Energy Efficient Routing Algorithms for Acquiring Information from Smart Badges

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***Abstract*—The terrorist attacks on the World Trade Center and the Pentagon on September 11, 2001 have drawn attention to the use of wireless technology in order to locate survivors of structural collapse. We propose to construct an ad hoc network of wireless smart badges in order to acquire information from trapped survivors. We investigate the energy efficient routing problem that arises in such a network and show that since smart badges have very limited power sources and very low data rates, which may be inadequate in an emergency situation, the solution of the routing problem requires new protocols. The problem is formulated as an anycast routing problem in which the objective is to maximize the time until the first battery drains-out. Then, we present two methodologies that can be used in order to develop distributed protocols for obtaining the optimal solution of the problem.**

***Keywords*—energy efficient routing, energy conserving routing, disaster recovery network, smart badge**

I. INTRODUCTION

The terrorist attacks on the World Trade Center and the Pentagon on September 11, 2001 have drawn ever-increasing attention to improving rescue efforts following a disaster. One of the technologies that can be effectively deployed during disaster recovery is wireless ad hoc networking[1]. For example, rescue forces can use a Mobile Ad Hoc Network (MANET) in the lack of fixed communication systems. Furthermore, a wireless sensor network can be quickly deployed following a chemical or biological attack in order to identify areas affected by the chemical/biological agents. We propose another application of an ad hoc network, which can be used in order to gather information from trapped survivors of structural collapse.

[1] An ad hoc network is an autonomous system consisting of wireless hosts that do not rely on the presence of any fixed network infrastructure [10].

There are various techniques for locating survivors of structural collapse trapped in the rubble: fiber optic scopes, sensitive listening devices, seismic sensors, search-and-rescue dogs, etc. [5]. Moreover, during the rescue attempts in the World Trade Center disaster site, the Wireless Emergency Response Team (WERT) attempted to locate survivors through signals from their mobile phones [14].

We propose to extend these capabilities and to enable the location of survivors by acquiring information from their smart badges. Smart badges (a.k.a. RF ID badges) will gain increased popularity in the near future and will apparently be used in any modern office building [12]. Since the transmission range of a badge is very short and since rescue equipment can usually be deployed at the periphery of the disaster scene, there is a need to construct an ad hoc network connecting victims trapped in the debris to the rescuers. In such a network, the information acquired from the badges (such as last known location, body temperature, etc.) will be repeatedly routed through other badges to wireless receivers deployed in the disaster scene. The receivers will forward the information through wired or wireless links to a central unit.

In the coming years, smart badges will use a proprietary technology (e.g. [13]) or the new IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (LR-WPAN) [6],[7]. Either way they will be simple devices with very low data rates and very limited power sources. These data rates and power sources are expected to be adequate for regular use. For example, the data rate of an IEEE 802.15.4 device will be 20 Kb/s or 250 Kb/s [7]. A smart badge based on this standard is expected to establish about 20 connections per day [12]. Thus, the average data rates are expected to be much lower than the possible data rate. Moreover, the duty cycle of such a device is expected to be less than 1%, thereby enabling a long battery life.

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However, in an emergency network constructed after a collapse, which may connect thousands of nodes and may route critical information, the required data rates and the consumed energy may be much higher than in daily use. Thus, the low data rates and the limited power sources are a major constraint on the performance of an emergency network. Furthermore, in such a network depleting the battery of a node may have tragic results.

This extended abstract focuses on energy efficient routing protocols for emergency networks of badges. We note that since wireless devices usually have a finite power supply, there is an increasing interest in research regarding energy-conserving protocols (see for example [8],[11], and references therein). Thus, our network model is based on the model for energy conserving routing in a wireless sensor network presented by Chang and Tassiulas [4]. However, unlike a wireless sensor network [1] in which the available bandwidth is usually sufficient, in the emergency network there is a strict bandwidth restriction along with a strict energy restriction. Thus, the solution of the problem calls for the development of new protocols.

Our major interest is in distributed algorithms for quasi-static anycast routing in a static network with stationary requirements and unchanging topology. The objective of the algorithms is to maximize the time until the first battery drains-out (i.e. to solve a max-min optimization problem). This objective function has been defined by Chang and Tassiulas [4] and although it is controversial when applied to MANETs or sensor networks, it is appropriate for an emergency network in which every node is critical. In the sequel we formulate the problem and present two different methods for developing distributed algorithms. The full development of the algorithms is subject of further research.

This paper is organized as follows. In Section 2, we present the model and formulate the routing problem. Methodologies for developing distributed algorithms that obtain the optimal solution of the problem are introduced in Section 3. In Section 4, we summarize the main results and discuss future research directions.

II. Formulation of the Problem

Consider the connected directed network graph $G = (N,L)$. N will denote the collection of *nodes* $\{1,2,\ldots,n\}$. A node could be a *badge*, a *receiver* (the collection of receivers is denoted by R), or the central unit (referred to as the *destination* and denoted by d). Recall that receivers are deployed at the periphery of the disaster scene (their role is to connect the badges network to the central unit).

The collection of the *directional links* will be denoted by L. We assume that since smart badges are intended to be very simple and cheap devices they will usually transmit in a constant power level. Thus, a unit j that is within the transmission range of node i is connected to i by a directional link, denoted by (i,j). For each node i, $Z(i)$ will denote the collection of its *neighboring nodes* (nodes connected to node i by a directional link).

Let F_{ij} be the average flow on link (i,j) ($F_{ij} \geq 0$ $\forall (i,j) \in L$). We define f_{ij} as the ratio between F_{ij} and the maximal possible flow on a link connecting smart badges[2] ($0 \leq f_{ij} \leq 1$). In the sequel, f_{ij} will be referred to as the *flow on link* (i,j). The ratio between the rate in which information is generated at node i and the maximal possible flow on a link connecting smart badges, is denoted by r_i ($0 \leq r_i < 1$).

The transmission energy required by node i to transmit an information unit is denoted by e_i. Let each node i have an initial *energy level* E_i (we assume that $E_i > 0$ $\forall i \in N$). If a node i is a receiver or the destination, its energy source is much larger than the energy source of a badge, and therefore, for such a node $E_i = \infty$.

For low-power devices operating in the 2.4 GHz ISM band, the transmitter and receiver currents are often similar [6]. Thus, we assume that energy is consumed only when a node transmits information (alternatively, the energy consumed when it receives information can be included in e_i). Moreover, since the energy required in order to receive a message is not negligible, we assume that although a few nodes are able to receive the same message, only the node to which it is intended will receive the full message and forward it. The other nodes will be in sleep mode or communicate with their other neighbors.

We have mentioned that the objective of our energy conserving routing protocols is to obtain link flows such that the time until the first battery drains-out will be maximized. Thus, following the formulation of [4] and using the above assumptions, we define the lifetime of a node and of the system as follows.

The *lifetime of node i* under a given flow is denoted by T_i and is given by:

$$T_i = \frac{E_i}{e_i \sum_{j \in Z(i)} f_{ij}}. \tag{1}$$

[2] For example, in IEEE 802.15.4 the maximal data rate (i.e. the maximal possible flow) is 20Kb/s or 250Kb/s.

The *lifetime of the system* under a given flow is the time until the first battery drains-out, namely the minimum lifetime over all nodes. It is denoted by T and is given by:

$$T = \min_{i \in N} T_i = \min_{i \in N} \frac{E_i}{e_i \sum_{j \in Z(i)} f_{ij}} . \quad (2)$$

The *energy efficient routing* problem can now be formulated as follows.

Problem EER

Given: Topology and requirements (r_i)

Objective: Maximize the system lifetime:

$$\max T = \max \left(\min_{i \in N} \frac{E_i}{e_i \sum_{j \in Z(i)} f_{ij}} \right) \quad (3)$$

Subject to:

$$f_{ij} \geq 0 \quad \forall (i,j) \in L \quad (4)$$

$$\sum_{k \in Z(i)} f_{ki} + r_i = \sum_{j \in Z(i)} f_{ij} \quad \forall i \in N - \{R, d\} \quad (5)$$

$$\sum_{k \in Z(i)} f_{ki} = \sum_{j \in Z(i)} f_{ij} \quad \forall i \in R \quad (6)$$

$$\sum_{k \in Z(i)} f_{ki} + \sum_{j \in Z(i)} f_{ij} \leq 1 \quad \forall i \in N - \{R, d\} \quad (7)$$

Constraints (4) - (6) are the usual flow conservation constraints. The meaning of (7) is that the total flow through a node cannot exceed the maximal node capacity (i.e. the maximal data rate of a badge).

Fig. 1 illustrates a simple network composed of five badges, two receivers, and a single destination. In the optimal solution, the system lifetime is 7.69 time units (the batteries of nodes 1,2,4 are depleted after 7.69 time units). It can be seen that node 5, whose battery has remaining power at time 7.69, utilizes its full capacity throughout the operation of the network.

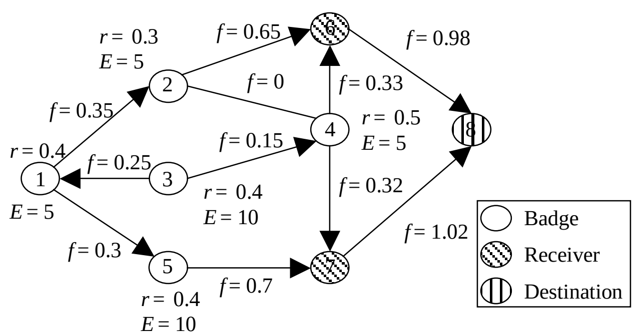

Fig. 1. The required transmission rates (r_i), the initial energy values (E_i), and the optimal flows (f_{ij}) in a network of badges (assuming that $e_i = 1 \; \forall i$)

III. Optimal Algorithms

In this section, we present an equivalent formulation of Problem EER. This formulation is required in order to develop distributed algorithms that obtain optimal results. Then, we discuss two different approaches to developing optimal distributed algorithms.

A. LP Formulation

The first step towards obtaining an optimal solution to Problem EER is converting it to a linear programming problem (Problem EER-LP). Following the approach in [4], we first define $\overline{f}_{ij}$ as the amount of information transmitted from node i to node j until time T ($\overline{f}_{ij} = f_{ij} \cdot T$). Then, we formulate Problem ERR-LP as follows.

Problem EER-LP

Given: Topology and requirements (r_i)

Objective: Maximize the system lifetime:

$$\max T \quad (8)$$

Subject to:

$$\overline{f}_{ij} \geq 0 \quad \forall (i,j) \in L \quad (9)$$

$$\sum_{k \in Z(i)} \overline{f}_{ki} + r_i \cdot T = \sum_{j \in Z(i)} \overline{f}_{ij} \quad \forall i \in N - \{R, d\} \quad (10)$$

$$\sum_{k \in Z(i)} \overline{f}_{ki} = \sum_{j \in Z(i)} \overline{f}_{ij} \quad \forall i \in R \quad (11)$$

$$e_i \sum_{j \in Z(i)} \overline{f}_{ij} \leq E_i \quad \forall i \in N - \{R, d\} \quad (12)$$

$$\sum_{k \in Z(i)} \overline{f}_{ki} + \sum_{j \in Z(i)} \overline{f}_{ij} \leq T \quad \forall i \in N - \{R, d\} \quad (13)$$

Problem EER-LP is a Linear Programming problem, and therefore, it can be solved by well-known algorithms (e.g. Simplex [3]). However, these algorithms cannot be easily modified in order to allow distributed implementation, which is required in an ad hoc network. Thus, analyzing the characteristics of the problem is required in order to develop distributed algorithms.

Notice that if the last set of constraints (13) is ignored, Problem EER-LP becomes a *concurrent max-flow problem* with constraints on the flows at the nodes.[3] Including (13) in the concurrent max-flow problem means that the flow through a node cannot exceed some percentage of the flow in the network. Recall that (13) results from the fact that the data rate of a badge might be lower than the required bandwidth in an emergency

[3] A concurrent max-flow problem is a multicommdity flow problem in which the objective is to maximize a common fraction of each commodity that is routed [9].

situation. As mentioned before, in the sequel we shall discuss two different methods for dealing with the complexities imposed by these constraints.

B. Iterative Solution

An optimal distributed algorithm can be based on repeated solutions of the concurrent max flow problem (8) - (12). Following the solution of the problem, the node capacities, which depend both on the energy (12) and the value of the network lifetime (13), are recomputed according to the obtained T. Then, the concurrent max flow problem with the new capacities has to be solved. This process is repeated until the optimal solution to Problem EER-LP is obtained.

Although this approach enables the development of distributed algorithms, the complexity of these algorithms is not necessarily polynomial in the number of nodes or links.

We note that at every iteration, the solution of the concurrent max-flow problem (8) - (12) can be obtained by a distributed algorithm (for instance, by a version of the approximate algorithm presented of Awerbuch and Leighton [1] or by the algorithms presented by Segall [15] for networks with a single origin). Moreover, since the capacities imposed by (12) and (13) are node capacities, each node i should be divided into two subnodes (i_{in} and i_{out}) connected by an internal link whose capacity is defined according to (12) and (13).

C. Polynomial Solution

An optimal distributed algorithm can be based on a few observations regarding the relationship between the optimal system lifetime and the capacities of $O(n)$ different cutsets. According to these observations, the system lifetime is a function of the minimum cuts obtained for $O(n)$ different values of node capacities. In order to obtain these minimum cuts, there is a need to solve $O(n)$ instances of the concurrent max-flow problem (8) - (12) (as mentioned before, it can be solved by the distributed algorithms presented in [1] or [15]). Thus, the complexity of the resulting algorithm is polynomial.

We note that the algorithm that is developed according to this approach works well for a network with a single origin. However, its scalability to a network with multiple origins requires further research.

IV. Conclusions and Future Research

We have proposed to enable the formation of a network composed of smart badges in order to acquire information from survivors of structural collapse. The two main aspects that affect the performance of such a network are the limited energy resources of the badges and their very low data rates (relatively to the requirements in a disaster scene).

Accordingly, an energy efficient routing problem in such a network has been formulated as an anycast routing problem. The problem has been formulated such that the objective function is to maximize the time until the first battery drains-out and the flow through the badges is bounded by their data rates. Then, we have presented two methodologies that can be used in order to develop optimal distributed algorithms for the solution of the problem. These methodologies are based on conversion of the max-min problem to a linear programming problem and on observations regarding the relationship between the network lifetime and the capacities of different cutsets.

The work presented here is the first approach towards an analysis of the routing problem in an emergency network of smart badges. Hence, there are still many open problems to deal with. For example, future study will focus on developing and evaluating optimal algorithms based on the methodologies presented above. Despite the theoretical importance of the optimal algorithms, in an emergency situation there is a need for low complexity approximate algorithms. Thus, a major future research direction is the development of *approximate algorithms* that will deal with the special characteristics of a smart badges network operated in a disaster site.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, “Wireless Sensor Networks: a Survey”, *Computer Networks*, Vol. 38, pp.393-422, Mar. 2002.

[2] B. Awerbuch and T. Leighton, “Improved Approximation Algorithms for the Multi-Commodity Flow Problem and Local Competitive Routing in Dynamic Networks”, *Proc. ACM STOC’94*, May 1994.

[3] D. Bertsimas and J. N. Tsitsiklis, *Introduction to Linear Optimization*, Athena Scientific, 1997.

[4] J. H. Chang and L. Tassiulas, “Energy Conserving Routing in Wireless Ad-hoc Networks”, *Proc. IEEE INFOCOM’00*, Mar. 2000.

[5] Federal Emergency Management Agency (FEMA) - The National Urban Search and Rescue Response System, Documentation available at URL http://www.fema.gov/usr, June 2002.

[6] J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter and B. Heile, “IEEE 802.15.4: A Developing Standard for Low-Power Low-Cost Wireless Personal Area Networks”, *IEEE Network*, Vol. 15, pp. 12-19, Sep./Oct. 2001.

[7] IEEE 802.15.4 Standard, Documentation available at URL http://www.ieee802.org/15/pub/TG4.html, June 2002.

[8] C. E. Jones, K. M. Sivalingam, P. Agrawal and J. C. Chen, “A Survey of Energy Efficient Network Protocols for Wireless Networks”, *Wireless Networks*, Vol. 7, pp. 343-358, July 2001.

[9] T. Leighton and S. Rao, “Multicommodity Max-Flow Min-Cut Theorems and Their Use in Designing Approximation Algorithms”, *Journal of the ACM*, Vol. 46, pp. 782-832, Nov. 1999.

[10] C. E. Perkins, *Ad Hoc Networking*, Addison-Wesley, 2001.

[11] C. Petrioli, R. R. Rao and J. Redi (eds.), “Special Issue: Energy Conserving Protocols”, *Mobile Networks and Applications*, Vol. 6, June 2001.

[12] D. Pokrajac, “Smart Badge Usage Model”, doc. no. IEEE802.15-01/039r0, Submitted Jan. 2001.

[13] J. M. Rabaey, M. J. Ammer, J. L. daSilva Jr., D. Patel and S. Roundy, “PicoRadio Supprorts AD Hoc Ultra-Low Power Wireless Networking”, *IEEE Computer*, Vol. 33, pp. 42-48, July 2000.

[14] K. F. Rauscher, “Wireless Emergency Response Team – Final Report for the Sep. 11 2001 NYC WTC Terrorist Attack”, Oct. 2001.

[15] A. Segall, “Decentralized Maximum-Flow Protocols”, *Networks*, Vol. 12, pp. 213-230, 1982.