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ε-Optimal Minimal-Skew Battery Lifetime Routing in Distributed Embedded Systems

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Most sensor networks and networked embedded systems operate on batteries. Minimizing the total power consumption in such systems is of paramount importance to increase their operational lifetime. In such systems, the power optimization becomes even more important, due to the small size of the batteries as well as the distributed nature of the power sources. To prolong the lifetime of such systems, the lifetime of each individual sensor or embedded system must be maximized. Therefore, ideally, the power consumption rate must be evenly distributed over all the nodes in the system. This objective cannot be satisfied by employing the traditional routing algorithms which attempts to minimize the total power consumption of the system. In this paper, we propose an ε-optimal polynomial time multi-hop routing technique that maximizes the lifetime of the system with respect to distributed battery sources. Furthermore, it aims to evenly distribute the power consumption rate which yields in a minimal-skew solution. We theoretically prove that our technique is efficient. Finally, we illustrate the quality of the solutions generated by our technique on a few benchmarks.

Keywords: Power Optimization, Battery-Aware Routing, Distributed Embedded Systems, Sensor Networks.

1. INTRODUCTION

Battery-powered portable embedded systems have been widely used in various applications such as mobile computing, wireless communications, information appliances, wearable computing and many more. Such systems mostly rely on distributed battery sources for their operation and depletion of batteries in some nodes may have a great impact on the network. Therefore, energy efficiency is one of the most important issues in such systems to prolong the lifetime of the system. Although research continues to reduce the power energy consumption of CPUs, user interface and storage devices, the transmission energy for a packet in wireless channels is still quite significant and may turn out to be the highest energy consuming component of the devices. Hence, there is a need for designing minimum energy consumption routing algorithm that ensures a longer battery life. For such a design, the existing minimum-hop routing scheme cannot be applied, and a new, power-aware routing scheme that takes the transmission energy into consideration explicitly is urgently needed. In such systems, the bottleneck of any given route is defined as the minimum residual node energy along the paths. Likewise, the lifetime of the system is defined as the minimum lifetime of the nodes. Any improvements in the power efficiency of such systems will extend sensor network lifetime and will reduce sensor network aggregate energy requirements.

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2. RELATED WORK

Most of the previous routing protocols[1–5] for wireless *ad-hoc* networks concentrate on finding and maintaining routes in the face of changing topology caused by mobility or other environmental changes. Typical protocols use shortest path algorithms based on hop count, geographic distance, or transmission power. The first two are important in minimizing delay and maximizing throughput. The third objective is peculiar to wireless *ad-hoc* networks, and is important because typically the nodes involved have a limited power supply, and radio communication consumes a large fraction of this supply. To address this issue, several power-aware routing protocols and topology control algorithms have been developed.[6–10] In most of these, the aim is to minimize the energy consumed per packet in order to deliver it to the destination. The typical approach is to use a distributed shortest path algorithm in which the edge costs are related to the power required to transmit a packet between the two nodes involved. The problem with this technique is that nodes on the minimum-energy path are quickly drained of power, affecting the network connectivity when they fail. Some of the more sophisticated routing algorithms associate a cost with routing through a node with low power reserves.[8, 9] But this remains at best a heuristic solution.

Researchers have explored the fundamental limits of energy-efficient collaborative data-gathering by deriving upper bounds on the lifetime of increasingly sophisticated sensor networks.[11] But they do not devise any efficient algorithm for routing.

Another method is proposed to extend the sensor network operational time by organizing the sensors into a maximal number of disjoint set covers that are activated successively. Only the sensors from the current active set are responsible for monitoring all targets and for transmitting the collected data, while nodes from all other sets are in a low-energy sleep mode [12]. The proposed method, however, is a heuristic. Furthermore, a shortest cost path routing algorithm is studied which uses link costs that reflect both the communication energy consumption rates and the residual energy levels at the two end nodes.[13] This approach also formulates the technique as a linear programming problem. Nevertheless, an ε-optimal polynomial time routing algorithm that maximizes the lifetime of the system with respect to the distributed energy sources has not been devised in any of the prior studies.

3. SYSTEM ARCHITECTURE

As a driver application, we consider an architecture recently proposed by our group. Our proposed system, called CustoMed, is a fascinating and critical class of distributed embedded systems for medical monitoring. The main attribute of CustoMed is its fast and easy customizability capability based on patients' needs. Firstly, the customization may be at the device level. The choice of the device, the placement of the device on the body, and the interaction level of the device with the environment will be tailored to the individual and his/her needs. Secondly, the software downloaded onto the devices can be customizable. Depending on the gender, age, medical condition, and other variables, the software downloaded onto the devices differs. The idea of customization has not been emphasized before, but is an important concern, if the system is made to be robust enough to handle many different needs, as well as unexpected needs that may arise.

CustoMed can be easily custom-built for patients by non engineering-staff. The system will be quickly assembled from basic parts and configured for use. The vision is that in the doctor's office in about five minutes, the appropriate devices and the correct number of them will be assembled and affixed to the patient. Other systems take months or even years to built, and hence lack the adaptability the system we propose. The physician will also pick from a wide range of code to download onto the devices. We developed such a tool which enables physicians to pick a specific variation of a code for a particular application and download it to the system components of CustoMed. Furthermore, it works with the environment made available to the patient. For example, in case of an emergency, the sensors can alert the security system in the house. In less urgent case, an email can be sent across the Internet or a home appliance can be turned off or on. The main component of our system is called "med nodes" which incorporate sensing, processing and communications (both wired and wireless). The processors of "med nodes" support variety of analog and digital sensors and are programmable to process the collected data from sensors. Figure 1 illustrates our CustoMed architecture connected to internet through a Pocket PC.

3.1. System Components

CustoMed is composed of the following devices:

3.1.1. Sensors:

We employ various types of sensors for continual physiological measurements as well as environmental measurements to identify wearer's physiological conditions and disorders and the case where people operating in hazardous environments. We have available to us pressure sensors, galvanic skin response sensors, flex sensors, and piezoelectric film sensors.

- Flex Sensors: The flex sensor changes resistance when bent. It will only change resistance in one direction. They can be used to measure the angular motion of various parts of body such as knees and neck.
- Pressure Sensors: These sensors are ideal for measuring forces without disturbing the dynamics of a test. They can be used to measure both static and dynamic forces. They are thin enough to enable non-intrusive

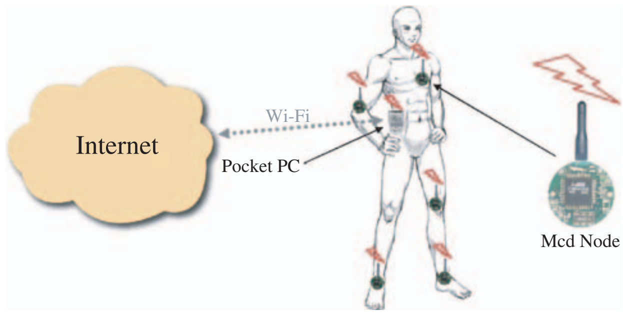

Fig. 1. System components.

measurement. Measurement of pressure under the foot is of particular interest to the clinician and researcher, particularly in the fields of diabetes, orthopedics, sports science, and rheumatology. Hence pressure sensors could be placed in shoes to perform such measurements.

- Piezoelectric Film Sensors: Piezoelectric thin film sensors generate analog voltage signals in response to applied dynamic forces. They can be used to monitor if a patient being attacked or abused by other patients.
- Galvanic Skin Response (GSR) Sensors: The galvanic skin response (GSR) also referred to as the electrodermal response (EDR), measures electrical skin conductance from the fingers or palms that is associated with sweat gland activity. It is commonly used in psychophysiology experiments to infer emotional state and cortical arousal. The GSR is commonly used in Biofeedback experiments.
- Temperature Sensors: The polymer based bulk heterojunction solar cells have demonstrated the ability to act as temperature sensor. These high performance photodetectors combined with organic-thin film transistors can be used to realize sensors that can be fabricated on flexible substrates including fabric. Such devices possess a combination of electrical performance with superior properties such as light weight, low cost of fabrication, and flexibility.[14]

3.1.2. Med Nodes

The most important component of our system is the "med nodes." "Med nodes" are stand-alone components equipped with processing units and batteries. They support various types of sensors for physiological reading from human body. These blocks enable the system to be flexible, however their basic structure remains fixed almost all the time and thus the reconfiguration time is no longer a severe limitation. Furthermore, customization of such system with a large number of "med nodes" is extremely fast. The "med nodes" can possess several parameters such that they can be complex enough to suit a range of applications. They can as well be more basic that can perform multiple operations. Furthermore, they support variety of analog and digital sensors such as flex sensors, piezoelectric sensors, pressure sensors, etc. Also the block is left software programmable which can be customized for various applications and sensors. On-chip memory blocks are also available for data storage. The processors of "med nodes" are dot-motes developed at University of California, Berkeley and manufactured by Crossbow Technology Inc. A "med node" along with a flex sensor is shown in Figure 2.

3.1.3. Pocket PC

A pocket PC is responsible for collecting data from "med nodes" and classifying them. It dispatches the critical events detected by "med nodes" or the pocket PC, itself, to the Internet. Moreover, it coordinates and controls the overall functionality of the system. The routing technique that we propose is implemented in Pocket PC.

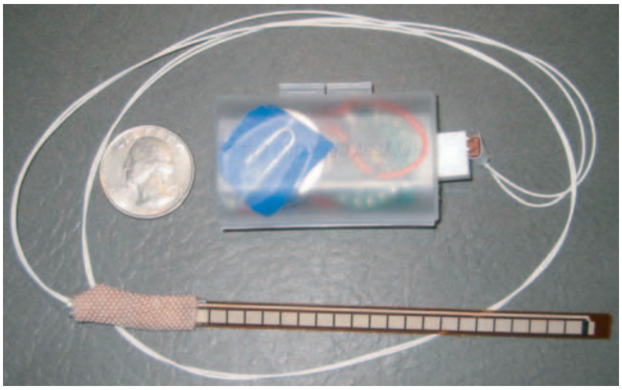

Fig. 2. A Med node along with a Flex sensor.

4. DRIVER APPLICATION

The design and development of the system framework is meant to be versatile enough to be applied to many different medical applications. The requirements of the system, specifically with the ability to quickly and easily make a custom-made system per patient, were deeply affected by this vision. The followings are two sample applications that have inspired the overall system requirements and the initial idea.

- Post-knee surgery tracking of patients: Structuring of imaging data from the musculoskeletal system will be accomplished utilizing novel MR pulse sequences to support canonical imaging values from tissue independent of acquisition techniques. Two "med nodes" are placed on knees and two on the ankles. The 'med nodes' on the knees are equipped with flex sensors while "med nodes" on the ankles utilizes pressure sensors. "Med nodes" on the knees are responsible for tracking the angular motion of the knees and transmitting the collected data to the pocket PC. "Med nodes" on the ankles, however, measure the forces and pressures under the foot as well as the load distribution. In addition, we place another "med node" on the neck to measure the angular motion of the back/neck.
- Used to aid Alzheimer's patients: The rise of Alzheimer disease is one of the greatest health crises facing the industrialized world. Today, approximately four million Americans suffer from Alzheimer's disease; by 2050, the number is expected to rise to 15 million people. CustoMed can make huge differences in the quality of life of Alzheimer's patients. It would be appropriate of the "walking well" Alzheimer's patients, who are patients that are fully mobile. Galvanic skin response sensors, which detect arousal and/or agitation by measuring skin conductance, can be placed on the patients' body. Perhaps they can be placed in their socks or in the nap of theirs neck,

two places, where there is large amount of perspiration. When agitation is sensed, proper verbal cues can be issues to the patient, to reorient them or calm them down. Also, in case of emergency CustoMed can email physicians and/or family members. CustoMed can extend the time span when patients are independent, and hence improves the quality of their life and reduce the cost incurred. CustoMed can prove to be very useful in assisted living homes, also, where the ratio of the staff to patients is about one to ten. In such situations, being hit or abuse has been a problem. Pressure sensors placed on the patients can determine a hit, but even more importantly the detection of agitation, before any harm has been done can be used to protect the patients and the staff. Perhaps, during times of agitation the staff's pagers can be cued.

5. PRELIMINARIES AND MODELS

The network model we consider is a wireless *ad-hoc* network, consisting of a set of nodes connected to each other through wireless links. The topology of the network is determined based on the physical location of the nodes, characteristics of the radio transceivers that nodes possess and the environmental effects. The nodes communicate among each other and are capable of relaying packets when needed. The problem is to design effective routing technique to satisfy our performance goal.

Consider a connected directed network graph $G_s = (V_s, E_s)$. V_s denotes the collection of nodes $1, 2, \ldots, n$. The collection of the directional links is represented by E_s. Let f_{ij} be the average flow on link (i, j) $(f_{ij} \forall (i, j) \in E_s)$ which represents the data rate from node i to j. The energy required to transmit/receive an information unit in node i is denoted by e_i. Let each node i have an initial energy level E_i (we assume that $E_i > 0\ \forall (i, j) \in V_s$). In our application E_i is the initial battery energy available. Therefore, the lifetime of node i is defined as:

$$T_i = \frac{E_i}{e_i \sum_{\forall j;\,(i,j)\in E} f_{ij}} \tag{1}$$

Where $\sum_{\forall j;\,(i,j)\in E} f_{ij}$ is the total transmission rate (i.e., packets per unit of time) of node i. For simplicity, we assume that the initial energy level is identical for the all nodes. Later, in Section 6.1, we will address how dissimilar energy levels in nodes may be accommodated.

6. PROBLEM FORMULATION

We describe a sensor network by a graph $G_s = (V_s, E_s)$, where V_s is the set of vertices, representing the sensor nodes, and E_s is the set of edges, representing their communication link. All links are directed. We will use min-cost flow formulation to address the problem. Max-flow technique applied to a network provides a feasible routing solution that guaranties the delivery of the packets from source(s) to destination(s). This observation led us to employ min-cost flow formulation to minimize our proposed power consumption objective while the routing is addressed. Furthermore, we define capacity u_i associated with each node $i \in V_s$. For each sensor node i, E_i is the current residual energy. Packets are sent in a multi-hop fashion. A 2-tuple (t_n, r_n) is associated with each node $v_n \in V_S$, where t_n is the transmission energy requirement per information unit for node n and r_n is the reception energy requirement per packet for node n. More precisely, if P information units are sent from node n to node m directly, an amount of energy equal to $P \times t_n$ will be subtracted from E_n, and $P \times r_m$ subtracted from E_m. For simplicity in writing, we assume t_n and r_n are the same for all the nodes. It is well-known that the amount of energy consumed for wireless communication of a single bit can be many orders of magnitude greater than the energy required for a single local computation. Thus, we focus our analysis to the energy used for wireless communication and we assume that the routing overhead is negligible. We allow packets from any source; however, the destination is always a certain node which we call the demand or the sink node. To solve power optimization problems in systems with distributed battery resources, we construct a network $G_t = (V_t, E_t)$ from the graph G_s based on node partitioning technique as discussed below:

Each node in graph G_s is split into $k+2$ nodes where k is a tunable parameter. Throughout the paper, we call the resulting set of nodes as a "partition." In each partition, two nodes serve as inputs and outputs and the rest are called splits. As shown in Figure 3, nodes $v_{(k+2)(i-1)+1}$ and

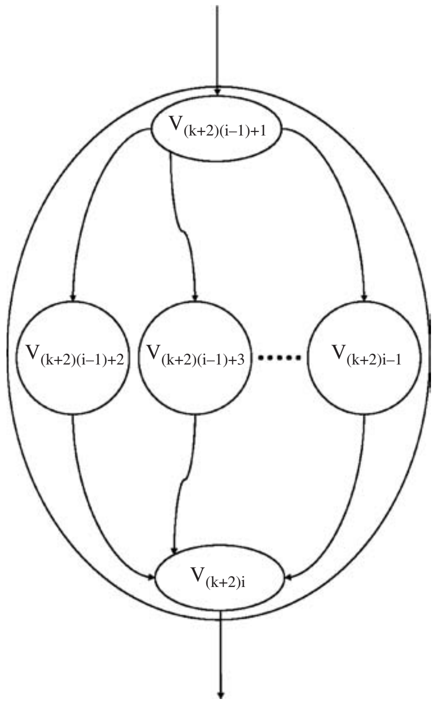

Fig. 3. Node partitioning.

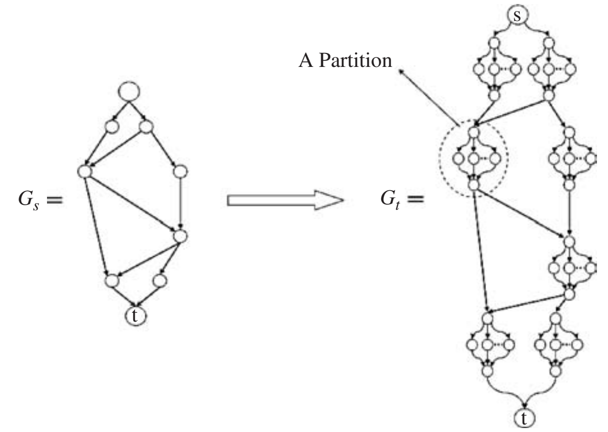

Fig. 4. original network and the resulting network after partitioning.

$v_{(k+2)i}$ are the input and the output to the partition respectively. We call the rest of the nodes split nodes, where they carry a special sequence of costs. Figure 4 shows an example of a given network and the resulting network after the transformation. Nodes s and t represent the source and sink, respectively. The cost of split nodes from left to right in Figure 3 is non-decreasing. This will ensure that when flow is being conducted through a partition, it fills up the split nodes from left to right (in min-cost flow problem, the flow tends to passes through nodes with lower costs). The capacity on each split represents a portion of the transmission capacity of a node. For further clarification, assume a node can transmit at the maximum rate of P packets per unit of time and is using l splits out of k. This is equivalent to transmission rate of $P(l/k)$ packets per unit of time and therefore will consume $1-(l/k)$ less power of the full transmission rate.

For each node i in G_s, we assign a capacity u_i. This capacity represent the amount of data per unit of time that node i can transmit. Therefore, the more flow passing through node i means the more transmission power is consumed in that node. In graph G_t, we define capacity $u_i^{'}$ associated with each split node in the network where $u_i^{'} = u_i/k$. The input and output nodes in the partition are called non-split nodes. The upper bound capacity on all non-split nodes is set to one.

For simplicity in writing the expressions, we assume that $u_i = 1$. The arc adjacency list $A(i) = \{(i, j) : (i, j) \in A\}$ contains all the arcs emanating from node i. Furthermore, we define x_{ij} as the flow through arc (i, j). Thus, the flow through node i is defined as follows:

$$y_i = \sum_{(i,j)\in A} x_{ij}$$

In sensor networks, there are a few source nodes that generate date (data from sensors) and a few destinations that the data should be delivered to. We associate with each node $i \in V_t$ a number $b(i)$ which indicates its supply or demand depending on whether $b(i) > 0$ or $b(i) < 0$. $b(i) > 0$ implies that node i is a source node which generates data with a rate proportional to $b(i)$ whereas $b(i) < 0$ represents the destination node i which responsible for gathering the information with a rate proportional to $b(i)$. The minimum cost flow problem can be stated as follows:

$$\text{Minimize} \quad z(y) = \sum_{\forall i} c_i y_i \tag{2}$$

Subject to:

$$\sum_{\{j:(i,j)\in A\}} x_{ij} - \sum_{\{j:(j,i)\in A\}} x_{ji} = b(i) \tag{3}$$

$$0 \le x_{ij} \le u_{ij}; \quad \forall (i, j) \in V_t \tag{4}$$

$$0 \le y_i \le u_i^{'}; \quad \forall (i) \in V_t \tag{5}$$

Equation (3) is the flow conservation condition at each node and Eqs. (4) and (5) are capacity constraints for the arcs and the nodes respectively. We assume that the lower bounds, l_{ij} on arc flows as well as the lower bounds, $l_i^{'}$, on node flows are all zeros. The higher bounds on arc flows are assumed to be infinity. Moreover, the number of nodes in network G_s is denoted by n. The cost on nodes in each partition is denoted by c_i and defined as follows:

$$\begin{aligned} c_{(k+2)(i-1)+1} &= 0 \\ c_{(k+2)(i-1)+2} &= 1 \\ c_{(k+2)(i-1)+3} &= n+\varepsilon \\ c_{(k+2)(i-1)+4} &= n(n+1+\varepsilon)+\varepsilon \\ &\vdots \\ c_{(k+2)i-1} &= n\left(\sum_{j=2}^{k} c_{(k+2)(i-1)+j}\right)+\varepsilon \\ c_{(k+2)i} &= 0 \end{aligned} \tag{6}$$

Without loss of generality, we assume that $\varepsilon = 1$. Thus, we have:

$$\begin{aligned} c_{(k+2)(i-1)+1} &= 0 \\ c_{(k+2)(i-1)+2} &= 1 \\ c_{(k+2)(i-1)+3} &= n+1 \\ c_{(k+2)(i-1)+4} &= n(n+2)+1 \\ &\vdots \\ c_{(k+2)i-1} &= n\left(\sum_{j=2}^{k} c_{(k+2)(i-1)+j}\right)+1 \\ c_{(k+2)i} &= 0 \end{aligned} \tag{7}$$

The cost on each split is enforced such that would be greater than the cumulative cost of the splits with smaller indices in a partition. This main property of our technique will be employed throughout the paper. In the next theorems, we will illustrate how this aids us to accommodate our objectives. The flow that passes through nodes

$v_{(k+2)(i-1)+1}$ or $v_{(k+2)(i-1)+k+2}$ (none-split nodes) in each partition represents the total flow passing through the partition. This determines the energy consumption rate at each partition which symbolizes an embedded system. The more the flow is, the shorter the lifetime of each partition is. Therefore, the objective is to minimize the amount of flow passing through each node. However, with respect to our assumptions on distributed battery sources, the lifetime of the system is determined by the minimum lifetime of the nodes in the network which corresponds to the maximum flow. Hence, the objective is to minimize the maximum flow streaming through the partitions. The flow passing through each partition passes through the splits and tends to fills the splits with lower costs. The number of splits that carries the flow is denoted by ψ.

$$\psi_i = \left\lceil \frac{\sum_{j=2}^{k+1} y_{(k+2)(i-1)+j}}{u'_i} \right\rceil \quad (8)$$

Theorem 6.1 *The objective function 2 minimizes the maximum flow in the nodes of network $G_s = (V_s, E_s)$ with maximum error ε where $\varepsilon \le u'_i = u_i/k = 1/k$. This is equivalent to maximizing the minimum battery lifetime of the nodes in network G_s (or its transformed network G_t) and therefore analogous to maximizing the lifetime of the system.*

Proof. Proof is formed by contradiction. Assume our technique generates solution L where the flow entering each partition is represented by f_i. Let $f_{\max} = (\max(f_i)\forall i)$. Assume there exist another solution L^* with maximum flow denoted by $f^*_{\max}$ where $f^*_{\max} < f_{\max} + \varepsilon$.

Thus, (8) conveys that:

$$\psi^*_{\max} < \psi_{\max}$$

Considering the cost on splits in Figure 3 and Eq. (7), we conclude that the overall cost of flow for solution L is greater than the overall cost of flow for solution L^*. This contradicts the optimality of min-cost flow technique since the solution found (L) has not minimum cost. Therefore, by contradiction, the solution L^* cannot exist and our formulation minimizes the maximum flow (or maximizes the minimum lifetime).

Due to the flow conservation condition in min-cost flow technique, it is trivial that the flow in any nodes may not be reduced individually to minimize the objective function.

The intuition behind our proposed technique is that the cost assignment on the splits forces the network to rout a flow from the kth split of node v_i, if it cannot be routed through any number of other nodes whose $(k-1)$th splits is empty.

Theorem 6.2 *The solution L, generated by our technique, minimizes the difference of the flow of every two nodes in G_s (every two partitions) with tolerance $\varepsilon = 1/k$ (minimal-skew).*

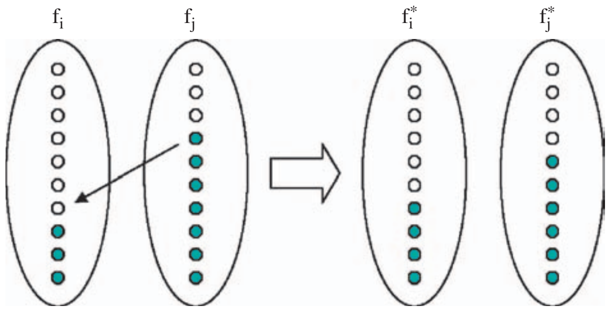

Fig. 5. Flow exchange to obtain minimal-skew solution.

Proof. This proof is presented by contradiction as well. Assume there exists a feasible solution L^* which was transformed from L and the flows of two partitions i and j was altered such that their difference is reduced. We denote the new flows in solution L^* by f^*_i and f^*_j. Without loss of generality, we assume $f_i < f_j$.

There are two scenarios that can be considered. One scenario occurs when the transformation involves changing the flow in only one partition (increasing f_i or decreasing f_j) such that $|f^*_j - f^*_i| < |f_j - f_i|$. However, according to the optimality of min-cost flow solution, this scenario is not feasible. The other scenario, as shown in Figure 6, takes place when the flow of partition i is increased and the flow of partition j is decreased (by greater than ε) such that:

$$|f^*_j - f^*_i| < |f_j - f_i| + \varepsilon$$

and (9)

$$f^*_j + f^*_i = f_j + f_i + \varepsilon$$

From Eq. (9), it is easily conveyed that:

$$f_i < f^*_i < f_j < f^*_j \quad (10)$$

Therefore, the number of splits that are utilized for passing the flow follows the same convention:

$$\psi_i < \psi^*_i < \psi_j < \psi^*_j \quad (11)$$

As discussed before, in each partition, each split has a cost that alone is greater than "n" times the cumulative cost of all the precedent splits with smaller indices ($n =$ number of nodes in G_s (original graph)). Since the solutions L and L^* are similar except in partitions i and j, therefore, the overall cost of solution L is greater than the cost of $L^*(\psi_j > \psi^*_j)$. This contradicts the optimality of min-cost flow algorithm as the solution L must have the minimum cost. Hence, solution L^* cannot exist.

Remark 6.3. Time Complexity Analysis: The time complexity of our technique is $O((m\log(nk))(m\_nk \log(nk)))$ where m is the number of edges in the graph; n and k are the number of nodes and splits in each partition, respectively. The time complexity can be easily derived from the time complexity of the min-cost flow algorithms and the size of our constructed network ($O(nk)$). The original time-complexity of min-cost flow is reported in Ref. [15]. Assume that once our technique is applied, the flow corresponding to partitions is stored in a vector denoted by F in sorted order. The next theorem states that such a vector is unique and thereafter it betrays the uniqueness of the minimal-skew solution.

Theorem 6.4 *The solution of minimal-skew routing is unique in the sense that the lifetime of nodes in the network in descending order is unique.*

Proof. Assume F and F' are the vectors containing the flow of all nodes in descending order for two optimal solutions, L and L'. Obviously $F[1] = F'[1]$, otherwise the two total costs would be different (that contradicts the optimality of the solution). Inductively, this argument holds for every index. Assume $F[i] = F'[i]$, for $i = 1 \dots k$. If $F[k+1] < F'[k+1]$ then because of the special cost assignment of the splits, the cost of $F'[k+1]$ itself would be larger than the total cost of $F[i]s$, $i = k+1 \dots n$. Therefore, the total cost of solution L' is greater than the cost of L. This contradicts the optimality of solution L'. This completes the proof.

6.1. Dissimilar Initial Energy Levels

Throughout our formulation, we assumed that the initial energy levels in all nodes are similar. Dissimilar initial energy levels, however, can be simply accommodated by modifying the capacity of the splits (upper-bounds on the splits). The throughout our formulation, we assumed that the initial energy level in all nodes are similar. Dissimilar initial energy levels, however, can be simply accommodated by modifying the capacity of the splits (upper-bounds on the splits). The main property of our technique is that we assign various costs to different levels of energy stored in a battery. When a battery is fully charged, it can be used more easily than the case it has half of the full charge. Therefore, in the case where some nodes in the network do not have full energy level, the already used portion of their battery corresponds to the splits with lesser cost. Hence, those splits could be assigned upper bound of zero in the min-cost flow formulation as if they have been already used.

6.2. Time Complexity Analysis

The formulation used for the proposed min-cost flow problem in Eqs. (2) through (5) is an LP formulation which can be solved with standard LP solvers. In our experiments, we used Matlab for this purpose. The use of LP-solvers enabled us the ability to have non-integral capacity in the formulation and non-integral flow in the solution. In order to provide combinatorial algorithms to solve such problem, integrality constraints must be enforced. Fortunately all the problem parameters such as supply/demands and capacities assigned to splits can be scaled by a factor of k (the number of splits) and meet the integrality constraints. Therefore, the time complexity of our technique is after scaling would be $O((m\log(nk))(m+nk\log(nk)))$ where m is the number of edges in the graph; n and k are the number of nodes and splits in each partition, respectively. The time complexity can be easily derived from the time complexity of the min-cost flow algorithms and the size of our constructed network ($O(nk)$). The original time-complexity of min-cost flow is reported in Ref. [15].

6.3. Discussion on Multicommodity and Distributed Routing Algorithms

In scenarios where several sources and destinations are involved and the communication pairs exchange "different" type of messages, routing problems can be modeled as multicommodity flow. Out technique can not directly address this class of problems. The problem itself is known to be NP-Complete. However, we believe that our methodology can be applied in conjunction with the known heuristics for multicommodity flow problems and generate reasonable results. We have not considered this class of networks but we plan to study it in near future.

Ideally any distributed network requires distributed algorithms for routing; yet, our proposed technique employs global and static information. We consider this as a restriction in our model and will be investigating possible solutions in future.

7. EXPERIMENTAL RESULTS

Despite power optimization is very critical in CustoMed, due to rather small number of nodes that our medical applications utilize (as of now, less than ten). We generate random graphs with relatively larger number of nodes to illustrate the effectiveness of our technique. We evaluate the effectiveness of our method on various benchmarks. We generate two set of random networks. Three source nodes with flow of one each and one sink node with flow of three is randomly placed in the network. For simplicity, we assumed that the energy level in all benchmarks is uniform. In the first set, the locations of the nodes are generated conforming to a random uniform distribution over an area of size 20×10. The connectivity between nodes is determined by their Euclidean distance. Moreover, we alter the communication range and generate various random networks. Throughout the experimental analysis, we refer to this class of random networks as uniformly distributed random networks. The other set of networks we considered more resembles real-world sensor networks. In most sensor network applications, it might be unlikely that a large portion of sensor nodes are placed within close proximity of each other. Instead, they are placed on a grid

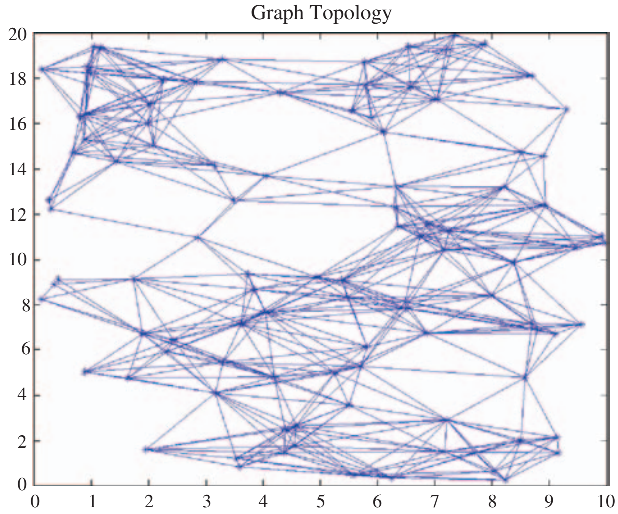

Fig. 6. Graph topology ($r = 3$, $n = 100$, uniform random distribution).

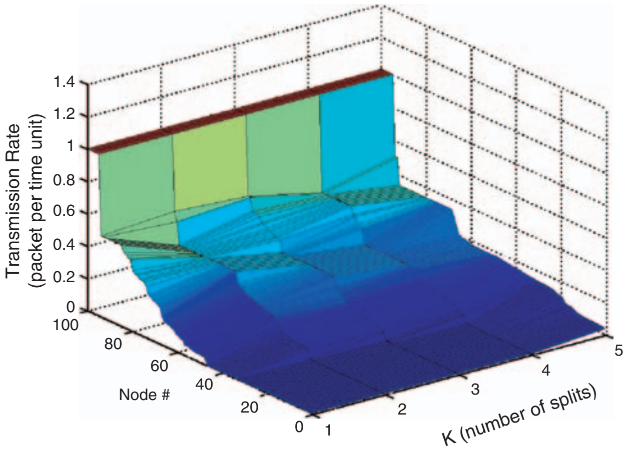

Fig. 7. Transmission rate in sorted order ($r = 3$, $n = 100$, uniform random distribution).

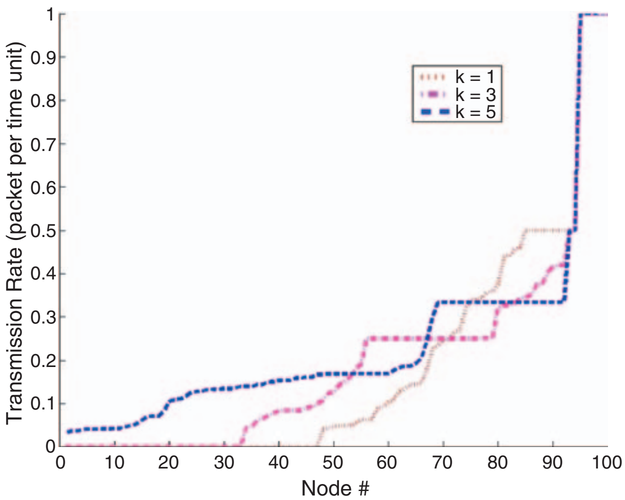

Fig. 8. Transmission rate for $k = 1, 3, 5$ ($r = 3$, $n = 100$, uniform random distribution).

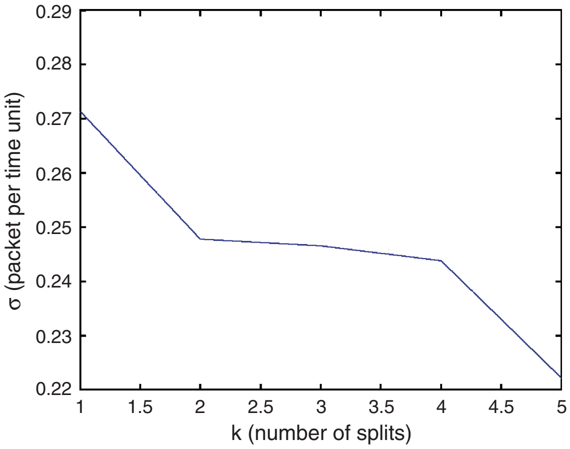

Fig. 9. Standard deviation for $k = 1 \ldots 5$ ($r = 3$, $n = 100$, uniform random distribution).

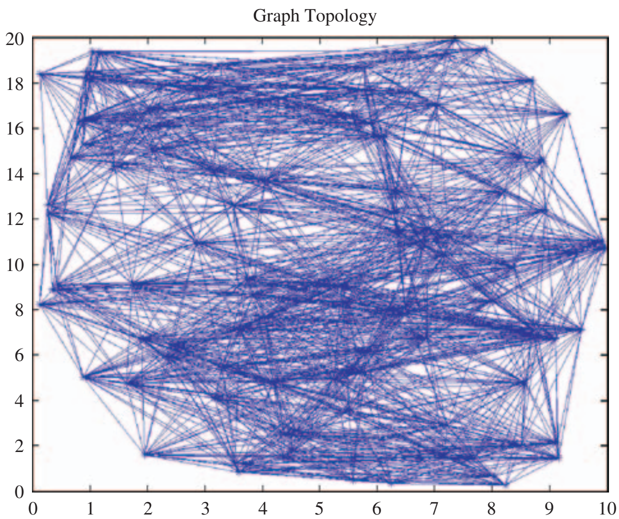

Fig. 10. Graph topology ($r = 6$, $n = 100$, uniform random distribution).

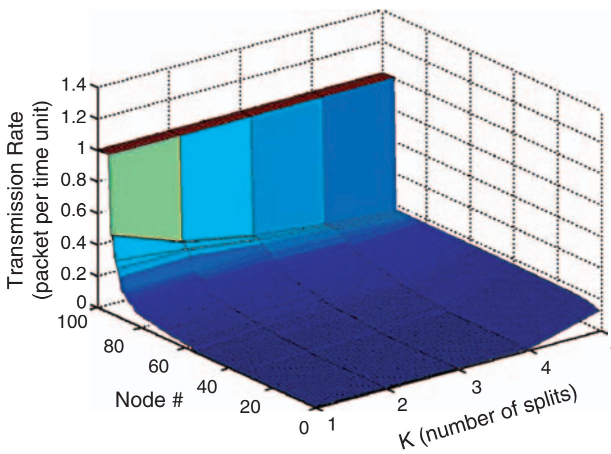

Fig. 11. Transmission rate in sorted order ($r = 6$, $n = 100$, uniform random distribution).

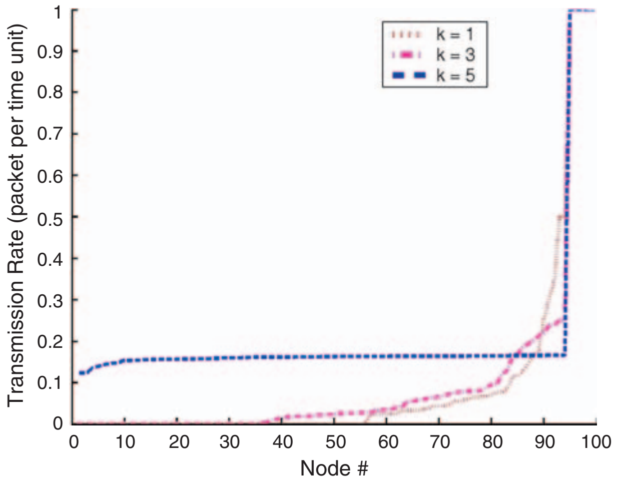

Fig. 12. Transmission rate for $k = 1, 3, 5$ ($r = 6$, $n = 100$, uniform random distribution).

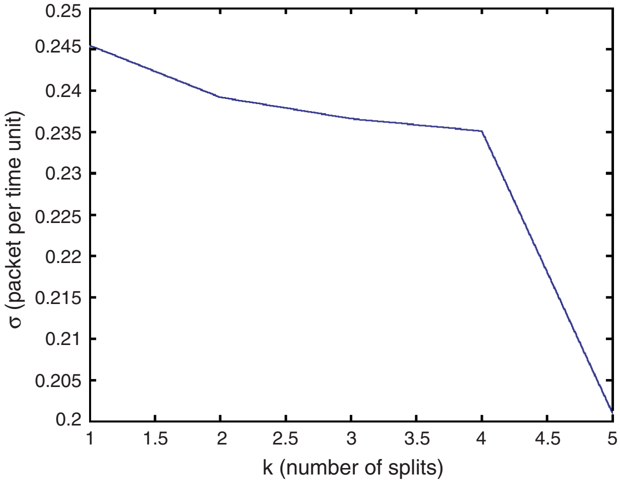

Fig. 13. Standard deviation for $k = 1 \ldots 5$ ($r = 6$, $n = 100$, uniform random distribution).

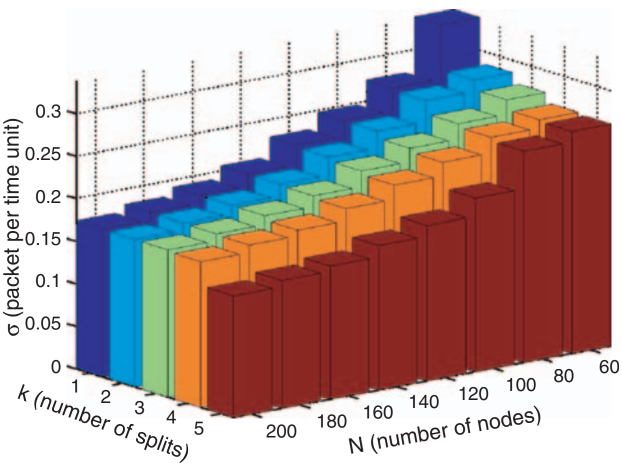

Fig. 14. Standard deviation of transmission rate ($r = 4$, uniform random distribution).

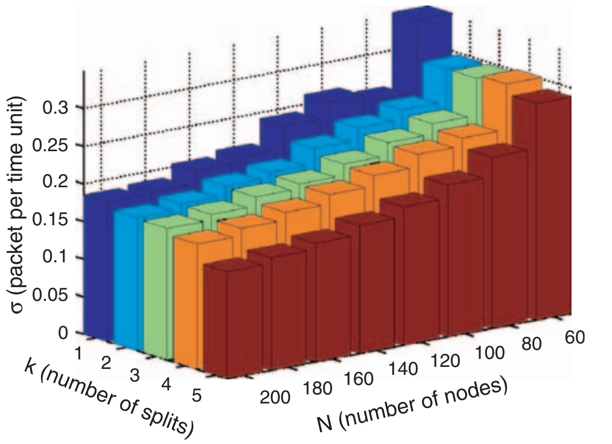

Fig. 15. Standard deviation of transmission rate ($r = 4$, random grid distribution).

with certain random properties. It can be envisioned as a 'locally random globally regular networks.' Such scenario can be imagined with the following example: Certain number of sensor nodes is required to be placed in a building. Each room has a specific number of sensor nodes which is constant, yet, the position of the nodes is random within each room. We call this set as random networks with grid distribution. We generate such benchmarks by dividing the area into unit-size tiles. A tile that does not have a sensor node is selected randomly. We place a node in the tile with uniform distribution. This procedure is repeated until all tiles are covered. If more sensor nodes are required to be inserted, the same course is recurred until all sensor nodes are placed.

Firstly, we evaluate our methodology one two different random networks. They are both uniformly distributed. In the first graph, the communication range is set to $r = 3$. It has 100 nodes placed with uniform random distribution as illustrated in Figure 6.

Figures 7 and 8 depict the normalized power consumption rate of the nodes in the system sorted in ascending

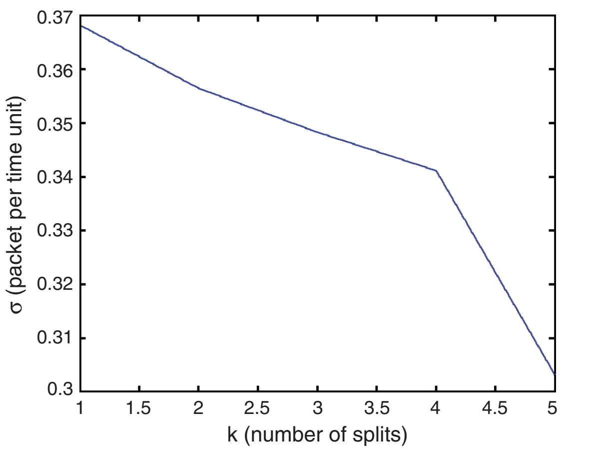

Fig. 16. Average standard deviation of transmission rate ($r = 4$, uniform random distribution).

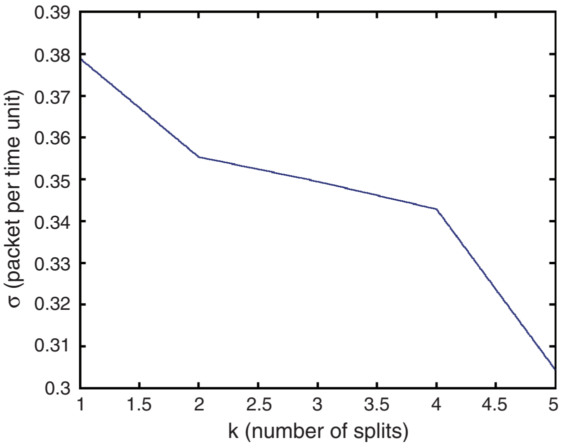

Fig. 17. Average standard deviation of transmission rate ($r = 4$, random grid distribution).

order for various numbers of splits (k). Figure 8 exhibits the effectiveness of our algorithm on how the power consumption rate becomes evenly distributed when k is increased. Standard deviation is an appropriate measure to show the skew of a set of data. As shown in Figure 9, as the number of splits (k) increases, the standard deviation decreases.

Figures 10, 11, 12, and 13 exhibit the same properties as Figures 6, 7, 8, and 9 respectively. In this graph, however, the communications range us changed to 6. This increases the connectivity of the network and therefore, our technique achieves a solution with better quality with larger value of k-number of splits. Figure 12 clearly shows the effectiveness for ($k = 5$).

In the next set of the experiments, the number of nodes is varied. Each sample data in Figures 14 and 15 represents an average on standard deviation of 10 random networks. The random networks generated for Figure 14 have uniformly distributed random nodes while the benchmarks for Figure 15 generated with random grid distribution property. It is evident from Figure 15 that our technique

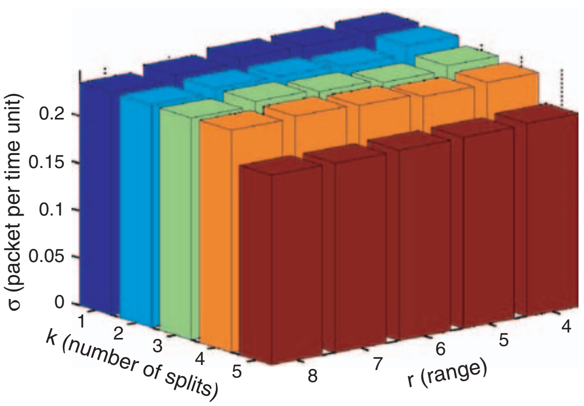

Fig. 18. Standard deviation of transmission rate ($n = 100$, uniform random distribution).

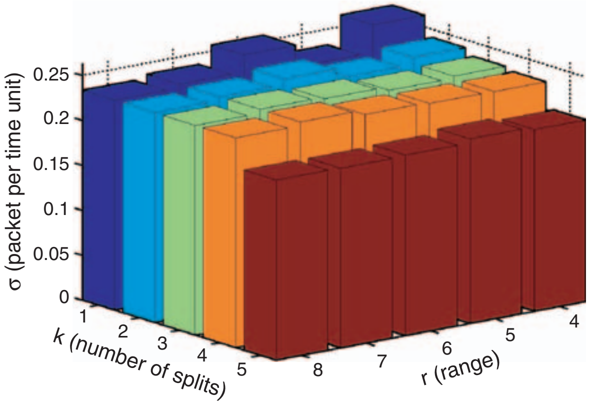

Fig. 19. Standard deviation of transmission rate ($n = 100$, random grid distribution).

performs better on random grid graphs since their structure has more regularity. This property can be clearly observed with the number of nodes is smaller.

Figures 16 and 17 illustrate the average standard deviation of benchmarks presented in Figures 14 and 15 over various number of nodes for $k = 1, \ldots, 5$. This provides an estimate on the performance of our scheme. In general, highly connected networks provide a large number of parallel paths between nodes which is of our interest and enhances the flexibility of data routing.

Figure 16 depicts data-points for uniformly distributed random networks while Figure 17 presents random grid networks.

In the final set of experiments, we fixed the number of nodes ($n = 100$) and varied the communication range ($r = 4, \ldots 8$). The communication range was not increased beyond 8 since the network became highly connected and the performance remained constant. Figures 18 and 19 correspond to uniformly random distributed networks and random grid distribution, respectively.

8. CONCLUSION

We proposed a polynomial time ε-optimal technique for multi-hop routing in wireless networks with distributed battery sources. Our technique maximizes the lifetime of the system. Furthermore, it evenly distributes the power consumption rate which yields in a minimal-skew solution for node utilization. We theoretically proved that our technique is efficient and has polynomial time complexity. Furthermore, our investigation on various benchmarks revealed the quality of the solutions generated by our methodology even for small number of splits.

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