Optimal Routing in Sensor Networks for In-home Health Monitoring with Multi-factor Considerations

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Abstract

Recent technological advances in wireless sensor networking have opened up new opportunities in healthcare systems. Future medical systems are expected to benefit the most in such areas as in-home assistance, smart nursing homes, and clinical trial. However the network system including body sensor networks and environmental sensor networks are normally comprised of energy constrained nodes. Furthermore, communication interference between multi mode nodes in such a dynamic system is also a challenge. This limitation has led to the crucial need for energy and mobility aware protocols to produce an efficient network. In this paper, we propose an energy and mobility aware multipath routing scheme for sensor networks in a smart homecare application. The remaining battery capacity, distance to the gateway, mobility and queue size of candidate sensor nodes in the local communication range are taken into consideration for next hop relay node selection, and Analytical Hierarchy Process (AHP) is applied for decision making. Simulation results show that this scheme can extend the network lifetime and reduce the packet loss rate and link failure rate since the mobility and buffer capacity is considered.

1. Introduction

Recent technological advances in wireless sensor networking have opened up new opportunities in healthcare systems [1] [2] [3]. Future medical systems are expected to benefit the most from it in such areas as in-home assistance, smart nursing homes, and clinical trial.

However, in the healthcare system including body sensor networks and environmental sensor networks, there exist some challenges, for example,

1) The routing link failure may happen during data transmission because of collision, node draining of energy, node busy, or other accidents. The pervasive healthcare applications normally require real time information and data, which means retransmission is not possible. This motivates us to design a multipath routing scheme for wireless sensor networks (WSNs).
2) There exists energy constraint in body sensor networks because most sensors are battery operated and a prolonged network lifetime is preferred. This motivates us to consider energy aware routing.
3) The patient or the elders wear garment with physiological sensor nodes on which are mobile during people walking relative to the background environmental sensor network. Moreover, if there are several users having daily activities in the same house, the communication interference between multi mode nodes in such a dynamic system is also a challenge. The mobility of the nodes may cause the existing point-to-point route invalid and an alternate route has to be chosen. In physical layer, sensor mobility generates channel fading during data transmission, which degrades the performance in terms of bit error rate (BER) and frame error rate (FER). This motivates us to investigate a mobility aware routing.

Routing protocols for sensor networks can be classified as either cluster-based or flat. The cluster-based routing divides the network into groups of nodes and utilizes a sleep mode to save energy. Alternatively, flat routing schemes achieve energy efficiency in an indirect way by reducing the routing overhead. In cluster-based routing protocols such as LEACH [4], TEEN [5], and APTEEN [6], nodes are organized into groups with one node from each group selected to be a cluster-head. A cluster-head receives data packets from

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cluster members, aggregates them and relays them to a data sink. Flat routing schemes, typically implement either forwarding, or data-centric based routing. Forwarding schemes utilize local information to forward messages. Some properties of greedy geographic routing algorithms are studied in [7]. Jain et al [8] proposes a geographical routing using partial information for WSNs. In data-centric based routing, an interest message is disseminated to assign the sensing tasks to the sensor nodes and data aggregation is used. There are two types of data-centric based routing: either the sink broadcasts the attribute for data, e.g. Directed Diffusion [9], or the sensor nodes broadcast an advertisement for the available data and wait for a request, e.g. Sensor Protocols for Information via Negotiation (SPIN) [10].

In this paper, we propose an Analytical Hierarchy Process (AHP) based Energy and Mobility-aware Geographical Multipath Routing (AEM-GMR) scheme for WSNs in a health care system, and compare with Geographical Multipath Routing (GMR) scheme.

The rest of the paper is organized as follows. We give the health care system architecture and state the problems in section 2. The third section presents the proposed AHP based AEM-GMR scheme. Section 4 evaluates and analyzes the performance of the proposed method. Finally, we draw the conclusion and discuss future work in section 5.

2. Problem statements

2.1 Architecture of the health care system

The architecture of the health care system is shown in Fig. 1. According to the state of illness, the patient wears the specific physiological sensors to measure the vital-sign parameters. Then the captured data is transmitted to the gateway by the short-range wireless communication module in the device in order to continuously monitor and record the patient's condition. Due to the limited transmission range of the body sensor nodes, the patient may walk everywhere in the house and go out of the transmission range. In order to ensure the transmission between the gateway and the body senor nodes, a sufficient amount of environmental wireless sensor nodes are deployed to build a WSN in the patient's home. The wireless sensor nodes utilize the same short-range wireless transmission media as that the body sensor nodes use. Consequently, no matter where the patient walks within the house, the body senor networks and WSN always can get connected with the gateway and transmit the vital-sign parameters to the gateway by means of multi-hop relay. The gateway is primarily responsible for collecting and recording the patient's vital-sign data and then uploading to the care server by way of the internet. The care server is located in the hospital. It is primarily in charge of analyzing and storing the data from every gateway into database so that the medical care providers can monitor the patients' conditions via a workstation. There is a friendly user interface in the workstation so that the medical care providers can log in to the care server.

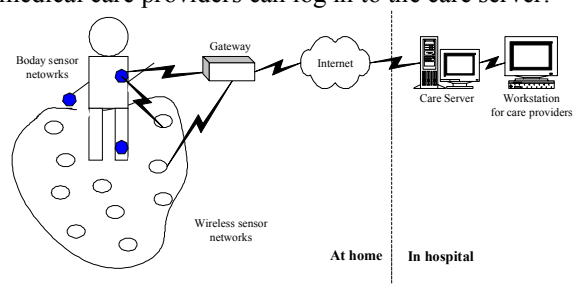

Figure 1. Architecture of the health care system

2.2 Energy model and design criteria

We investigate the multipath routing problem in pervasive in-home health care system and propose an AHP based Energy and Mobility-aware Geographical Multipath Routing (AEM-GMR) scheme. In the existing geographical routing approach (e.g., [8]), the path selection doesn't consider the remaining battery capacity and mobility of the node, which is important factors for energy efficiency and network lifetime in the health care system. In our AEM-GMR, we consider *distance to the gateway*, *remaining battery capacity*, *mobility* and *queue size* of each sensor node. Our scheme is a fully distributed approach where each sensor only needs the above four parameters, and we use AHP to handle these parameters in the AEM-GMR.

A. Energy model

We adopt the same radio model as stated in [4] with ε_{fs} =10*pJ/bit/m*^{2} as amplifier constant, E_{elec}=50*nJ/bit* as the energy being dissipated to run the transmitter or receiver circuitry. It is assumed that the transmission between the nodes follows a second-order power loss model. The energy cost of transmission for common sensor nodes at distance *d* in transmitting an *l*-bit data is calculated as:

$$E_T(l,d) = lE_{elec} + l\varepsilon_{fs}d^2 \quad (1)$$

and to receive the message, the radio expends:

$$E_R(l) = lE_{elec} \quad (2)$$

and the energy for data aggregation is set as E_{DA} = 5 *nJ/bit*.

B. Design criteria

In our AEM-GMR design, we set up four criteria for node selection, and they are:

1) Distance to gateway (GW): The geographical location of gateway is known to the source node (as in [8]), and the physical location of each sensor node can be estimated easily if the locations of three sensor nodes (within a communication range) are known in wireless sensor network. The node with shorter distance to the gateway is preferred to be selected.
2) Residual energy: Remaining battery of the sensor node. The initial energy is predefined. In addition, the energy consumption for transmission and reception can be calculated using Eq. (1) and Eq. (2).
3) Mobility: It is the mobility of the body sensor nodes relative to the environmental sensor networks. The nodes with less mobility are preferred to be selected as the next hop relay.
4) Queue size: It indicates the buffer capacity at the node. This parameter helps avoid packet drops due to congestion at the receiver.

The optimized node selection in multipath routing is a multiple factors optimization problem and can be achieved using the AHP approach which is introduced in the next section.

3. Node selection in multipath routing by AHP

In our AEM-GMR for *M*-path routing, the source node select *M* nodes in its communication range for the first hop relay. Assume there are *N* (*N* > *M*) nodes in its communication range, nodes that are farther to the gateway than the source node are not considered. Choosing *M* nodes from remaining eligible nodes is based on AHP (as will be described in detail). Starting the second hop, each node in the *M*-path selects its next hop node also using AHP.

The Analytical Hierarchy Process (AHP) [11] is a multiple criteria decision-making method which decomposes a complex problem into a hierarchy of simple sub problems (or factors), synthesizes their importance to the problem, and finds the best solution. In this paper, AHP is used to determine the nodes which are eligible to be selected as next hop relay. It is carried out in three steps:

Step 1: Collect information and formulate the next hop routing nodes selection problem as a decision hierarchy of independent factors.

Step 2: Calculate the relative local weights of decision factors or alternatives of each level.

Step 3: Synthesize the above results to achieve the overall weight of each alternative node and choose the nodes with largest weight as the eligible next hop relay nodes.

A. Structuring hierarchy

The goal of the decision "Select a node as next hop relay" is at the top level of the hierarchy as shown in Fig. 2. The next level consists of the decision factors which are called criteria for this goal. At the bottom level there exist the *N* alternative sensor nodes to be evaluated.

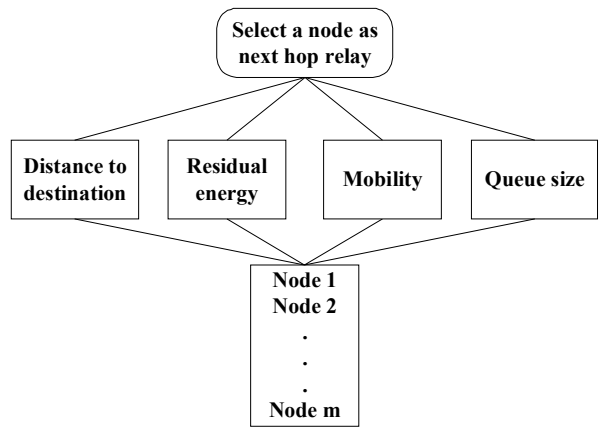

Figure 2. AHP hierarchy for next hop relay nodes selection

B. Calculating local weights

Local weights consist of two parts: the weight of each decision factor to the goal and the weight of each nominee to each factor. Both of them are calculated with the same procedure. Taking the former as an example, we describe the procedure as the following three steps.

1) Making pairwise comparison

The evaluation matrices are built up through pairwise comparing each decision factor under the topmost goal. The comparison results are based upon user expertise experience by asking questions such as "Which is more important and by how much?" These initial values are captured in square matrix A as

$$A = \left(a_{ij}\right)_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}, \quad (3)$$

where a_{ij} denotes the ratio of the ith factor weight to the jth factor weight, and *n* is the number of factors. The

fundamental 1 to 9 scale can be used to rank the judgments as shown in Table 1.

Table 1. A fundamental scale of 1 to 9

Number Rating	Verbal Judgment of Preferences
1	Equally
3	Moderately
5	Strongly
7	Very
9	Extremely

2, 4, 6, 8 indicate the medium value of above pairwise comparison.

2) Calculating weight vector

For the given matrix A in Eq. (3), we calculate its eigenvalue equation written as AW = $\lambda_{\max}$W, where W is non-zero vector called eigenvector, and $\lambda_{\max}$ is a scalar called eigenvalue. After standardizing the eigenvector W, we regard the vector element of W as the local weight of each decision factor approximately, which can be denoted as:

$$\mathbf{w}_j^T = \{w_1, w_2, \cdots, w_n\} \tag{4}$$

3) Checking for consistency

If every element in Eq. (3) satisfies the equations $a_{ij} = 1/a_{ji}$ and $a_{ik} \cdot a_{kj} = a_{ij}$, the matrix A is the consistency matrix. However, the evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency ratio (CR), which is defined as the ratio of consistency index (CI) to random index (RI). CI can be achieved by

$$CI = (\lambda_{\max} - n)/(n-1), \tag{5}$$

where

$$\lambda_{\max} = (1/n)\sum_{i=1}^{n}(AW)_i / W_i \cdot \tag{6}$$

The *RI* is given in [11]. When $CR \le 0.1$, the judgment errors are tolerable and the weight coefficients of the global weight matrix W_j are the weights of decision factor under the topmost goal. Otherwise, the pairwise comparisons should be adjusted until matrix A satisfies the consistency check.

C. Calculating global weights

From above steps, we can obtain not merely the weights of decision factors towards the topmost goal from W_j but also the weights of alternative nodes towards each factor. If there are four candidate nodes in the communication range, all the four weight matrixes of alternatives under 4 factors construct a 4×3 matrix, denoted as $W_{n_i/j}$, *i*=1, 2, … 4, *j*=1, 2, 3.

The global weight of each senor node can be achieved through multiplying the local weight by its corresponding parent. So the final weight matrix in the symbol of W_{n_i} is calculated as

$$W_{n_i} = W_{n_i/j} \cdot W_j, \tag{7}$$

where the final weight of each alternative is calculated as

$$W_{n_i} = \sum_{j=1}^{3} W_{n_i/j} \cdot W_j. \tag{8}$$

The larger the final weight of node, the higher the probability of node which is eligible to be selected. Thus, the *M* nodes with the largest weight are selected as the next hop relay nodes in multipath routing.

In this paper, we assume that each sensor node keeps a table which has some information about its neighbor nodes: locations, battery level, mobility and queue size. The table is updated periodically by the locally-broadcasted information (beacon) from each neighbor node. We define a time interval *T*, during which the four parameters (locations, battery level, mobility and queue size) do not change very much. This time interval *T* is the shortest time duration that a sensor node will send another beacon. Each sensor examines itself the status of the four parameters in every period *T*, and if a certain parameter has changed above a threshold, it will locally broadcast a beacon.

D. Path set up

In the route discovery phase, the source node uses AHP model to evaluate all eligible nodes (closer to the gateway) in its communication range based on the parameters of each node: distance to GW, remaining battery capacity, mobility and queue size. The source node chooses the top *M* nodes based on the local weight that this node will be selected. The source node sends a Route Acknowledgement (RA) packet to each desired node, and each desired node will reply using a REPLY packet if it is available. The structure of RA and REPLY is summarized in Table 2. If after a certain period of time, the source node did not receive REPLY from some desired node, it will pick the node with highest weight among the remaining *N-M* ndoes. In the second hop, the selected node in each path will choose its next hop node using the same process. As illustrated in Fig. 3, node B needs to choose one node from four eligible nodes C, D, E, and F based on their four parameters, and sends RA packet to the selected node

and waits for REPLY. If the top one node is unavailable (for example, selected by another path), then the top second node will be selected. Consequently, *M* paths can be set up.

Table 2. RA and REPLY message structure

Type
Desired Node ID
Self Node ID
Dest_X
Dest_Y
Src_ID

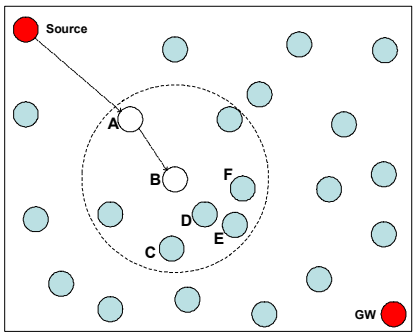

Figure 3. Illustration of next hop node selection

4. Performance evaluations

In order to evaluate the nodes selection in multipath routing by AHP, we have used J-Sim [12] as the simulation environment. 60 sensors are randomly deployed in an area of 100m x 100m. The source sensor node is set as 2J initially. All the other sensors have initial energy of 0-2J. The buffer capacity of each sensor node has been taken as 5 packets with packet length 512 bit and bit rate 9.6kb/sec. The time interval *T* is set as 10s in our simulation. The source node select *M=3* nodes in its communication range for the first hop relay. From the second hop, each node along the 3 paths selects only one node toward its next hop.

In AHP modeling, the matrix A is determined as follows according to Section 3:

$$A = \begin{array}{c} \\ \alpha \\ \beta \\ \gamma \\ \eta \end{array} \begin{array}{c} \begin{array}{cccc} \text{Distance to GW } (\alpha) & \text{Residual energy } (\beta) & \text{Mobility } (\gamma) & \text{Queue size } (\eta) \end{array} \\ \begin{bmatrix} 1 & 1/2 & 3/2 & 3/1 \\ 2/1 & 1 & 3/1 & 4/1 \\ 2/3 & 1/3 & 1 & 2/1 \\ 1/3 & 1/4 & 1/2 & 1 \end{bmatrix} \end{array}$$

where the four criteria are denoted by α, β, γ and η respectively.

The computed eigenvector W = [0.2593 0.4723 0.1728 0.0956]. It indicates the local weight of the distance to GW, remaining battery capacity, mobility and queue size, respectively, so that we can see clearly that the remaining battery capacity is the most important criterion, and queue size is the least. According to Eq. (6), we can get the eigenvalue λ_{max} = 4.0174. Consequently, consistency ratio can be calculated as *CR*= 0.0058 < 0. 1, thus matrix A satisfies the consistency check.

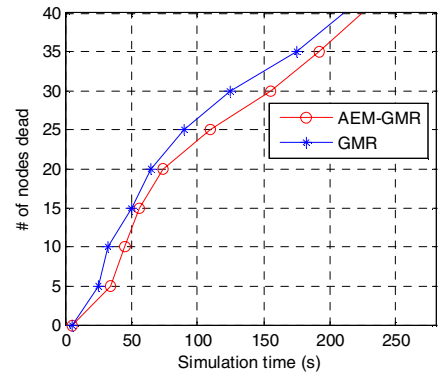

Figure 4. Lifetime comparison

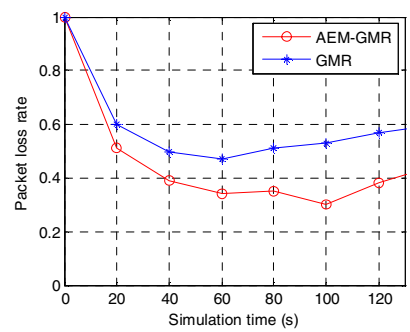

Figure 5. Simulation time vs. packet loss rate

Each sensor node determines the weight matrixes of alternatives under four factors and then gets global weight based on its specific situation. Its eligibility as next hop relay node can be finally decided by the AHP hierarchy model.

We compare our AEM-GMR against the geographical multipath routing (GMR) [8]. In Fig. 4, we plot the simulation time versus the number of nodes dead. It shows that when 50% nodes (30 nodes) die out, the network lifetime for AEM-GMR has been extended about 23%. In Fig. 5, we compare the packet loss rate of these two schemes. Packets are dropped either due to insufficient buffer capacity at the receiver or because of the lack of energy needed to transmit the packet. Observe that our AEM-GMR outperforms the AEM-GMR with about 22% less packet loss resulting in greater reliability. The average latency during transmission (end-to-end) is 428.21ms for our AEM-

GMR and 407.5ms for GMR, and link failure rate for AEM-GMR is 6.33%, but for GMR is 10.42%.

5. Conclusion and future work

In this paper, we proposed an energy and mobility aware geographical multipath routing scheme for WSNs in a pervasive healthcare system. Four factors contributing to the next hop relay node selection are considered and they are the distance to the gateway, remaining battery capacity, mobility and queue size of candidate sensors in the local communication range, respectively. Analytical Hierarchy Process (AHP) was applied for optimal decision making. We evaluated the efficiency of our proposed scheme and the simulation results showed that this scheme could extend the network lifetime longer than the original geographical routing scheme. Moreover, the proposed scheme could reduce the packet loss rate and link failure rate.

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