A Min-Max multi-commodity flow model for Wireless Body Area Networks routing

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Abstract—**The increasing use of wireless networks and the constant miniaturization of electrical devices has empowered the development of Wireless Body Sensor Networks (WBSNs). The wireless nature of the network and the wide variety of sensors offer numerous new, practical and innovative applications to improve health care and the Quality of Life. WBSNs like any other sensor networks suffer limited energy resources and hence preserving the energy of the nodes is of great importance. Unlike typical sensor networks WBSNs have few and dissimilar sensors. In addition, an extremely low transmit power per node is needed to minimize interference to cope with health concerns and to avoid tissue heating which means that the existing solution for preserving energy in wireless sensor networks might not be efficient in WBSNs. Most of the attention has been given to the energy routing where energy awareness is an essential consideration. In this paper, we propose a Min-Max multi-commodity flow model for WBSNs which allows to prevent sensor node saturation, by imposing an equilibrium use of sensors during the routing process taking into account the specific characteristics of the wireless environment on the human body. The Min-Max objective is transformed to a Min objective by adding a set of constraints to the model. Based on the energy consumption for sending and receiving data and the available residual energy of nodes, the max-min based mathematical programming model is designed to find optimal routing. Simulation results show that the algorithm balances the energy consumption of nodes effectively and maximize the network lifetime.**

I. INTRODUCTION

In order to realize communication between body sensors, techniques from Wireless Sensor Networks (WSNs) and ad hoc networks could be used. However, because of the typical properties of a WBSN, current protocols designed for these networks are not always well suited to support a WBSN. The following illustrates some important differences between a Wireless Sensor Network and a Wireless Body Sensor Network: (1) The devices used have limited energy resources available as they have a very small form factor. (2) An extremely low transmit power per node is needed to minimize interference and to cope with health concerns; (3) The propagation of the waves takes place in or on a (very) lossy medium, the human body. As a result, the waves are attenuated considerably before they reach the receiver; (4)WBSNs should therefore be robust against frequent changes in the network topology; (5)The data mostly consists of medical information. Hence, high reliability and low delay is required[12]. This poses a number of challenges on the design and analysis of WBSNs. The most important design consideration for WBSN is to extend their operational lifetime by minimizing power consumption. This is the reason why, protocol with low energy consumption has been an important research orientation in this field. Maximizing lifetime and other constraints are conflicting objectives and thus warrant a trade-off [9]. Thereby, the problem should be formulated as a Multi-objective Optimization Problem (MOP) [3]; since all objectives are considered equal and there is not a single solution to optimize them at the same time. The remainder of this paper is as follows: In section II, we present works related to our problem. In section III, we expose the system description. We introduce in section IV the min-cost multi-commodity flow formulation and propose in section V a Min-Max multi-commodity flow formulation for our problem. Finally, an experimental comparative study between the two studied models is presented in section VII and we conclude this paper in section VIII.

II. RELATED WORK

Developing efficient routing protocols in WBSNs is a nontrivial task because of the specific characteristics of the wireless environment. First of all, the available bandwidth is limited, shared and can vary due to fading, noise and interference, so the protocol's amount of network control information should be limited.Although a lot of research is being done toward energy efficient routing in ad hoc networks and WSNs [5], the proposed solutions are inadequate for WBSNs. For example, in WSNs maximal throughput and minimal routing overhead are considered to be more important than minimal energy consumption. Energy efficient ad-hoc network protocols only attempt to find routes in the network that minimize energy consumption in terminals with small energy resources, thereby neglecting parameters such as the amount of operations (measurements, data processing, access to memory) and energy required to transmit and receive a useful bit over the wireless link. Specialized protocols for WBSNs are therefore needed. In the following, an overview of existing routing strategies for WBSNs is given. They can be subdivided in two categories: routing based on the temperature of the body and cluster based protocols. When considering wireless transmission around and on the body, important issues are radiation absorption and heating effects on the human body. To reduce tissue heating the radio's transmission power

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can be limited or traffic control algorithms can be used. In [6] rate control is used to reduce the bio-effects in a single-hop network. Another possibility is a protocol that balances the communication over the sensor nodes. An example is the Thermal Aware Routing Algorithm (TARA) that routes data away from high temperature areas (hot spots) [8]. The node temperatures are converted into graph weights and minimum temperature routes are obtained. A better energy efficiency and a lower temperature rise is obtained, but the protocol has as main disadvantage that a node needs to know the temperature of all nodes in the network. The overhead of obtaining this data was not investigated. Anybody [7] is a data gathering protocol that uses clustering to reduce the number of direct transmissions to the remote base station. It is based on LEACH that randomly selects a cluster head at regular time intervals in order to spread the energy dissipation. The cluster head aggregates all data and sends it to the base station. LEACH assumes that all nodes are within sending range of the base station. Anybody solves this problem by changing the cluster head selection and constructing a backbone network of the cluster heads. Doing so, the energy efficiency is improved. Reliability, however, is not considered. This overview clearly shows that routing protocols for WBSNs is an emerging area of research. To achieve the above, new routing schemes have been proposed. Routing protocols must select the best path to minimize the total power needed to route packets on the network and to maximize the lifetime of all nodes. A Multi-commodity Flow Model (MFM) [1] concerns routing of a number of commodities through a capacitated network at minimal cost. In this paper we first present a min-cost MFM for routing in WBSN where the total energy consumption is minimized, second, we propose another MFM based on a Min-Max formulation, called a Min-Max MFM. Our objective throw this new formulation is a fair distribution of requests over body sensor nodes for maximizing the network lifetime. Our work is based on the following assumptions: (1) The MAC protocol is 802.14.5 based; (2) All nodes have the same transmission radius in fixed topology; (3) All nodes have the same initial energy supply; (4) Mobility is not considered; (5) The sink is with unlimited energy.

III. THE SYSTEM DESCRIPTION

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. In this paper, based on the max-min mathematical model, considering the efficiency and balance of energy consumption of nodes comprehensively, the mathematical programming model is constructed to seek for the optimal routing. We present a description of our WBSN system model. We consider a static 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 problem where we have a set of source nodes performing sensing task as well as a set of destination nodes (base stations) that receive data from the source nodes. A source node may initiate a routing request for sending its sensed data to a destination node. A routing request does not imply a single data packet, rather it represents a sequence of data packets to be sent from the source node to a sink node. The goal of the proposed routing algorithm is to efficiently route each routing request in such a manner that maximize the number of successful routing requests before the end of WBSN lifetime. The energy consumption model used in this work is based on the first order radio propagation [**?**]. In this model, the energy expended by a sensor transmission and reception of a p-bit packet is give by equations (1) and (2), respectively:

$$TR_{ij} = p(Q + Bd_{ij}^{m}) \tag{1}$$

$$RE_{ij} = Qp \tag{2}$$

where Q is distance-independent and accounts energy consumed in running transmitter or receiver circuitry and B denotes the energy required by the transmitter's amplifier, whereas m is a field constant typically in the range $[2, 4]$ and depends on certain characteristics of the wireless medium. We use a simple, but commonly used, WBSN lifetime definition: The WBSN lifetime is equal to the minimum of the lifetime values of all the node in the network, i.e., the network lifetime ends as soon as any node in WBSN runs out of its battery. If the lifetime of a WBSN node is denoted by T_i, the WBSN lifetime may be expressed as given by the following equation: $T = \min_{i \in N} T_i$.

IV. MULTI-COMMODITY FLOW FORMULATION

The multi-commodity network flow problem is one of the best-known problems in network optimization [1]. The problem involves several flow types or commodities, which simultaneously use the network and are coupled through either link capacities, with the objective of maximizing a cost function. Multi-commodity flow formulations tend to spread the traffic and keep the link flows away from link capacity, thereby resulting in efficient bandwidth utilization and minimizing blocking of new traffic. The problem finds important applications, such as in transportation and telecommunications [11]. In the context of WBSN, different commodities correspond to different data sets represented by p-bit packets to be established between nodes of the network, flow is measured in terms of the proportion of packets, i.e., flow on a link corresponds to the proportion of packets send from the origin node that cross that link. We design a multi-commodity flow model for WBSN routing problem that maximizes the system lifetime by minimizing the total energy consumption on sensor nodes. 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 (1) and (2), the energy consumption at node j for routing (receiving and transmitting) a packet providing from a node i is given as follows:

$$e_{ij} = p(2Q + Bd_{ij}^m). \tag{3}$$

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: $\sum_{c\in C}\sum_{i\in\delta^-(j)} e_{ij}D_c f_{ij}^c \le E, \forall j \in N$. We recall that E is the amount of energy available at each sensor node. We obtain therefore the optimization model:

$$\begin{aligned}
\min \quad & \sum_{c\in C}\sum_{(i,j)\in A} e_{ij}D_c f_{ij}^c & (4)\\
s.t. \quad & \sum_{j\in\delta^+(i)} f_{ij}^c - \sum_{j\in\delta^-(i)} f_{ji}^c = b_i^c, \forall i \in N, c \in C & (5)\\
& \sum_{c\in C}\sum_{i\in\delta^-(j)} e_{ij}D_c f_{ij}^c \le E, \forall j \in N & (6)\\
& f_{ij}^c \in [0,1], \forall (i,j) \in A, c \in C & (7)
\end{aligned}$$

The multi-commodity flow model is well adapted to manage simultaneously different requests that have to be routed over the communication network, but the solutions of this model do not always guarantee fair solutions. In fact, with this model, a maximum of commodities are routed on the optimal paths, i.e. paths that minimize the total energy consumption, so the nodes on these paths can be saturated (out of energy).

Remark 1: For obtaining guarantee an homogeneous use of sensors, sensor node saturation has to be prevented, by imposing an equilibrium use of sensors during the routing process.

Proposition 1: The maximization of the network lifetime is equivalent to the maximization of the minimum of the energy consumption of the network sensors (nodes).

Proof 1: We consider that the Network Lifetime (NL) is equivalent to the minimum remaining energy of the sensors. In fact, when at least one sensor is out of energy, the network communication stops. The NL can be formulated as follows: $NL = \max(E - \max_{i\in N} e_i) \Leftrightarrow NL = \max(-\max_{i\in N} e_i) \Leftrightarrow NL = \min\max_{i\in N} e_i)$.

For obtaining an homogeneous use of sensors, another multi-commodity flow model based on a Min-Max objective function is used. This model can allow to prevent sensor node saturation, by imposing an equilibrium use of sensors during the routing process.

V. 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 sensor node, 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 $z \ge \sum_{c\in C}\sum_{i\in\delta^-(j)} e_{ij}^c D_c f_{ij}^c, \forall j \in N$. The optimization model is therefore as follows:

$$\begin{aligned}
\min \quad & z & (8)\\
s.t. \quad & \sum_{j\in\delta^+(i)} f_{ij}^c - \sum_{j\in\delta^-(i)} f_{ji}^c = b_i^c, \forall i \in N, c \in C & (9)\\
& z \ge \sum_{c\in C}\sum_{i\in\delta^-(j)} e_{ij}^c D_c f_{ij}^c, \forall j \in N & (10)\\
& \sum_{c\in C}\sum_{i\in\delta^-(j)} e_{ij}D_c f_{ij}^c \le E, \forall j \in N & (11)\\
& f_{ij}^c \in [0,1], \forall (i,j) \in A, c \in C & (12)
\end{aligned}$$

Realization of optimal routing algorithm

The optimal routing algorithm proposed in this paper is a centralized algorithm run 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.

VI. A DEMONSTRATIVE EXAMPLE

We implement the formulations (4)-(7) and (8)-(12) in AMPL (A Modeling Language for Mathematical Programming) [4]. 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 (1) 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 3). 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 senseor 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 (4)-(7) (Max MFM), and (8)-(12) (Min-Max MFM) respectively, we present on table I the obtained results.

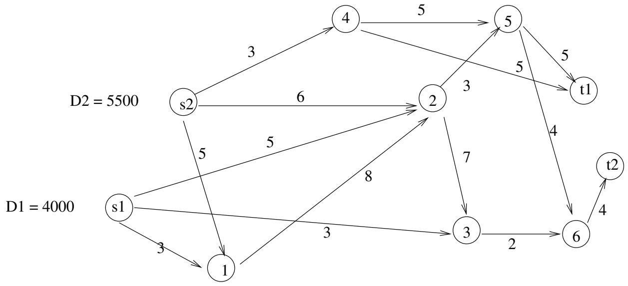

Fig. 1. An illustrative example

	Min MFM	Min-Max MFM
Sol	$c1$. 1-4-7-10 $c2$. 2-6-7-8-9	$c1$. 1-4-7-10 $c2$. 2-4-5-8-9 2-6-7-8-9
TE	140000	145318
$MinE$	0	0
$MaxE$	39500	30636.4
Gap	39500	30636.4

TABLE I
MIN MFM AND MIN-MAX MFM MODELS

The row Sol give the solution obtained (sequence of nodes belonging to the path) for the associated commodity. As expected, the Min MFM formulation ensure a lower total energy consumption compared to the Min-Max MFM formulation, but the gap is the greater. The Min-Max MFM formulation ensure an equitable distribution of tasks over the network by using more sensors than the Min MFM. In order to establish a compromise between the two objectives, we study aggregated objective models equivalent to (8)-(12) with the aggregated objective function (AG(α, β)):

$$\min \alpha (\sum_{c \in C} \sum_{(i,j) \in A} e_{ij} D_c f_{ij}^c) + \beta z$$

Table II presents the obtained results: All solutions obtained with $\alpha \geq 0,7$ are equivalent and all solutions obtained with $\alpha \leq 0,5$ are equivalent. When the weight β decreases Gap and TE increases, we deduce that the two objectives (1) minimize the total energy consumption and (2) minimize the maximum of the energy consumption over sensor nodes are conflicting.

	AG(0.7, 0.3)	AG(0.6, 0.4)	AG(0.5, 0.5)
Sol	$c1$. 1-4-7-10 $c2$. 2-6-7-8-9	$c1$. 1-4-7-10 $c2$. 2-4-7-8-9 2-6-7-8-9	$c1$. 1-4-7-10 $c2$. 2-4-5-8-9 2-6-7-8-9
TE	140000	142438	145318
$MinE$	0	0	0
$MaxE$	39500	34625	30636.4
Gap	39500	34625	30636.4

TABLE II
AGGREGATED MFM MODELS

We observe also that unlike the solution (Sol) obtained with Min MFM formulation (integer solution), solutions of Min-Max MFM and AG(α, β) formulations are fractional, because the Min-Max objective tends to spread requests on as much as possible nodes, so the flow is fractioned on many different paths.

VII. 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, which we are preparing to conduct performance evaluations on a real platform within medical applications.Firstly nodes are approximatively 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. Some parameters are shown in Table III . 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 scheme with two other schemes: LHop and LEnergy scheme. Figure 2 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 others. In the LHop case, the routing is constructed based on the minimum hop count from nodes to the sink.

Parameter	Area of WBSN	n	$E0$	Eelec
Value	2 m × 2 m	10 ∼ 30	0.5 J	50 nJ/bit
Parameter	Data packet	Control packet	R	
Value	4000 bits	100 bits	0.3 m	

TABLE III
SIMULATION PARAMETERS

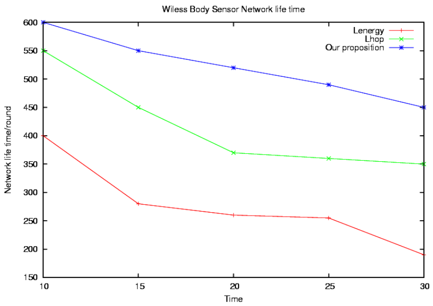

Fig. 2. Network lifetime

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 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 routing is constructed dynamically based on the optimized amount of transmitted data through different paths and the residual energy of nodes. So the network lifetime is maximized and the energy consumption of nodes is balanced. Figure 3shows the average residual energy of nodes in different algorithms when the first node becomes incapable. The average residual 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.

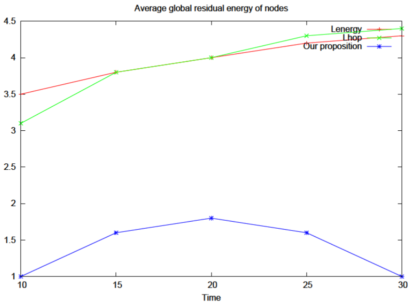

Fig. 3. Average residual energy of nodes

VIII. CONCLUSION

This work presents a Min-Max multi-commodity flow model for wireless body sensor network routing for maximizing the sensor nodes lifetime by maximizing the minimum lifetime of sensor nodes or equivalently minimizing the maximum energy consumption of sensor nodes in the network. We compare the Min-Max multi-commodity flow model with the Min multi-commodity flow model where the total energy consumption is minimized. 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 [2] 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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