A Reliable, Efficient Routing Protocol for Dynamic Topology in Wireless Body Area Networks using Min-Max multi-commodity flow model

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***Abstract*—WBSNs (wireless body sensor network) like any other sensor networks suffers limited energy and are the highly distributed network, in which its nodes are the organizer itself and each of them has the flexibility of collecting and transmitting patient biomedical information to a sink. When knowledge sent to sink from a path that doesn't have a definite basis, the routing is a crucial challenge in Wireless Body Area Sensor Networks, additionally reliability and routing delay are the considerable factors in these type of networks. Most of the attention should be given to the energy routing where energy awareness is an essential consideration in WBSNs and the frequent topology change increases the dynamics of network topology, and complicates the process of relay selection in cooperative communications.**

In this paper, we propose a Min-Max multi-commodity flow model for WBSNs which allows to prevent sensor node saturation and take best action against reliability and the path loss, by imposing an equilibrium use of sensors during the routing process. Simulation results show that the algorithm balances the energy consumption of nodes effectively and maximize the network lifetime. It will meet the enhanced WBSNs requirements, including better delivery ratio, less reliable routing overhead.

I. Introduction

WBSNs should be robust against frequent changes in the network topology; The data mostly consists of medical information. Hence, high reliability and low delay is required; The devices used in WBSN have limited energy resources available and consequently the computational power and available memory of such devices will be limited; [5].

This poses a number of challenges on the design and analysis of WBSNs. Considerable attention had been paid to developing reliable sensor network communication protocols. In summary, new ideas on the fundamental limits for routing and reliability in such systems are needed. The new mechanism can maintain the features of WSNs such as multihop routing and dynamically environmental changes in a complete autonomous mode. Maximizing lifetime and other constraints as reliability are conflicting objectives and thus warrant a trade-off [3], [4].

The remainder of this paper is as follows: In section II, we expose the system description. We introduce in section III a Min-Max multi-commodity flow formulation based on reliable model and network energy consumption problem. Finally, an experimental comparative study is presented in section V and VI and we conclude this paper in section VII.

II. Topology Representation and Network Model

In order to maximize the WBSN lifetime, the energy consumption of nodes should be balanced and the nodes with less residual energy should decrease the energy consumption for data transceiver as much as possible.

We present a description of our WBSN system model. We consider a WBSN deployment, and model it as a directed graph $G = (N, A)$ where N is the set of nodes (sensors) and A is a set directed arcs representing directed communication links between distinct nodes in N. An arc $(i, j) \in A$ exists if the Euclidean distance between the two nodes is within a certain maximum transmission radius range. Each node $i \in N$ has the same initial energy E and the node batteries are neither rechargeable nor replaceable. We assume a many-to-many communication model for our WBSN. The goal of the proposed routing algorithm is to efficiently route each routing before the end of WBSN lifetime, for dynamic topology in WBSN using Min-Max multi-commodity flow model. The energy consumption model used in this work is based on the first order radio propagation [1]. We denote by $\mathcal{C}$ the set of commodities (routing requests), each commodity $c \in \mathcal{C}$ consists of routing D^c packets from a source node s^c to a destination node t^c. We introduce a flow variable f_{ij}^c defining the portion of commodity c being transported on arc (i, j). These variables are subject to flow conservation constraints

$$\sum_{j\in\delta^+(i)} f_{ij}^c - \sum_{j\in\delta^-(i)} f_{ji}^c = b_i^c \qquad \forall i \in N, c \in C$$

where $\delta^-(i) = \{j \in N : (j,i) \in A\}$, $\delta^+(i) = \{j \in N : (i,j) \in A\}$, and $b_i^c = 1$ if $i = s^c$, $b_i^c = -1$ if $i = t^c$, and $b_i^c = 0$ otherwise. Classically, multi-commodity flow models involve capacity constraints on arcs, in our model, capacity constraints are imposed on nodes. In fact, each sensor node has a limited energy capacity over of which the sensor is unusable. Using the equations aforementioned, the energy consumption

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at node j for routing (receiving and transmitting) a packet providing from a node i is given as follows:

$$e_{ij} = p(2Q + Bd_{ij}^{m}). \qquad (1)$$

We define the energy consumption of sensor i as a linear combination of the flow variables:

$$e_j := \sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij} D_c f_{ij}^c$$

where $D_c f_{ij}^c$ is the number of packets of commodity c transmitted on arc (i, j). Capacity constraints are formulated as follows:

$$\sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij} D_c f_{ij}^c \leq E, \forall j \in N$$

we recall that E is the amount of energy available at each sensor node. We obtain therefore the optimization model:

$$\min \quad \sum_{c \in C} \sum_{(i,j) \in A} e_{ij} D_c f_{ij}^c \qquad (2)$$

$$s.t. \quad \sum_{j \in \delta^+(i)} f_{ij}^c - \sum_{j \in \delta^-(i)} f_{ji}^c = b_i^c, \forall i \in N, c \in C \qquad (3)$$

$$\sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij} D_c f_{ij}^c \leq E, \forall j \in N \qquad (4)$$

$$f_{ij}^c \in [0, 1], \forall (i, j) \in A, c \in C \qquad (5)$$

III. A Min-Max multi-commodity flow formulation

For distributing requests in an equitable way over the communication network, instead of minimizing the total energy consumption on sensor nodes, we propose to minimize the maximum energy consumption sensors nodes, or equivalently maximize the minimum lifetime sensor node in the network. The objective is then formulated as follows: $\min \max_{j \in N} e_j$. We add a new variable $z := \max_{j \in N} e_j$, which therefore is subject to the constraints

$$z \geq \sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij}^c D_c f_{ij}^c \qquad \forall j \in N.$$

The optimization model is therefore as follows:

$$\min \quad z \qquad (6)$$

$$s.t. \quad \sum_{j \in \delta^+(i)} f_{ij}^c - \sum_{j \in \delta^-(i)} f_{ji}^c = b_i^c, \forall i \in N, c \in C \qquad (7)$$

$$z \geq \sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij}^c D_c f_{ij}^c, \forall j \in N \qquad (8)$$

$$\sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij} D_c f_{ij}^c \leq E, \forall j \in N \qquad (9)$$

$$f_{ij}^c \in [0, 1], \forall (i, j) \in A, c \in C \qquad (10)$$

Realization of optimal routing algorithm: The optimal routing algorithm proposed in this paper is a centralized algorithm run periodically by the sink. At the beginning of the algorithm, each node forwards its neighbor set, residual energy and the amount of data generated by itself to the sink. After the sink has received the information of all nodes, it runs the optimal routing algorithm to obtain the optimal solution through solving max-min mathematical programming model. Then it will send informations to every node in the network.In fact, the algorithm incurs some overhead in exchanging messages between the sink and nodes to determine the optimal matrix and this will consume energy. But, for some applications in which the amount of data collected by a node during a given time interval is almost unchanged and neighbor set will not change because it is determined by the relative position among nodes. So, the amount of data generated by nodes and neighbor set only need to be sent to the sink in the first running of the routing algorithm. When a node transmits data, the information of its current battery level (1 byte) is sent to the sink attached to the data. The amount of information on current battery level is very small compared with the transmitted data, so its energy consumption can be ignored. All these methods can reduce the control packet overhead.

IV. Reliability Computation

We propose to complete our optimal model routing with a hight reliable level model, which is a proactive link state routing protocol. Its operation is table driven through periodically exchanging topology information with other nodes in the network based on the link quality estimation. The objective of the protocol is to give as well as providing guarantees of the reliable transmission packets. During reliability computation, the monitored events are normalized and assigned weights so as to compute the direct reliability in other nodes. These computed levels are then associated with the routing process during reliability application. There are two reliability values associated with a routing protocol : reliability route and reliability node. **reliability route** : Reliability route is computed by every node for each route in its routing table. It is a measure of the reliability with which a packet can reach the destination assimilated as a link quality estimation, if forwarded by the node on that particular route. The route reliability are initially unknown. Reliability route is calculated as a ratio of the number of packets received at Y to the number of packets forwarded by the node under consideration (from X to Y on that route).The route selection criterion is inversely proportional to the number of hops in the route. Many methods can be devised for selecting a route from the available routes. A source node calculates the reliability route for all its available routes to the destination and it finally chooses the route which has the highest reliability route. If two routes have the same reliability route then the following criteria are used to break the tie: i) the routes with highest value are selected then the shortest route is chosen. ii) If all the above are same then it will choose randomly among those routes with same reliability route.

A. Reliability model formulation

We consider the parameter y_i representing the reliability of sensor i. A communication between two nodes i and j can be hold if and only if the node j has a reliability greater than Y, i.e. $y_i \geq Y$. The objective is the maximization of the nodes reliability route along the paths and this can be expressed as follows:

$$\max \sum_{c \in C} \sum_{(i,j) \in A} f_{ij} y_j \qquad (11)$$

We introduce the constraint of the minimum reliability on nodes:

$$f_{ij}^c (y_j - Y) \geq 0, \forall (i,j) \in A, \forall c \in C$$

When $y_j < Y$, the variable f_{ij}^c takes a zero value. To establish a compromise between the objective (II) and the objectives proposed in section III: $AG(\alpha, \beta, \gamma) = \alpha(\sum_{c \in C} \sum_{(i,j) \in A} e_{ij} D_c f_{ij}^c) + \beta z - \gamma \sum_{c \in C} \sum_{(i,j) \in A} f_{ij}^c y_j$ with $\alpha + \beta + \gamma = 1$, we study the aggregated objective model equivalent to (8)-(11) by considering the reliability level:

$$\begin{aligned} \min \quad & \alpha(\sum_{c \in C} \sum_{(i,j) \in A} e_{ij} D_c f_{ij}^c) + \beta z - \gamma \sum_{c \in C} \sum_{(i,j) \in A} f_{ij}^c y_j \\ \text{s.t.} \quad & \sum_{j \in \delta^+(i)} f_{ij}^c - \sum_{j \in \delta^-(i)} f_{ji}^c = b_i^c, \forall i \in N, c \in C \\ & z \geq \sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij}^c D_c f_{ij}^c, \forall j \in N \\ & \sum_{c \in C} \sum_{i \in \delta^-(j)} e_{ij} D_c f_{ij}^c \leq E, \forall j \in N \\ & f_{ij}^c (y_j - Y) \geq 0, \forall (i,j) \in A, \forall c \in C \\ & f_{ij}^c \in [0,1], \forall (i,j) \in A, \forall c \in C \end{aligned}$$

V. An experimentations model

We implement the formulations (2)-(5) and (6)-(10) in AMPL (A Modeling Language for Mathematical Programming) [2]. In this section, we present a demonstrative example to show the importance of having an equilibrium use of sensors during the routing process for minimizing the network lifetime. We examine the instance on figure (4) with two commodities ($c1$ and $c2$) and 10 nodes $N = \{s1, s2, 1, ..., 6, t1, t2\}$. With each arc (i,j) we associate a weight e_{ij} corresponding to the energy consumption resulting from the transmission of one packet on arc (i,j) (formulation 1). The source node of commodity $c1$ (resp. $c2$) is node $s1$ (resp. $s2$) and the destination node of commodity $c1$ (resp. $c2$) is node $t1$ (resp. $t2$). The capacity of each sensor is $E = 50000$. We aim to observe the total system energy consumption ($TE = \sum_{i \in N} e_i$), the minimum energy consumption of sensor nodes ($MinE = \min_{i \in N} e_i$), the maximum energy consumption of sensor nodes ($MaxE = \max_{i \in N} e_i$) and the gap between $MinE$ and $MaxE$ (Gap). Our test instance is solved using models (2)-(5) (Max MFM), and (6)-(10) (Min-Max MFM) respectively, we present on table I the obtained results. Table I presents the obtained results, where T represents the sum of the reliability level on paths. Each node reliability level is indicated between brackets on figure (4): We have achieved number of evaluations regarding the chosen weights. We are based on the configuration provided in Table I. For lack of space we do not represent all the conducted experiments, more detailed experimentations can be found here[6]. The aggregated objective model equivalent to (8)-(11) by considering the reliability level, taking into account $\alpha = 0.4, \beta = 0.2 and \gamma = 0.4$, shown that, when the weight β decreases Gap and TE increases, we deduce that the objectives (1) minimize the total energy consumption and (2) minimize the maximum of the energy consumption over sensor nodes are conflicting and (3) maximize the route reliability. Note that the solution set may contain those sensor routes which are not the best from the viewpoint of a single objective, but is non dominated and offers a fair compromise when all three objectives are considered simultaneously. The computational time taken by our proposed protocol is within 0.0001 second even for a sensor network of 10 nodes.

	AG(0.3, 0.3, 0.4)	AG(0.1, 0.1, 0.8)	AG(0.4, 0.2, 0.4)
Sol	$c1$. s1-2-5-t1 $c2$. s2-2-3-6-t2 s2-4-5-6-t2	$c1$. s1-1-2-5-t1 $c2$. s2-1-2-5-6-t2 s2-4-5-6-t2	$c1$. s1-2-5-t1 $c2$. s2-4-5-6-t2
TE	145318	182000	140000
$MinE$	0	0	0
$MaxE$	30636.4	50000	39500
Gap	30636.4	50000	39500
T	53	61.45	53

TABLE I
The aggregated model

VI. Simulation results

An evaluation performance of our proposed algorithm via OPNET are described in this section. We calculate node energy dissipation for all data transmission per round. In order to analyze energy efficiency of the algorithm we use the time till the first node become inoperative, due to energy depletion. Later, we compare the results performance of our max-min based optimal routing algorithm with least energy tree based routing algorithm (LEnergy) least hop count based routing algorithm (LHop) where each one take into account only energy and hop respectively parameters. We led the experimentations in an environment and parameters close to reality. Firstly nodes are deployed in the regular field. The sink is located at the center of the area. In the initial phase, optimal values of sensors parameters are calculated using a min max multi-commodity flow algorithm. The amount of transmitted data and routes will be determined. In this part of simulation, we compute the average energy consumption of nodes in each round, the average residual energy of nodes and the network lifetime. We compare our optimal reliability routing scheme with two other schemes: LHop and LEnergy scheme. Figure 3 gives the network lifetime in different routing algorithms, we vary node density by increasing the number of nodes in the network and compare the performance of our optimal algorithm. As we see the network lifetime is prolonged in our proposed algorithm compared with LHop and LEnergy . In the LHop case, the routing is constructed based on the minimum hop count from nodes to the sink. The LEnergy is the worst case scheme, the routing decision is made based on the minimum energy consumption from nodes to the sink. LHop and LEnergy both want to minimize the overall energy consumption of the network. The routes will

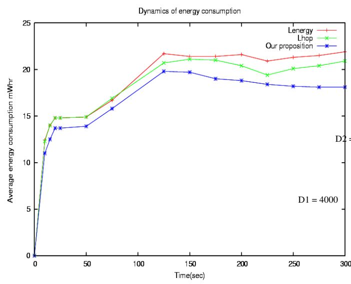

Fig. 1. Dynamics of energy consumption

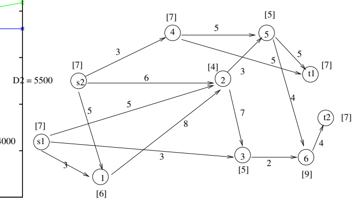

Fig. 2. An illustrative example

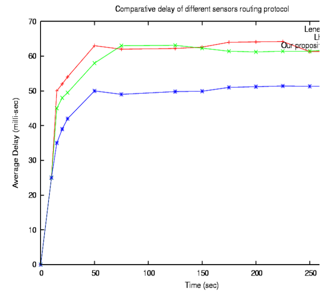

Fig. 3. Comparative delay of different sensor routings

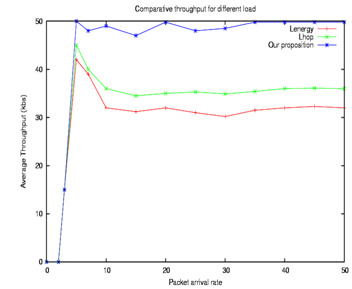

Fig. 4. Comparative throughput for different load

not change as soon as they are determined. This will cause the nodes in the relay paths, especially near the sink, with heavy load, and a serious impact on the network lifetime. In our proposed algorithm, the route is constructed dynamically based on the optimized amount of transmitted data through different paths, the residual energy and the reliability level of nodes. So the network lifetime is maximized and the energy consumption of nodes is balanced.Figure 3shows the average residual/consumption energy of nodes in different algorithms when the first node becomes incapable. The average consumed energy of nodes in our solution is obviously less than the both schemes described above, which shows that the proposed solution has effectively balanced the energy consumption of nodes. At the time that the first node become inoperative, due to energy depletion in LHop and LEnergy, the nodes in the network still have much residual energy because these two algorithms dont take any measure to balance energy consumption of nodes.The end-to-end delay metric is compared between our proposition, LHop and LEnergy for wireless sensor traffic in Figure 3. It explains that end-to-end delay for wireless video traffic is lowest for our proposition. Figure 4 depicts a comparative study of the wireless sensor throughput between different wireless sensor routing for different traffic arrival rate. It is clear, that with traffic arrival rate more than 40 packets/sec,the throughput of both LHop and LEnergy reduces, thereby incurring packet-loss. On the other hand, our proposition provides more steady throughput, even for pretty high packet arrivals 80 packets/sec.In order to investigate further into the dynamics of sensory energy consumption,in Figure 6, we have shown the average energy consumption in our proposition , LHop and LEnergy, with different increasing traffic arrival rate 20, 40, 60, 80, 100 packets/sec. While all the strategies result in increase of energy consumption with increasing traffic arrival, our proposition results in lowest energy consumption for different traffic arrival rates. This shows the efficiency of the protocol in reducing the energy consumption to near-optimal values, while optimizing the delay and bandwidth as well.

VII. Conclusion

This work presents a Min-Max multi-commodity flow model for wireless body sensor network routing. Our solution maximize the network lifetime, by minimizing the maximum energy consumption of sensor nodes in the network and maximizing the route reliability.We deduce that minimum total energy consumption and min-max energy consumption are conflicting criteria. A good compromise can be obtained with weighting methods. In order to find an optimal integer solution to our problem, we project to implement a powerful optimization method: the branch-and-price-and-cut algorithm where column generation approach and polyhedral cuts are coupled with a branch-and-bound algorithm. Thus, we contribute in a WBSN area research which is an expected to be a very useful technology with potential to offer a wide range of benefits to patients, medical personnel and society through continuous monitoring and early detection of possible problems. With the current technological evolution, sensors and radios will soon be applied as skin patches. Doing so, the sensors will seamlessly be integrated in a WBSN. Step by step, these evolutions will bring us closer to a fully operational WBSN that acts as an en-abler for improving the Quality of Life.

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