Mobile Ad Hoc Data Networks for Emergency Preparedness Telecommunications - Dynamic Power-Conscious Routing Concepts

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I. Introduction

In the next generation of wireless communication systems, there will be a need for the rapid deployment of independent mobile users. Significant examples include establishing survivable, efficient, dynamic communication for emergency/rescue operations and disaster relief efforts, e.g., the bombing of the Oklahoma City Federal Building, or the aftermath of a hurricane where cellular/PCS service may not be available. Typically, emergency/rescue communication is centralized, and the network is dependent on proper function of the central controllers. If the centralized infrastructure were to fail due to a disaster or any other reason, the network may collapse. Hence, advances in wireless communication should aid in making emergency preparedness systems and disaster relief networks robust and autonomous, and provide for reliable and secure inter-group communication.

Rescue operations and disaster relief scenarios cannot rely on centralized and organized connectivity, and can be termed as wireless mobile ad hoc networks (MANETs) for emergency telecommunication. A MANET is an autonomous collection of mobile nodes that communicate over relatively bandwidth-constrained wireless links. Each node is equipped with wireless receivers and transmitters using antennas that may be omni-directional, highly directional, or possibly steerable. Since nodes are mobile, the network topology may change rapidly and unpredictably over time. The network is *decentralized*, where all network activity including discovering the topology and delivering messages must be executed by the nodes themselves, i.e., routing functionality will be incorporated into mobile nodes. A MANET for emergency telecommunication may operate in a stand-alone manner or be connected to a larger network.

The set of applications for emergency MANETs is diverse, ranging from small, static networks that are constrained by power sources, to large-scale, mobile, highly dynamic networks. The design of network protocols for these networks is a complex issue. Regardless of the application, emergency telecommunication MANETs need efficient distributed algorithms to determine network organization (connectivity), link scheduling, and routing. However, determining viable routing paths and delivering messages in a decentralized environment where network topology fluctuates is not a well-defined problem. While the shortest path (based on a given cost function) from a source to a destination in a static network is usually the optimal route, this idea is not easily extended to MANETs. Factors such as variable wireless link quality, propagation path loss, fading, multiuser interference, power expended, and topological changes, become relevant issues. An emergency telecommunication network should be able to adaptively alter routing paths to alleviate any of these effects in order to maintain the performance and dependability of the network.

In this report, we focus on the Network Layer operation of *routing* and implications of power consumption for emergency MANETs. We discuss the benefits of power consciousness and conduct an initial investigation on the effects of energy-efficient wireless routing in MANETs. We develop an initial dynamic power-conscious routing scheme (minimum power routing - MPR) that incorporates physical layer and link layer statistics to conserve power, while compensating for the propagation path loss, shadowing and fading effects, and interference environment at the intended receiver. The main idea of MPR is to select the path between a given source and destination that will require the least amount of total power expended, while still maintaining an acceptable signal-to-noise ratio (SNR) at each receiver. A "cost" function is assigned to every link reflecting the transmitter power required to *reliably* communicate on that link. Routing decisions and cost updates are made based on feedback or information extracted from the received signal and special control packets. As an initial approach, we use the distributed Bellman-Ford algorithm to perform "shortest" path routing with the cost functions as the link distances. The resulting "shortest path" is the MPR path from a given source to a destination. We compare the performance of MPR to the common routing protocols of shortest distance routing with power control (SD-PC) and minimum hop routing with power control (MH-PC), and present our preliminary results.

II. Benefits of Power Consciousness

In an emergency telecommunication scenario, power may be supplied to static nodes through a generator, while mobile nodes operate off a battery supply. Clearly, a vital issue for emergency MANETs then is to conserve power while still delivering messages reliably, i.e., achieving a high packet success rate. This can be accomplished by altering the transmitter power of the emergency telecommunication nodes to use just that amount needed to maintain an acceptable SNR at the receiver. Reducing the transmitter power allows spatial reuse of the channel and thus, increases network throughput [1]. Using power control in an emergency situation mitigates the multiuser interference since a transmission will not interfere with as many nodes. This will increase the number of emergency or rescue mission nodes that may communicate simultaneously. Altering the transmission power also reduces the amount of interference caused to other emergency preparedness telecommunication networks or any other wireless network operating on adjacent radio frequency channels. In networks where nodes operate on battery power, e.g, hand-held radio being used by a rescue worker, conserving power is crucial since battery life determines whether a network is operational or not. For certain emergency telecommunication MANET applications - for example, hostage situation or terrorist attack - it is desirable to maintain a *low probability of intercept* and/or a *low probability of detection* [4]. Hence, rescue mission nodes would prefer to radiate as little power as necessary and transmit as infrequently as possible, thus decreasing the probability of detection (or interception).

The benefits of power conservation/control for emergency MANETs prompt the important question: What is the most power efficient way to route a packet from a source to a destination such that the packet is received with an acceptable packet success rate [5]? Since channel conditions and multiuser interference levels in an emergency situation are constantly changing with time, the transmitter power necessary on a particular link must be determined dynamically.

Previous research in the area of routing for MANETs has focused on establishing routes between different source and destination pairs (protocols proposed in the Internet Engineering Task Force - MANET Working Group). A connection between two nodes is considered either "present" or "absent" depending on if the distance between the nodes is less than or greater than a *threshold* distance. All links that are "present" are regarded as having the same link quality. This is a generalization (assumption) since the quality of any particular link depends on its location and surroundings. It is known that a node can exhaust its power supply trying to communicate reliably over a link that has a severe fade. Moreover, a centrally located node may experience excess traffic and multiuser interference. Communicating through this node may be inefficient and require many retransmissions, thereby expending more power. More recently, in [7], Wieselthier, Nguyen, and Ephremides addressed the problem of power conservation in the context of wireless multicasting, and in [3], Pursley, Russell, and Wysocarski considered this problem in a frequency-hopping ad-hoc network.

III. Power-Conscious Routing

There are clear benefits to conserving power in emergency telecommunication MANET applications, as discussed in Section II. In this Section, we develop a new power conscious routing concept for MANETs.

A. System Model

Consider a transmitter communicating with a receiver at a distance of r_0 in a MANET. As the transmitted signal propagates to the receiver, it is subject to the effects of shadowing and multipath fading, and its power decays with distance, i.e., $P_R \propto KFP_T r_0^{-\eta}$, where K is a constant, F is a non-negative random attenuation for the effects of shadowing and fading, P_T is the transmitter power, and η is the path loss exponent. At the receiver, the desired signal is corrupted by interference from other active nodes in the network. We assume that nodes know the identity of all other nodes in the network and the distances to their immediate neighbors, i.e., nodes that are within transmission range. Interfering nodes use the same modulation scheme as the transmitter and nodes can vary their transmit power up to a maximum power P_{max}. We assume that the multiuser interference is a Gaussian random process. At the receiver, the decoder maintains an estimate of the average SNR.

B. Minimum Power Routing Concepts

The aim of MPR is to route a packet on a path that will require the least amount of total power expended and for each node to transmit with just enough power to ensure that the transmission is received with an acceptable bit error rate Υ. Threshold Υ is a design parameter and may be selected according to the network performance desired. Let $\mathcal{E}$ be the bit-energy-to-noise-density ratio, $\mathcal{E}_b/\mathcal{N}_{0_{eff}}$, necessary at a node to achieve Υ.

Without loss of generality, consider a transmission from node i to node j, where $i \neq j$, and $i, j \in \{1, \ldots, N\}$, where N is the number of nodes in the network. The received $\mathcal{E}_b/\mathcal{N}_{0_{eff}}$ is given by

$$\left[\frac{\mathcal{E}_b}{\mathcal{N}_{0_{eff}}}\right]_{ij} = \frac{P_{R_{ij}}/D}{\mathcal{N}_0 + P_{I_{ij}}/W}, \tag{1}$$

where D is the data rate in bits per second, W is the system bandwidth in Hertz, $\mathcal{N}_0/2$ is the power spectral density of the thermal noise, $P_{I_{ij}}$ is the power of the interference at node j due to all nodes excluding node i, and $P_{R_{ij}}$ is the received power at node j due to node i. From the description in Section III-A, it follows that the received power is given by

$$P_{R_{ij}} = KF_{ij}P_{T_{ij}}r_{ij}^{-\eta}, \tag{2}$$

where $P_{T_{ij}}$ is the transmitter power used at node i to communicate with node j, F_{ij} is a non-negative random attenuation for the effects of shadowing and fading on link $\overline{ij}$, and r_{ij} is the distance between node i and node j. Substituting (2) into (1), we obtain

$$\left[\frac{\mathcal{E}_b}{\mathcal{N}_{0_{eff}}}\right]_{ij} = S_{ij}P_{T_{ij}}r_{ij}^{-\eta}, \tag{3}$$

where

$$S_{ij} = \frac{KF_{ij}}{D(\mathcal{N}_0 + P_{I_{ij}}/W)}, \tag{4}$$

may be interpreted as a dynamic *link scale factor* reflecting the current channel characteristics and interference on link $\overline{ij}$. These scale factors reflect a link's most recent reception environment. Note that $S_{ij} \neq S_{ji}$ since channel conditions are not symmetric.

It is desirable for $[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]_{ij}$ to equal the energy ratio $\mathcal{E}$, since this is the minimum $\mathcal{E}_b/\mathcal{N}_{0_{eff}}$ necessary to achieve the bit error rate Υ. Hence, with knowledge of scale factor S_{ij}, node i can easily determine the power $P_{T_{ij}}$ necessary to achieve this goal using Eq. (3), i.e.,

$$P_{T_{ij}} = \frac{\mathcal{E}}{S_{ij} r_{ij}^{-\eta}}. \tag{5}$$

Let $\overline{[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]}_{ij}$ be an estimate of the received bit energy ratio at the output of the decoder at node j. Many methods may be used to determine $\overline{[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]}_{ij}$, e.g., using side information by embedding known test symbols in packet transmissions [2]. Although $P_{T_{ij}}$ was selected to achieve energy ratio $\mathcal{E}$ at the receiver, since network conditions are changing, the actual received $[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]_{ij}$ may differ from $\mathcal{E}$. If node j has knowledge of the transmitter power $P_{T_{ij}}$ (which can be accomplished by including $P_{T_{ij}}$ in the packet header), it can update its estimated scale factor using a smoothing function as follows,

$$\hat{S}_{ij} = (1-\alpha) \cdot \frac{\overline{[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]}_{ij}}{P_{T_{ij}} r_{ij}^{-\eta}} + \alpha \cdot \hat{S}_{ij} \ , \tag{6}$$

which mitigates the fluctuations due to multiuser interference (and α is a smoothing factor). An initial value for $\hat{S}_{ij}$ may be computed as described in Section III-C. The estimated link scale factor $\hat{S}_{ij}$ accounts for variable channel conditions and for all types of Gaussian interference, e.g., multiuser interference and partial-band jamming. If the received bit error rate Υ_{ij} on link $\overline{ij}$ is less than threshold Υ, the effect of (6) is that node j *decreases* its link $\hat{S}_{ij}$ value, indicating an *increase* in its interference (noisy channel) level, and thus, an *increase* in the power necessary to communicate on link $\overline{ij}$ as computed by (5). The opposite behavior occurs when Υ_{ij} is greater than Υ.

Each time node j receives a packet from a node i, it computes and stores a value for $\hat{S}_{ij}$ that accurately reflects its current SNR on link $\overline{ij}$. We assume that the rate of change of the network is much slower than a packet transmission interval, and hence the value for $\hat{S}_{ij}$ is valid for many packet transmissions.

For every pair of nodes i and j, a cost C_{ij} given by

$$C_{ij} = \begin{cases} P_{T_{ij}}(1+\kappa) & \text{if } P_{T_{ij}}(1+\kappa) \leq P_{max}, \\ \infty & \text{otherwise,} \end{cases} \tag{7}$$

is assigned, where κ is a dampening constant to inhibit oscillations. The inequality in (7) is necessary since the transmitter power is limited by P_{max}. The cost C_{ij} is the power necessary to communicate from node i to node j to compensate for channel conditions and interference. Since nodes only know *estimates* of the link scale factors, the power required on a link must be overplayed. Thus, κ provides an extra margin for the transmission power and is a design parameter that must be selected. As an initial approach, the distributed Bellman-Ford algorithm can be used to perform "shortest" path routing with the C_{ij}s as the link distances. The resulting "shortest path" is the MPR path from a given source to a destination. If there is more than one path with the same minimum total cost, the MPR path is chosen as the one with the smallest maximum cost on any one link. MPR avoids congested areas and is also *minimax* optimal, i.e., given some uncertainty in the link scale factors, it minimizes the worse case total path cost.

C. Network Implementation

Initially, nodes transmit using power P_{max}, and the cost of every link is set to a constant d, where $d = P_{max}(1+\kappa)$. This will result in nodes initially routing packets according to the *minimum number of hops* to the destination. The first time node j for $j \in \{1, \ldots, N\}$, receives a transmission from another node, say node i, it will compute its link scale factor $\hat{S}_{ij}$, i.e,

$$\hat{S}_{ij} = \frac{\overline{[\mathcal{E}_b/\mathcal{N}_{0_{eff}}]}_{ij}}{P_{max}\ r_{ij}^{-\eta}}. \tag{8}$$

The link costs will be computed as described in Section III-B and propagated throughout the network. If the cost of a particular link has not yet been computed within a specified amount of time because no data packet was transmitted on that link, a "boost" packet is transmitted on the link and the link cost is computed. Once all of the link costs have been computed, the routing protocol is now MPR.

The MPR path costs must be periodically circulated around the network. This information can be passed around via data packets, acknowledgments, and special control packets known as packet radio organization packets (PROPs) [6]. For this initial implementation, we assume an underlying information dissemination scheme.

A dynamic routing table is maintained by each node. For each destination, a node stores the outgoing link for the most power-efficient route and the corresponding path cost, distance to the destination, and the necessary transmitter power. Since network conditions are changing, routing tables are continually updated based on an *update interval*, and the transmission power is altered on a per packet basis according to Eq. (5). Before an update, if a link cost is deemed *out-dated*, i.e., the cost has not been recomputed within a specified interval before an update, a "boost" packet is transmitted on that link in order to compute a current link cost.

IV. Performance of Power Conscious Routing

We compare the performance of MPR to that of SD-PC and MH-PC, and present our preliminary results. The transmission power for SD-PC and MH-PC is altered to overcome the distance between the transmitter and intended receiver. We use the modeling and simulation tool OPNET to build a network prototype and execute the simulations. We assume a MANET using the ALOHA random access protocol. We consider a slow fading (log-normal shadowing) environment, and vary the random attenuation effects on a link every T_S seconds according to a β correlation factor. We assume that a node has knowledge of the transmitter power used to communicate with it and hence, uses (6) to update the estimate of its link scale factor. A list of the simulation parameters is given in Table I.

Performance measures of *end-to-end throughput*, *end-to-end delay*, *efficiency*, and *average power expended* are used to analyze the performance of the routing protocols. End-to-end throughput is defined as the number of packets that successfully reach their final destination per unit time. End-to-end delay is based only on successful packets and is defined as the average time required for a packet to arrive at its destination. Efficiency is the number of received data packets divided by the total number of data packets and control packets transmitted. Average power expended is the average power consumed in the network relaying successful packets (including necessary control packets) from their source to their final destination per unit time.

First, we consider a 16 node static network with packet generation rate $\rho = 10$ packets/second/node and a total of $10,000$ packets being exchanged. The routing table update interval is $10s$, and the shadowing parameters are $\beta = 0.8$ and $T_S = 5s$. From Table II, we see that MPR achieves approximately *double* the throughput for similar power consumption levels, or alternatively, requires approximately 2.5 times *less* power for similar throughput levels. The overall end-to-end delay is comparable for all schemes. While MPR does not optimize on the number of hops, it routes around undesirable links and hence, requires overall lower power consumption.

Parameter	Value
Network area	900 m x 600 m
Data rate	1 Mbps
Max TX power/range	500 mW/250 m
Min frequency	2.4 GHz
Bandwidth	83 MHz
Modulation	Direct-Sequence BPSK
Processing Gain	20 dB
Packet length	100 bits
Shadowing	$10 \log F \sim N(0, 64dB^2)$
Υ, η, α, κ	3×10^{-4}, 2.6, 0.8, 0.2

Table I: Network simulation parameters.

Next, with the same network configuration, we vary the packet generation rate ρ and plot the efficiency and average power expended in Figures 1 and 2 respectively. We see that as ρ increases, the efficiency increases until the point where further packet generation causes excess levels of network traffic, and thus, a decrease in efficiency. MPR achieves approximately double the efficiency as SD-PC and MH-PC for low values of ρ and approximately

Measure	MPR	SD-PC	SD-PC	MH-PC	MH-PC
Hops	30682	24945	15321	25075	17485
Overhead	0.0077	0	0	0	0
Pk delay*(μs)	28.5	24.5	26	24.8	27.6
Pk pwr*(mW)	305	660	279	702	266
Hop pwr*(mW)	91.3	244	94.1	255	91.3
Efficiency	0.95	0.92	0.51	0.92	0.6
Thruput (pk/s)	9.58	9.2	5.15	9.13	5.7

Table II: Simulation results for a 16 node static network. (* *mean* value of three trials)

a striking 4.5 times higher efficiency for larger values of ρ, since MPR adapts to changing interference levels. For low values of ρ, MPR utilizes from $30\% - 50\%$ less power relaying successful packets than SD-PC and MH-PC. For higher values of ρ, although MPR utilizes approximately $50mW$ more power than SD-PC and MH-PC, since both MH-PC and SD-PC achieve low efficiency, most of the total power expended in those schemes is on unsuccessful transmissions.

Finally, we introduce mobility into the network with nodes moving at a speed of $4m/s$ and investigate the effect of different routing table update intervals on MPR. The packet generation rate is $\rho = 10$ packets/second/node. In Figure 3, we plot the network efficiency verses update interval frequency (s). We consider the efficiency of only data transmissions, and the global efficiency of both data and control packets, i.e., data packets received divided by total communication packets - both data and control. We see that as the update interval decreases, the data efficiency increases since the routing information utilized is more current. However, the global efficiency increases until it reaches a point where further updates cause too much overhead communication, and hence, a decrease in network efficiency. Clearly, there is a trade-off between utilizing current routing information and the communication overhead generated. It is our conjecture, that the optimum update interval is the same as the slow fading duration T_S.

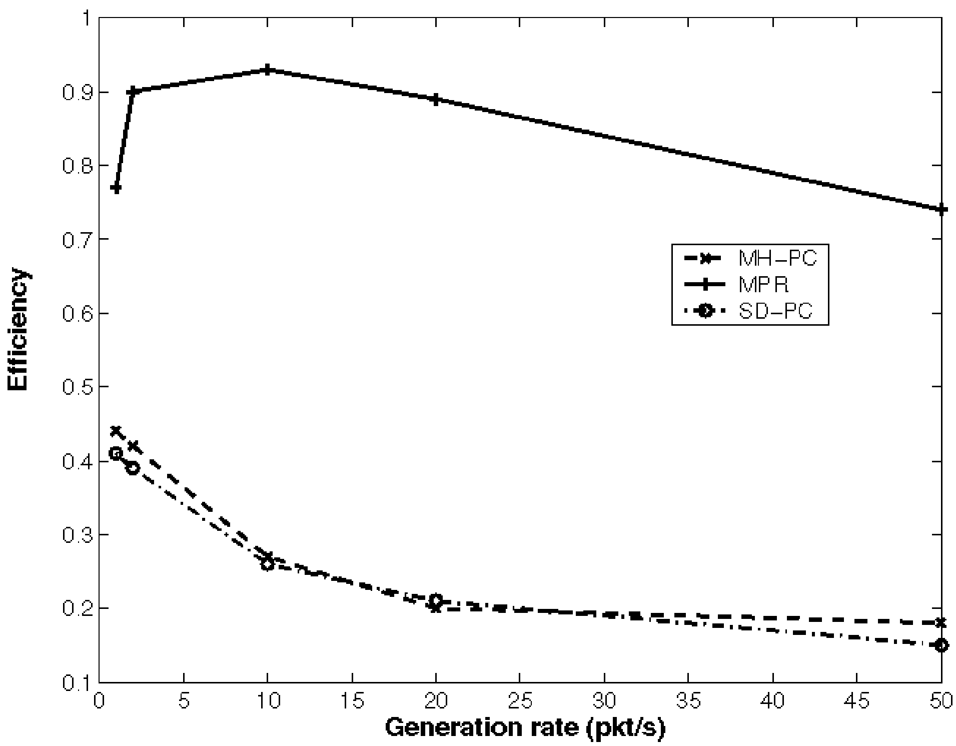

Figure 1: Efficiency vs. Packet generation rate ρ.

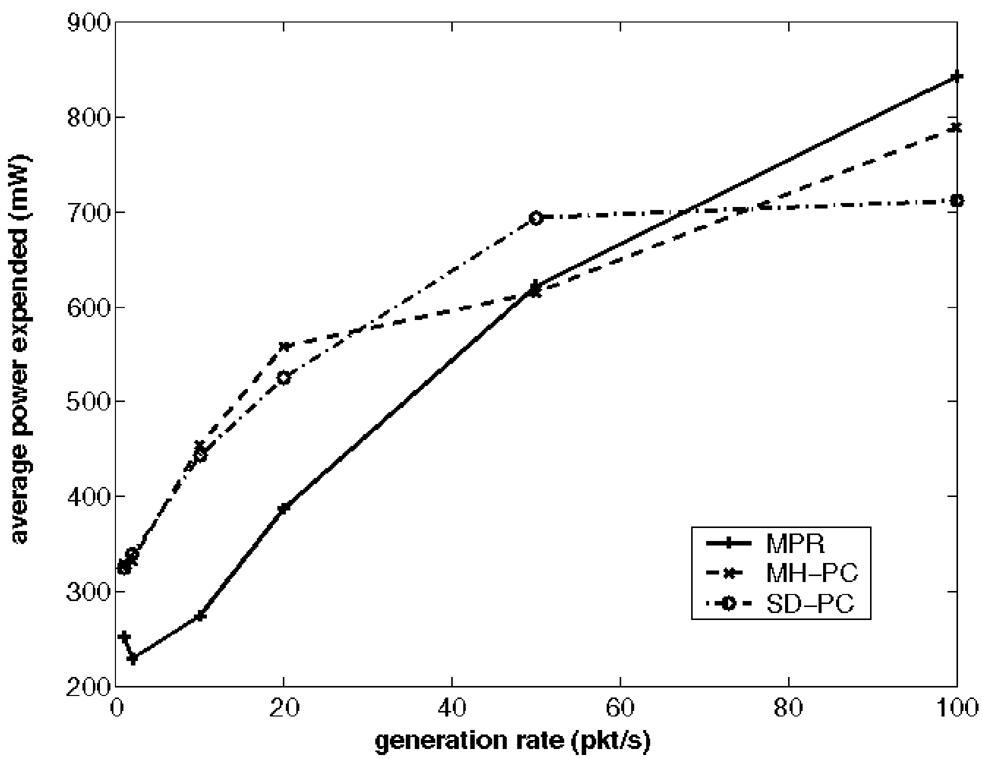

Figure 2: Average power expended vs. Packet generation rate ρ.

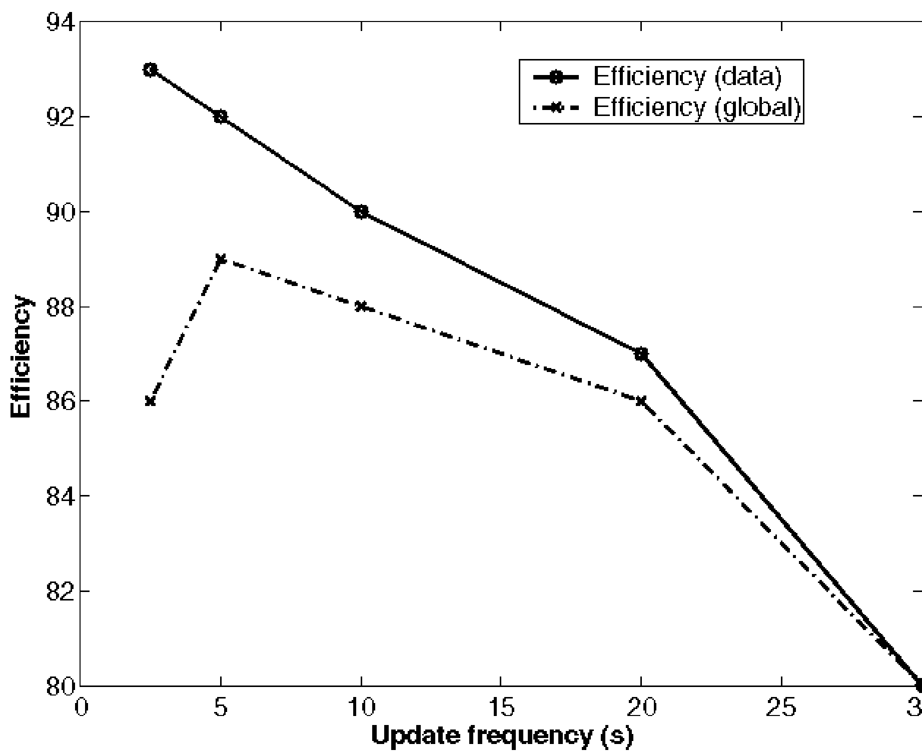

Figure 3: MPR: Efficiency vs. Update frequency (s).

V. Conclusion and Future Directions

Rescue operations and disaster relief scenarios cannot rely on centralized and organized connectivity, and fall in the domain of MANETs for emergency telecommunication. In this study, we discussed the benefits of power consciousness for emergency application MANETs and conducted an initial investigation of energy-efficient wireless routing in MANETs. We developed power conscious concepts - MPR -, which adapt to the changing channel conditions and interference environment of a node. We presented our preliminary results and conclude that MPR shows promise as a power conscious routing scheme for MANETs.

The performance of MPR indicates clear benefit to employing power conscious concepts in the routing operation for MANETs. As an initial investigation, we used the distributed Bellman-Ford algorithm to determine the routing paths. Since MANETs have various applications and network configurations, it is unlikely that one routing algorithm will obtain the best performance in all situations. Hence, it is important to be able to apply the power conscious concepts to other distributed MANET algorithms. As a future direction, we will extend the power conscious concepts developed herein to other MANET routing algorithms. As a supporting study to this work, we will provide a survey of existing wireless radios and their respective power adjustment capabilities. This will aid in determining which wireless radios are better suited for power adjustment in emergency preparedness telecommunication.

VI. Resulting Publications

- J.S. Pegon and M.W. Subbarao, "Simulation Framework for a Mobile Ad-Hoc Network," Proceedings of OPNETWORK 1999, Washington DC., Sept. 1999.
- M.W. Subbarao, "Dynamic Power-Conscious Routing for MANETs: An Initial Approach," Proceedings of IEEE VTC Fall 1999, Amsterdam, The Netherlands, Sept. 1999.
- M.W. Subbarao, "Dynamic Power-Conscious Routing for MANETs", NIST Journal of Research, Volume 104, Number 6, Nov.-Dec. 1999.

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