

Establishment and Maintenance of a Delay Tolerant Network through Decentralized Mobility Control

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Abstract— In this paper we investigate the establishment and maintenance of a delay tolerant network through decentralized mobility control. A set of geographically dispersed wireless radio nodes wish to communicate with one another. These nodes are free to move about the environment and are not constrained to remain in direct communication range of one another. A second set of helper nodes exist in the environment that can form connected chains between nodes and that can ferry data back and forth between sensor nodes and/or other helper nodes. The mobility of the helper nodes is controlled based on local information about neighboring nodes and the communication flow through the network. A hierarchical approach is described in which helper nodes are assigned specific sensor nodes or regions of activity through resource allocation algorithms while communication flow through established links is maintained by decentralized control based on local measures only such as received signal strength or signal to noise ratio.

I. INTRODUCTION

A new class of mobile ad-hoc networks is emerging in which source and destination nodes do not need to be connected through a multi-hop link at a given time. Instead, data is passed between nodes that come into close contact with one another and a data packet eventually reaches its destination. Such protocols are well suited to networks that are sparse, dynamic, and can tolerate end-to-end transmission delays in the data. Not surprisingly, this new class is referred to as *delay tolerant networking (DTN)*.

The mobility of network nodes is an essential component of the DTN architecture. Node mobility enables message passing in partially-connected networks where standard ad-hoc networking (in which wireless nodes cooperate to relay packets over multiple relay hops from source to destination [1]) fails. Mobility-based data packet delivery is known to be effective when long delays can be tolerated [2]. Approaches that consider given node movement typically

assume nodes have similar capabilities, nodes move in random patterns, and the communication is separated from the other activity of the node [3-6]. The main advantages of these approaches are their ability to overcome network partitioning due to sparse numbers of nodes and reduced network congestion, since data is physically carried rather than transmitted multiple times through relays. Depending on the transmission protocols, mobility can also save overall power in the network. The main drawbacks of these approaches are their reliance on chance encounters to relay data and scalability issues due to their inherent flooding nature.

A second class of protocols exploits known, periodic, or non-random mobility in subsets of nodes. The use of unmanned aircraft for ad-hoc networking in battlefield networks exploits the coordinated, hierarchical organization of moving troop units [7-10], improving the coverage and load balancing of these types of networks. The notion of general *support* nodes described in [11] where sub-protocols dictate the motion of dedicated relay nodes is shown to improve basic message passing, especially in highly dynamic environments. The concept of data ferrying also uses non-random movement to form efficient ferry routes that minimize delay and support bandwidth requirements for a group of nodes with known locations and known communication requirements [12].

The central question addressed by this work is how to control the mobility of helper nodes in a DTN *based on local network information* to establish and maintain (delayed) communication between other nodes in the network. A small body of work exists that explicitly incorporates communication objectives into larger multi-objective control frameworks [11, 13-18]. Most often these systems assume a predefined minimum communication radius and simply add a relative position or line-of-sight constraint between cooperating vehicles [13, 14, 18, 19].

A handful of works address communication-reactive control strategies for ad-hoc networks that go beyond simple position-based constraints. Reference [20] addresses deliberate trajectory changes to make message passing between two communicating nodes possible. Movement control for fault tolerance was investigated in [16] by moving a subset of nodes to new locations in order to achieve biconnectivity in the network graph. Repositioning

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of a base station and trajectory design of mobile sinks and relays enhances the performance of energy-constrained sensor networks by extending their lifetime [21, 22]. A geometric connectivity robustness metric has been developed that enables consideration of motion constraints imposed by (range-based) connectivity requirements [23]. Finally, [17] presents a self-adaptive distributed feedback control scheme to obtain desirable network properties such as connectivity and power efficiency. Although the goal is to optimize these network parameters, the performance metrics are transformed into position constraints based on a basic energy cost function.

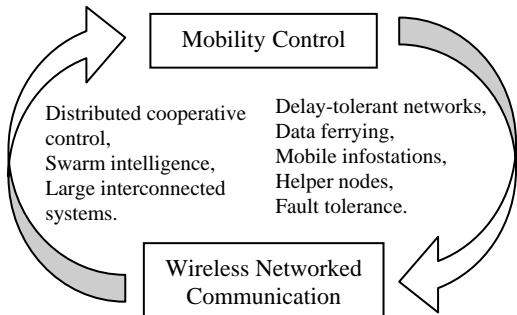


Figure 1. Joint analysis and design of communication and control systems.

Networked communication and mobility play central roles in the performance of cooperating multi-agent dynamic systems. Their interaction can be viewed as a closed loop system in which the status of the communication network determines the performance and stability of the multi-agent system whose motion in turn changes the performance of the communication network (Fig. 1). Both sides of this loop have received attention in different communities. The cooperative control field typically assumes an imposed network, models its performance, and studies the stability of the resulting system. Formal study of distributed cooperative control, swarm intelligence, and networked control systems, rely on this approach. Likewise, the mobile ad-hoc networking community has embraced node mobility within the concepts of delay-tolerant networking, data ferrying, mobile infostations, and fault tolerance.

The fundamental contribution of this paper is the recognition that the well-known Shannon-Hartley law [24] imposes a relationship between SNR, data rate, and insertion delay that unifies several concepts in mobile networking and cooperative control into a single framework. Rather than using simple mobility models in conjunction with the Shannon-Hartley Law to impose range-based connectivity limits to wireless communication, we exploit the continuous variability of data rate with SNR and cast seemingly different scenarios as examples along a continuous spectrum.

II. PROBLEM STATEMENT

In this work we define a delay tolerant network as the set N of network nodes partitioned into two smaller sets, T and H . Set T consists of *task nodes* that are accomplishing some primary task that requires transmission or reception of data packets. Let $t_i \in T, i=1, \dots, n_t$ denote a task node with arbitrary (possibly known) position $\mathbf{p}_i(t) = [x_i(t), y_i(t)]^T$ and speed $v_i(t) = \sqrt{\dot{x}_i(t)^2 + \dot{y}_i(t)^2}$.

The second set H consists of *helper nodes* who collect and relay data from task nodes, and other helper nodes. These nodes have the ability to move to a location between a source and destination node, where it can act as an intermediate relay node. In addition, a helper node can also physically ferry the traffic by moving to the vicinity of a source node, receiving the data, and then carrying the data to the vicinity of a destination node where it transmits it to the destination. The ferry portion adds a significant delay, but at long distances, a ferry can deliver a block of data faster than a weak direct signal. Let $h_j \in H, j=1, \dots, n_h$ denote a helper node with position $\mathbf{p}_j(t) = [x_j(t), y_j(t)]^T$ that evolves according to the dynamical equation $\dot{\mathbf{p}}_j(t) = f(\mathbf{p}_j(t), \mathbf{u}_j(t))$ where $\mathbf{u}_j(t)$ is the control input to node h_j .

For any two wireless nodes in N , let $\mathbf{r}_{kl} = \mathbf{p}_k - \mathbf{p}_l$ represent the position of node k w.r.t node l . The power received at node k from l 's transmission is modeled by the standard empirical model as

$$P_l(\mathbf{r}_{kl}) = \frac{K_{kl}(\mathbf{r}_{kl})}{\|\mathbf{r}_{kl}\|^\alpha} \quad (1)$$

where $\alpha \geq 2$ is the exponential decay of the signal ($\alpha = 2$ is the ideal propagation model in free space) and $K_{kl}(\mathbf{r}_{kl})$ represents the directional gain of the link, and is dependent upon the gain patterns of each antenna, the orientation of direction between the two, the transmitted power, and the quality of the radio electronics used by each node. The noise $N_k(\mathbf{p}_k)$ that a receiver has on its input is dependent upon the quality of the receiver electronics, the noise temperature of the system, the local RF environment of the node, and adversarial or inadvertent jamming. The signal-to-noise ratio at node k of l 's transmitted signal is

$$SNR(\mathbf{p}_k, \mathbf{r}_{kl}) = \frac{P_l(\mathbf{r}_{kl})}{N_k(\mathbf{p}_k)} \quad (2)$$

The problem addressed in this paper is the control of helper nodes to aid the transmission of data between task nodes in a delay tolerant network. Here we restrict ourselves to two stationary (i.e. $V_i(t) = 0, \forall t$) task nodes $[t_1, t_2]$ separated by distance R_r . The nodes wish to transmit data packets of size d (in bits) at a rate of C_i bits per second. We assume the presence of an additional n_h helper nodes capable of collecting and distributing data from the task nodes and other helper nodes in the DTN. The helper nodes have a maximum speed V_h and can carry b bits of data. A subset of

the available helper nodes are deployed with their motion control based on local communication information to maximize network performance in the DTN.

III. SOLUTION APPROACH

Our solution approach uses the well-known Shannon-Hartley Law to model node communication at different ranges (or more precisely as a function of signal and noise power). The Shannon-Hartley Law [24] states that the channel capacity C , which is the theoretical maximum rate at which information passes error free over a channel, is equal to

$$C = B \log_2(1 + SNR) \quad (3)$$

where B is the bandwidth of a signal and SNR is the signal-to-noise ration. Signal power generally decreases with increasing distance, so this model captures the relationship between distance and rate. This is a continuous abstraction to a real channel which uses discrete power levels. It is a theoretical maximum, but, modern coding theory can approach to within a fraction of a dB to this rate.

The assumption of a wireless propagation model which links distance and SNR in the fashion $SNR = k / d^\alpha$ leads to a relationship between data rate and distance

$$C = B \log_2 \left(1 + \frac{k}{d^\alpha} \right) \quad (4)$$

where k is a constant. Hereby, there exists an obvious trade-off between data rate and distance, which can be leveraged for providing improved connectivity of multiple nodes through controlled mobility.

The traditional network control model assumes some fixed communication range within which communication is possible at some rate and beyond which no communication is possible. The model in reality is richer than this. Many digital wireless interfaces such as IEEE 802.11 have multiple data rates [25]. When communicators are close the communication rate is high (e.g. 54 Mbps in 802.11g). When communicators are far the communication rate is lower (802.11g has 14 different rates between 54 and 1 Mbps). The rate decision is based on signal power to noise power ratio (SNR) and packet success measurements made over the channel.

IV. DATA FERRYING

Delay tolerant networks can accomplish a variety of tasks, among others are to aid coordination of flocking swarms of UAVs and to relay data of interest back to a common server node. In a DTN the range from high-rate contemporaneous connections to low-rate, long-delay communication needs to be supported. Hereby the eventual delivery of data is important, not a steady flow of packets. It is sufficient to know an upper bound of time delays. Our variable data rate

communication approach combined with reliable connections established through data ferrying nodes span this spectrum. The following section describes one specific ferry route design model, focusing on throughput and delay metrics, in the fixed and variable data rate framework.

A. Ferry Route Design

The design of efficient ferry routes through a network is important for achieving network and control goals. The following model describes one possible approach of designing ferry movement.

Chain-Relay Model - In this model it is assumed that all participating ferries are distributed along a connecting path from source to destination, forming a chain. The source passes available data on to the first ferry, which physically transports it some way along the path, hands it off to the next ferry, and returns to the source. This hand-off procedure is repeated until the last ferry hands the data to the destination. The throughput in this model, given a fixed wireless data rate R , follows as [26]

$$T_{chain-relay} = \frac{b}{2 \left(\frac{l - (n+1)r}{nv} + \frac{b}{R} \right)}, \quad (5)$$

with l : separation distance between source and destination, r : maximum wireless coverage radius, v : speed of each ferry, b : ferry buffer size, and n ferries in the system. Average packet delay can be expressed as

$$delay_{chain-relay} = \left(1 + \frac{1}{n}\right) \frac{l - (n+1)r}{v} + \left(n + \frac{1}{2}\right) \frac{b}{R}. \quad (6)$$

The chain-relay model performs best with high data rate radios.

B. Variable Data Rate Communications

In this paper we are concerned with the region of Figure 2 when the ferries and nodes are relatively widely spaced. In this regime, $SNR \ll 1$ and we can approximate the Shannon capacity as:

$$R(d) = 1.44W \frac{k}{d^\alpha} = R_0 \frac{d_0^\alpha}{d^\alpha}, \quad (7)$$

where R_0 is the data rate at a reference location d_0 .

Consider a node sending data to a sink. The nodes are separated by distance l . The optimal strategy for a single ferry is for the ferry to start at the midpoint, fly toward the node until its buffer is half full, then fly away from the node. Upon reaching the midpoint, its buffer will be full. Continuing to fly toward the sink, it will start to unload its buffer, until it has unloaded half of its buffer, then fly away from the sink. Upon reaching the midpoint, the rest of the buffer will have been unloaded and the transfer will be complete. In this way, the plane only moves as close to a node as is necessary to complete a transfer.

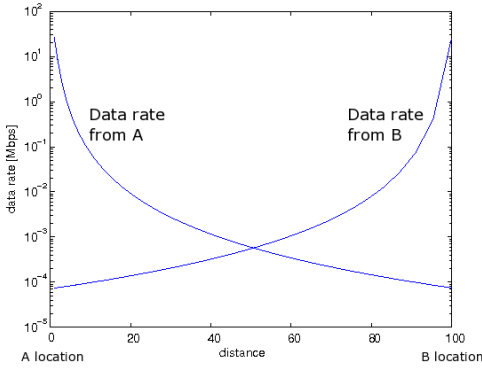


Figure 2. The achievable data rate between a ferry and node as a function of their separation distance for two nodes A and B.

Consider two nodes separated by distance l . When a ferry is at distance y from a node and flying at velocity v , as it moves over a distance dy , it will relay $R(y)dy/v$ bits. So moving from the midpoint to within x of the node it will load:

$$B(x) = \int_x^{l/2} \frac{R_0 d_0^\alpha}{v y^\alpha} dy = \frac{R_0 d_0^\alpha}{v(\alpha-1)x^{\alpha-1}} \left(1 - \left(\frac{2x}{l} \right)^{\alpha-1} \right). \quad (8)$$

Setting $B(x)=b/2$, setting $d_0=l/2$ and solving for x yields;

$$x = \frac{l}{2} \left(\frac{1}{1 + \frac{b(\alpha-1)v}{R_0 l}} \right)^{\frac{1}{\alpha-1}} \quad (9)$$

The cycle time is then

$$T_{cycle} = \frac{2l}{v} \left(1 - \left(\frac{1}{1 + \frac{b(\alpha-1)v}{R_0 l}} \right)^{\frac{1}{\alpha-1}} \right) \quad (10)$$

The time $2l/v$ is the total time for the vehicle to fly from one node to the other and back. The quantity in the brackets is the fractional savings in time because of the transferred data enroute. To better see what is going on, we compute the throughput for the special case of free-space path loss, $\alpha=2$:

$$T = \frac{b}{T_{cycle}} = \frac{R_0}{2} + \frac{vb}{2l}. \quad (11)$$

In this case we see that if v or b are large or R_0 or l are small then the throughput is one buffer per round-trip flight between nodes, $vb/2l$. If v or b are small or R_0 or l are large then the throughput is half the rate at the midpoint, $R_0/2$.

It would be instructive to compare this to the fixed radius communication model. In this model the data rate is R at radius r . Substituting this into the rate model yields $R_0=Rr^\alpha/(l/2)^\alpha$ and:

$$T_{vr} = \frac{2Rr^2}{l^2} + \frac{vb}{2l}. \quad (12)$$

Let T_{vr} be the above throughput with variable rates, and T_{fr} be the fixed radius throughput in. We note that $T_{fr} < R/2$, while T_{vr} is unbounded as v or b increases. In the best case, when $l=2r$, $T_{fr} = R/2$ which is less than $T_{vr} = R/2 + vb/4r$.

While T_{vr} is generally superior, for large l they both have similar throughput of about $vb/2l$.

The superiority of the variable rate model is more pronounced in the case of multiple ferries. In the chain relay, the effective l is shortened with each additional ferry and the communication is more into the regime where the variable rate method dominates. Thus the variable rate model differs qualitatively in that the throughput can always be increased by adding more ferries. Analysis [26] shows that

$$T_{vr} = n^2 \frac{Rr^2}{2l^2} + n \frac{vb}{2l}. \quad (13)$$

V. DATA RELAY: DECENTRALIZED MOBILITY CONTROL

As amount of delay that can be tolerated in the network decreases and the separation of the task nodes relative to the transmission power of the helper nodes shrinks, mobility control transitions from data ferrying to data relaying. In these scenarios, helper nodes position themselves in locations that optimize the end-to-end throughput between task nodes.

The Shannon-Hartley law (Eq. (3)) states that a system must maintain constant SNR in order to maintain constant communication capacity. Thus position-based strategies based on ideal assumptions break down in the presence of unknown noise sources. Under the ideal position-based model, orbit about a node with radius R provides constant capacity. However, the presence of a noise source distorts the SNR field and constant capacity requires tracking of a level set of the distorted field. Using only the measured SNR path gradient, as opposed to relative position, robust radio leashing (when single sensing platform is electronically tethered to a command center to provide constant streaming of sensory data) can be realized through controllers that work in the presence of unmodeled noise disturbances that would otherwise cause position based algorithms to fail [27].

A. Equal Transmission Power

When more than one node must communicate, helper nodes self-organize to form a chain that provides multi-hop link between task nodes. Helper node mobility is determined by local decentralized control algorithms that optimize end-to-end round trip throughput

$$T_{1,n} = \min[T_{1,2}, T_{2,1}, T_{2,3}, \dots, T_{n-1,n}, T_{n,n-1}]. \quad (14)$$

Consider a one-dimensional example in which four helper nodes, labeled h_i , $i=\{2,3,4,5\}$ in order of their position, provide a link between two stationary task nodes t_1 and t_6 , where all nodes have the same transmission power. A linear chain that provides the optimal end-to-end throughput can be achieved by the velocity command

$$u_i = \dot{x}_i = -\lambda \cdot (T_{i,i-1} - T_{i,i+1}), \quad i = \{2,3,4,5\} \quad (15)$$

Where $T_{k,l}$ is the ideal throughput defined by (3). Figure 3 shows the result of a simulation in which the task nodes are separated by a distance of 3000 meters. Because each node has the same transmission power, equal throughput across each node corresponds to equal separation distance.

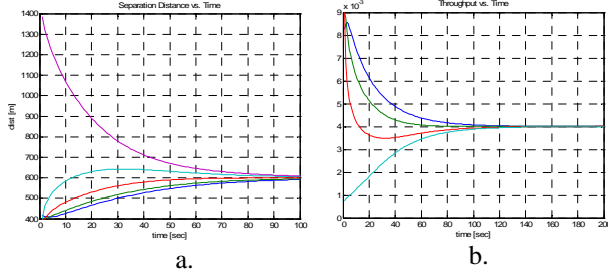


Figure 3. Linear chaining of four helper nodes with equal transmission power. a.) Separation distance between nodes versus time. b.) Node throughput versus time.

B. Unequal Transmission Power

Optimal chaining can also be achieved through decentralized node mobility when helper nodes have uneven transmission power, e.g. due to uneven battery usage. With uneven power transmission, channel capacity between two links is not symmetric, i.e. throughput T_{kl} from node l to node k is not necessarily equal to T_{lk} . Thus, in order to accomplish optimal chaining in this scenario, a new variable L_{kl} called the link capacity is defined

$$L_{kl} = \min(T_{kl}, T_{lk}). \quad (16)$$

Optimal end-to-end throughput is then achieved by the velocity command

$$u_i = \dot{x}_i = -\lambda \cdot (L_{i,i-1} - L_{i,i+1}), \quad i = \{2,3,4,5\}. \quad (17)$$

Figure 4 shows an example simulation where nodes have relative transmission powers $\{0.75, 1.0, 1.0, 4.0, 2.0, 1.0\}$. In this example the link capacities of each node converge to the same value even though the separation distance between pairs does not. In the two example scenarios described above, local decentralized mobility control laws give rise to optimal end-to-end performance of the multi-hop link between two task nodes.

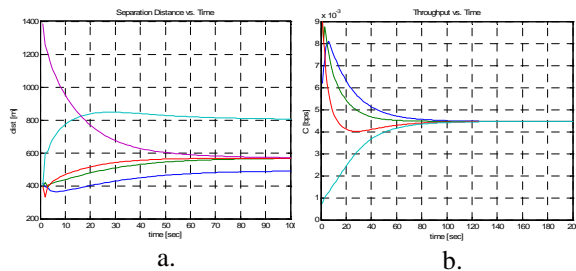


Figure 4. Linear chaining of four helper nodes with unequal transmission power. a.) Separation distance between nodes versus time. b.) Node throughput versus time.

C. Complex Vehicle Model and Interference

The simple decentralized control scheme presented above can be extended to more realistic scenarios. Consider nodes

modeled as UAVs with maximum and minimum velocity bounds that prevent them from stopping at a single location. Each UAV is equipped with a transceiver that measures the SNR at a single point, requiring estimation of the SNR field gradient. Furthermore, noise sources are modeled that include a malfunctioning node that continually broadcasts, causing position-dependent interference.

The continuous motion of the UAV is used to obtain information about the structure of the SNR field. UAV motion is specified as a circular orbit about a control point whose motion is then controlled. The time rate of change of the measured signal-to-noise ratio is related to the path of the UAV and the location of the UAV within the SNR field. This rate of change is known as the path gradient and is given in discrete time as

$$\vec{g}_i[k] = \langle \nabla \bar{S}[k], \Delta \bar{x}[k] \rangle \cdot \Delta \bar{x}[k] \quad (18)$$

where $\langle \cdot, \cdot \rangle$ is the inner product, $\nabla \bar{S}_i[k]$ is some average of the gradient vector over the positions of the node at time index k and $k-1$, and $\Delta \bar{x}[k]$ is the change in position of the UAV over the time interval. Though the UAV can only measure the gradient of the field along the direction of travel, the sum of path gradients over an orbit will point in the direction of the true gradient at the orbit center.

For the motion controller, the control point is treated as point mass acted upon by virtual forces generated by the communication links to nearby nodes. The forces that are applied to the orbit center are generated from the estimated gradient vectors of the SNR fields of nodes neighboring the helper UAV. With \vec{g}_i determined from (18), the force applied to the center point is

$$u_i = f_{virtual} = \sum_{j=1}^n (k \cdot \vec{g}_{i,j}) - b \cdot \vec{v}_i. \quad (19)$$

The parameter b is a virtual damping coefficient that works to remove excess energy from the motion of the control point.

Simulations of the above controller were implemented with radio characteristics taken from measurements made of an 802.11b wireless node used in operation of the Ares UAV in the AUGNet project at CU Boulder [28]. The specific values used for the UAV model are a flight speed of $V_T = 25$ m/s, with a bounded turn rate of $\omega_{max} = 0.22$ rad/s. In the simulation the radio propagation model given in (1) is used where $\alpha = 3.5$, $K_0 = 1$ W $^\alpha$ and $N_j(\bar{x}_j) = N_0 + J(\bar{x}_j)$ where $N_0 = 1e-5$ W and $J(\bar{x}_j)$ represents noise seen by the UAV at its current position in local environment due to a faulty radio so that $J(\bar{x}_j) = P(\bar{r}_{jl})$, where l is the index to the faulty node.

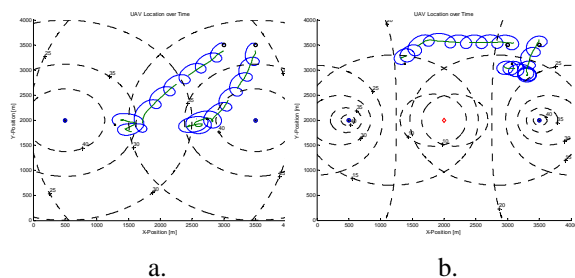


Figure 5. Two-dimensional chaining of two helper nodes to two task nodes. a.) No noise, b.) A low-power noise source in the middle of the task nodes.

Figure 5a shows a scenario with two helper UAVs and no noise sources. The two helper UAVs spiral into loiter patterns evenly spaced between the transmitting task nodes. Figure 5b highlights the failure of position-based methods by including a noise source in between the two main nodes. The final positions shown in Fig. 5a (which would be derived by a position-based method) are clearly not optimal and the control described here achieves better performance by moving the nodes upward and away from the noise (Fig. 5b).

VI. CONCLUSION

The fundamental contribution of this paper is the recognition that the Hartley-Shannon Law imposes a relationship between SNR, data rate, and insertion delay that unifies several concepts in mobile networking and cooperative control into a single framework. Rather than using simple models in conjunction with the Hartley-Shannon Law to imposing range-based connectivity limits to wireless communication, we exploit the continuous variability of data rate with SNR which allows us to cast seemingly different scenarios as examples along a continuous spectrum.

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