RELIABLE BROADCAST IN MOBILE WIRELESS NETWORKS[1]

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ABSTRACT

This paper presents preliminary results of our research on wireless networking that supports reliable communications between nomadic hosts engaged in distributed computing and collaborative conferencing. Our network model consists of a set of low-power, radio frequency (RF) transceivers which move relative to each other across an irregular terrain subject to RF propagation impairments. The low transmitter power defines a radio coverage which limits the probability of intercept and the number of neighbors but optimizes frequency reuse. The combination of low power and propagation environment produces a network characterized by stochastic link failures. The rapidity of these failures and perturbations to the network topology defeats the use of routing policies based on maintaining routing tables or determining least cost paths. With these conditions as the background, our work addresses the need to provide reliable information exchange, mitigate bottlenecks, avoid excessive traffic, and offer scalable services without the benefit of static base station or fixed backbone support. Meeting such challenges demands a robust, flexible information transport system that delivers all required information for diverse operational scenarios. The approach emphasizes the importance of achieving guaranteed delivery across a network of limited size operating in a hostile environment rather than obtaining a high throughput per unit area, typical of commercial enterprises.

The basic premise of the protocol is that host mobility and terrain prevents *a priori* knowledge of any host location and optimum path. Message broadcasting, or flood routing, provides the means for reliable delivery of information in the presence of uncertain connectivity and node locations. Knowledge of the network results, instead, from a measure of transmitted and received message traffic. Central to the protocol is the provision for each mobile host to retain a *HISTORY* of messages broadcast to and received from its neighbor(s). A host which receives a message broadcasts an acknowledgment to the sender, updates its local *HISTORY*, and then retransmits the message if it is not a duplicate message. Duplicated messages are discarded. If a sending host does not receive an acknowledgment from a neighbor within a certain time, it timeouts and resends the message. If a host does not receive an acknowledgment after several retries, it assumes that the link disconnection is not transient and stops sending the message. When a host detects a new neighbor, a handshake procedure results in the exchange of active messages not common to the respective *HISTORY* of each host. Once the handshake procedure terminates, the contents of the *HISTORY* for each host are identical. Thus, using handshake procedures, mobile hosts receive messages that they did not receive previously due to link disconnections. Idle hosts will periodically broadcast a sounding message to maintain their network presence.

1. INTRODUCTION. Winning the information war with complete and up-to-date intelligence is vital to the entire spectrum of possible operational requirements, whether engaged in war or corporate strategic planning. Military commanders engaged in rapid force projection, as well as public safety officers, medical staff, and corporate managers, demand accurate information regardless of location or situation. Each requires a clear and accurate picture of a changing situation to reach well-informed decisions and successful conclusion. Information must flow throughout the network toward the users at each level of the management hierarchy whether at the sustaining base or at the forward most part of the mission. Participating staff must have the capability to acquire or send accurate information that defines their space and situation. The information transport network must extend reliable voice, data, video, and imagery transmissions to nomadic users at any location. The availability of assured communications directly relates to mission success through computing, conferencing, and synchronized tasking while fixed or on-the-move. Invariably, this critical information is required when communications services normally provided by a reliable,

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fixed infrastructure are unavailable or severely degraded.

The wireless networking of mobile (i.e., nomadic) subscribers is an emerging paradigm in the field of distributed command, control, and computing, with the potential to improve command and control responsiveness. In our context, the phrase "mobile wireless network" means that the network does not contain any static support stations. This network model supports the needs of subscribers to mobile command posts and mobile satellite ground entry points. In this role, the network must provide reliable information transfer, mitigate bottlenecks, avoid excessive traffic, offer scalable services, and, above all, adapt to dynamic topologies. The RF coverage area should conform as closely as possible to the area over which subscribers move, thereby offering a low probability of detection and improving frequency re-use. Low-cost implementation and operation are critical.

Nomadic wireless networks currently are characterized by limited bandwidth and frequent changes in link connectivity. The challenge is to allow updates from multiple users simultaneously, but only for those users that require the service. The major requirements include the capability to: minimize updates, provide fault-tolerant service, provide service scalability, and minimize communication and computation overhead. Many of the algorithms that assume static hosts or well-defined point-to-point links cannot be directly used for mobile systems due to the changes in physical connectivity and limited bandwidth of the wireless links. This has spawned considerable research in mobile computing: designing communication protocols [1, 2, 3, 4], file system operations [5, 6], managing data efficiently [7, 8], and providing fault tolerance [9]. Most research on these topics is based on a model in which the mobile hosts are supported by static base stations such as cellular telephony or personal communications systems (PCS). A typical PCS topology takes the form of a single-hop network in which each host is within radio range of the base station or all other hosts. In this paper, we consider the problem of providing reliable broadcast in mobile wireless networks where single-hop and known topologies may not exist. Applications include disaster relief operations, highly mobile military or law enforcement operations, and rapid response contingency operations where it is not economical to place support stations.

2. WIRELESS NETWORK MODEL. The model of the mobile wireless network consists of several mobile hosts distributed over an irregular terrain (Figure 1). The mobile hosts use low-power transmitters and novel, efficient receivers [10] to communicate. Emerging technologies and products for PCS applications that operate in the ISM bands with a transmitter power of 1W [11] provide the basis for practical implementation. In this network concept, the *cell* of a mobile host is the geographical area within which the mobile hosts can directly communicate with other mobile hosts. Note that the cell of a host does not remain fixed, but moves with each attached host. The nominal cell size (R) is determined by a path loss model that denotes the *local average* received signal power relative to the transmit power. A general path loss (PL) model that has been demonstrated through measurement uses a parameter $2 \leq \mu \leq 5$ [12] to denote the power law relationship between distance and received power. Based on both analysis and measured results, $\mu \approx 4$ for the microcell propagation environment beyond a characteristic distance R_o. The power law model takes the form [13]:

$$PL(R) = PL(R_o) + 10\mu \log(R/R_o) + X_\sigma \qquad \textbf{(1)}$$

where $PL(R_o)$ gives the power loss at the characteristic distance R_o and X_σ denotes a zero mean Gaussian random variable that reflects the fluctuations in average received power. Nelson and Kleinrock [14] show that for a slotted ALOHA network protocol, the optimum throughput occurs with a cell size defined by a range that includes an average of six nearest neighbors. Their results are reproduced in Figure 2. These results assume a random distribution of nodes across the terrain and a perfect capture condition. Perfect capture occurs when a node will always receive and detect the strongest of several simultaneous transmissions within its hearing range. The weaker signals appear as noise to the detection process. A non-caputre condition occurs if simultaneous transmissions always result in collisions. The reduced power supports frequency reuse, as well as low probability of detection. Their analysis also shows that mobile hosts with sufficient

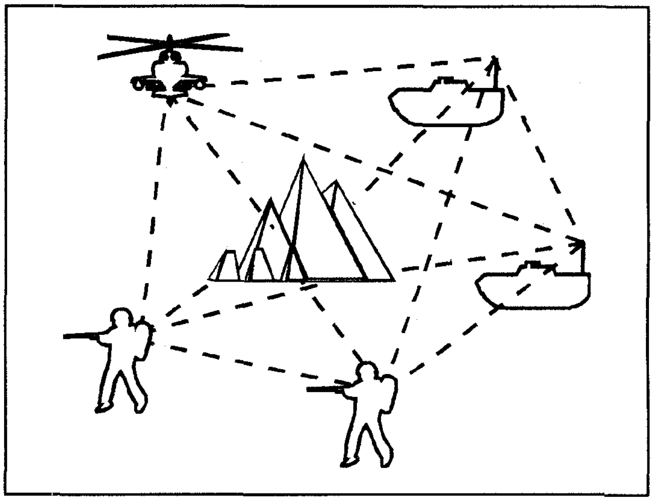

Figure 1. Model of a wireless computer network that experiences link failures due to range limitations and terrain impairments.

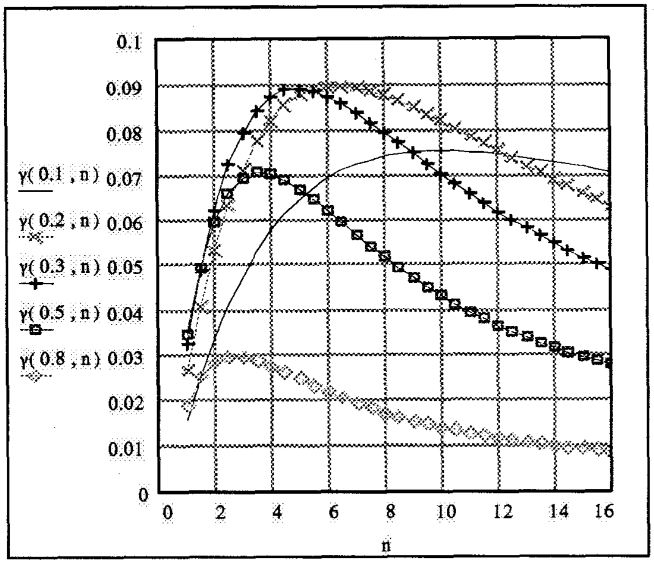

Figure 2. Normalized throughput for perfect capture with the slotted ALOHA protocol versus the average number of nearest neighbors for different probabilities that a node is busy.

transmitter power to reach all other hosts (i.e., a single-hop network) support a significantly lower throughput.

Detecting Neighbors. Neighbors are detected by a strategy common to a general class of survivable and adaptive network protocols that use sounding procedures [15, 16]. Two mobile hosts are *neighbors* if they can "hear" each other. Each host detects its neighbors by periodically broadcasting a probe message. A host that hears a probe message sends an acknowledgment to the probing host. Every host maintains a list of neighbors and periodically updates the list based on acknowledgments received. When two hosts become neighbors, a wireless link is established between them, and they execute a *handshake* procedure. As part of the handshake procedure, they each update their list of neighbors.

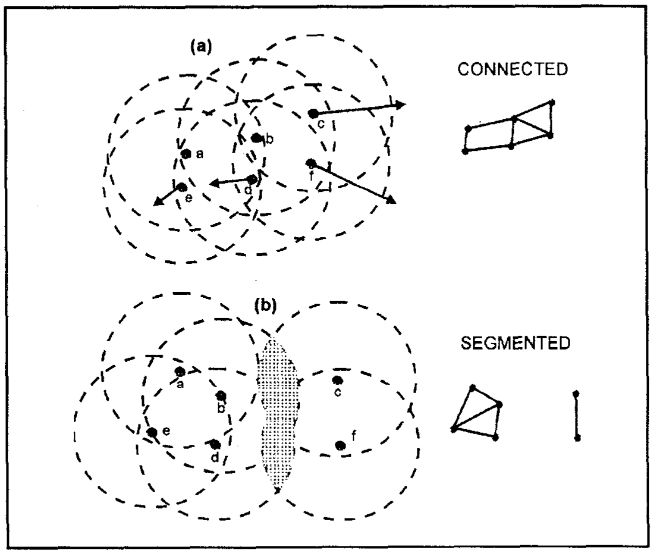

Figure 3. Examples of (a) a fully connected mobile wireless network and (b) a decomposed network due to mobility of hosts *c* and *f*. The shaded region indicates the common area within the range of hosts *c* and *f* and the rest of the network.

Link Disconnections. The wireless link between two neighbors is unreliable due to RF propagation effects such as loss of line-of-sight (LOS), moving out of range, multipath fading, or inclement weather. There are two types of link disconnections: (1) transient and (2) permanent. In the transient case, a host is unable to communicate briefly with a neighbor due to: (a) the neighbor moving out of sight; (b) multipath fading; or (c) inclement weather. Multipath fading has a time dependence that varies from microseconds to seconds, depending on the terrain and the host velocity [17]. Fade depths range up to 20 dB. The stochastic behavior of such transient link disconnections is very similar to that encountered for high frequency radio networks [18]. In the permanent case, a host is unable to communicate with a neighbor because their separation exceeds the range described by the cell geometry. We assume that each mobile host can communicate with an arbitrary mobile host in its cell without any interference (from other mobile hosts in the same cell) using techniques such as TDMA or code division multiple access (CDMA) spread spectrum signaling. One such technique is presented in [16].

3. BROADCAST CONSIDERATIONS. Terrestrial networks provide the means to manage RF spectrum utilization to minimize the inherent latency for transmission, the probability of detection, and the cost of utilization not afforded by satellite services. Reliable broadcast in a mobile wireless network is not easy due to the following reasons: (1) It may be difficult to maintain a convenient structure (spanning tree, virtual ring) for broadcasting because of the mobility of hosts and the absence of an established backbone network. While an adaptive algorithm can be used to maintain the structure, the small cell size leads to cases where two neighbors may frequently move out of each others' range leading to the invocation of the adaptive algorithm frequently. (2) The wireless network itself may not be connected always (see Figure 3). They may be decomposed into several connected components for a while and merge after some time (we assume "quite often"). We also assume that permanent disconnections do not occur. In the next section we present a preliminary solution for reliable broadcast in mobile wireless network. Our solution is based on simple (restricted) flooding and handshaking.

Flooding ultimately involves transmitting the message to every node in the network, which is a disadvantage, particularly for large networks. The main advantage of flooding is that there is little explicit overhead and network management. As a consequence, no provisions are made to store or maintain routing or management data. Instead, hosts keep track of individual messages received and determine whether or not to retransmit the message. It is well suited to network requirements for highly mobile user groups on the digitized battlefield or in disaster relief operations where there is a need for reliable delivery in the presence of uncertain connectivity and rapid topology changes [19].

4. BROADCAST PROTOCOL. To broadcast a message, a mobile host transmits the message to all of its neighbors. On receiving a broadcast message, an intermediate mobile host retransmits the message to all of its neighbors. The technique would suffice if the network remained connected forever. Additional steps are necessary to cope with network link disconnections.

For example, mobile host h_i maintains a sequence counter, CNT_i. At any instant, the value of CNT_i denotes the number of messages broadcast by host h_i. CNT_i is incremented when h_i is about to broadcast a new message. In addition, host h_i maintains a history of messages ($HISTORY_i$) it has broadcast as well as received from other hosts. The j^{th} component of $HISTORY_i$ contains information about messages broadcast from h_i and received from h_j. A rebroadcast count and a time stamp provide the means to limit the propagation of the message in a large network.

A sample pictorial representation of $HISTORY_i$ is shown in Figure 4. Host h_j has received messages 1 and 4, but not messages 2 and 3. Similarly, h_k has received messages 2 and 4 from h_k, but not messages 1 and 3. It is easy to maintain *HISTORY*, for each *h*, as an array of lists. We now describe our solution for reliable broadcast.

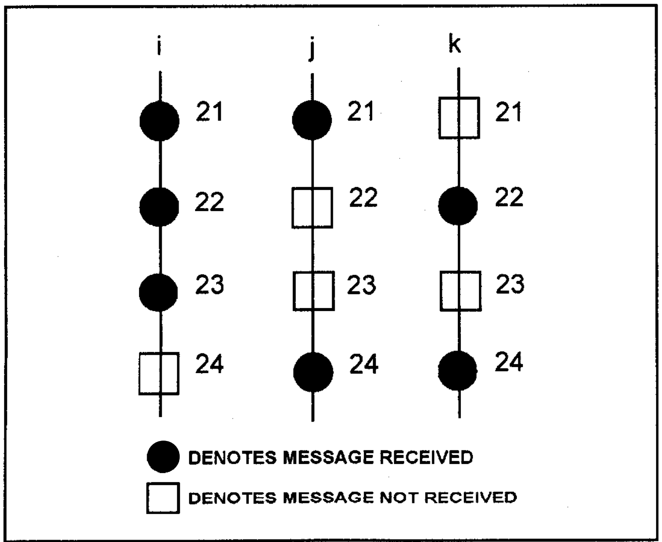

Figure 4. A snapshot of the status of the $HISTORY_i$ showing messages stored in h_i, h_j and h_k.

Normal Operation. Let us assume that host h_i wants to broadcast message m. The following occurs:

- Host h_i first increments CNT_i and then transmits message (m , h_i, CNT_i) to all neighbors. It also stores (m , h_i , CNT_i) in a buffer locally.
- When host h_j receives message (m , h_i , CNT_i), it sends an acknowledgment to the sender, updates the i^{th} component of $HISTORY_j$ and buffers the message locally. Host$_j$ h then retransmits the message (m , h_i , CNT_i) to its neighbors.
- If h_j receives another copy of (m , h_i , CNT_i), it discards the message, but sends an acknowledgment to the sender.
- A mobile host *h*, after sending a message (m , h_i , CNT_i) to its neighbors, waits for acknowledgments from all of its neighbors. If *h* does not receive acknowledgment from a neighbor within a certain time, *h* timeouts and resends the message (with a hope that link disconnection is transient). If *h* does not receive acknowledgment after several retries, *h* assumes that the link disconnection is not transient and stops sending the message.

During periods of heavy message exchange activity, this strategy substitutes for the polling or sounding procedure described in Section 2.

Handshake Procedure. When host h_j detects a new neighbor, h_k, a handshake procedure is executed by hosts h_j and h_k:

- h_j sends $HISTORY_j$ to h_k and receives $HISTORY_k$ from h_k.
- h_j compares $HISTORY_k$ with $HISTORY_j$ to identify messages available in $HISTORY_j$, but not in $HISTORY_k$, and broadcasts those messages. Host h_k does likewise.
- h_k then receives the "new" messages send by h_j and updates $HISTORY_k$. h_j does the same for messages received from h_k. also sends these "new" messages to other neighbors.

At the conclusion of the handshake procedure, the contents of $HISTORY_j$ and $HISTORY_k$ are equal. Thus, using handshake procedure, mobile hosts receive messages that they did not receive due to link disconnections. The size of *HISTORY* stored at each *h* can be reduced as follows. If the first message received by h_j from h_k is CNT_k=t then it is sufficient for the k^{th} component of $HISTORY_i$ to start from *t*. Storage for entry of messages 1 to *t* - 1 need not be provided. Further optimization can be done by storing either the *HISTORY* of messages received or the *HISTORY* messages not received depending on which list is smaller.

5. CONCLUSIONS AND FUTURE WORK. We have presented a protocol model designed to achieve assured delivery of information in a multi-hop nomadic wireless network. To mitigate a handicap of flood routing, the protocol includes a mechanism to restrict the retransmission of messages. The protocol accounts for the temporary separation of a node, or node segments, from other network members. Our continued research is devoted to methods which improve the protocol efficiency given the limitation of flood routing. In order to reduce the size of the buffer at each mobile host, a buffered message can be deleted after it is received by all the hosts. For each message a host receives, the host sends an acknowledgment to the sender of the message. Once acknowledgments from all hosts have reached the originator, the originator can direct the hosts to delete the message from the buffer [2]. To this end, we may have to broadcast and buffer acknowledgments also, which will increase the overhead. One of our objectives is to design an efficient acknowledgment policy that does not adversely increase the congestion and storage required at each host. Another option in deleting the buffered messages is to use timeouts, but this may not be suitable in critical applications where messages cannot be lost. Also the timeout period has to be chosen carefully (incorporating the mobility and link disconnections) so that the probability of message loss is very low. Some related research issues are: (1) deriving the necessary conditions, with respect to the host mobility pattern for our protocol to work; (2) identifying structures that are easy to maintain and are suitable for broadcasting; and (3) designing efficient routing schemes for unicasting messages.

We are investigating the efficiency and performance characteristics of survivable and adaptive network protocols with computer simulation techniques. Preliminary results will be reported on the evaluation of the algorithm in terms of message delay and acknowledgment overhead for different network sizes and routing restrictions. Our preliminary results indicate the viability of the message management protocol for collaborative computing in a dynamic computer network topology when the reliability of information is paramount.

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