}$ is a partition of Z.

3. $f(\mathcal{R})$ denotes the cost of routing plan $\mathcal{R}$.

The problem of finding the routing plan for mobile relays is then:

$$\min_{\mathcal{R} \text{ is a routing plan}} f(\mathcal{R}) \tag{9}$$

The cost function $f(\cdot)$ depends on the required objective. For instance, in our problem f could quantify the worst case delay suffered by any packet, when the mobiles move as per plan $\mathcal{R}$.

Our problem is a GPDP, which is known to be NP-complete [26], [27]. However, several applicable heuristics exist for finding a good routing plan $\mathcal{R}$. For example, the approximations for the static multiple vehicle pickup and delivery problem in [24], [28] employ the decomposition of the problem in clusters and chains. This algorithm is based on set partitioning and column generation.

So far we did not explicitly consider the buffer limit in the mobile relays and that the sender-receiver requests may not all be known at the start of the mobile relays' journey. However, these constraints could be incorporated into the GPDP formulation and practical algorithms are also known [24], [29], [30].

Thus, practical methods are available to control the trajectories of the mobile relays and can be employed with the appropriate objective function.

4. Conclusions

We considered the fundamental limits on goodput, throughput and delay for a network with mobile nodes using a new model for mobility. While previous work considered random mobility patterns, we discussed the scenario with controllably mobile data relays. We saw that this scenario is applicable for an emerging class of wireless network applications, such as sensor networks. Our analysis showed that controlled mobility can significantly change the throughput and delay tradeoffs. In particular, networks scalability can be ensured using only a small fraction of mobile nodes and still achieve constant per node throughput at constant delay. We reduced the problem of routing mobile nodes to a special case of GPDP. This formulation allows optimizing for several practical concerns that network designers may have for their particular application, such as optimal number of mobile agents, total travelling time, or the worst case data transfer delay. Further work is required to determine the optimal combination of wireless multihop routing and the use of mobile relays to obtain a required performance for a given network size.

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BIOGRAPHY

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Dr. Greg Pottie was born in Wilmington DE and raised in Ottawa, Canada. He received his B.Sc. in Engineering Physics from Queen’s University, Kingston, Ontario in 1984, and his M.Eng. and Ph.D. in Electrical Engineering from McMaster University, Hamilton, Ontario, in 1985 and 1988 respectively. From 1989 to 1991 he worked in the transmission research department of Motorola/Codex in Canton MA, with projects related to voice band modems and digital subscriber lines. Since 1991 he has been a faculty member of the UCLA Electrical Engineering Department, serving in vice-chair roles from 1999-2003. Since 2003 he has also served as Associate Dean for Research and Physical Resources of the Henry Samueli School of Engineering and Applied Science. His research interests include reliable communications, wireless communication systems, and wireless sensor networks. His current focus is on the information theory of sensor networks. From 1997 to 1999 he was secretary to the board of governors for the IEEE Information Theory Society. In 1998 he received the Allied Signal Award for outstanding faculty research for UCLA engineering. In 2005 he became a Fellow of the IEEE for contributions to the modeling and applications of sensor networks. Dr. Pottie is the deputy director of the NSF-sponsored science and technology Center for Embedded Networked Sensing, a member of the Bruin Master's Swim Club (butterfly) and the St. Alban's Choir (2nd bass).