Optimum Multi-Hop Transmission Strategies for Energy Constrained Wireless Sensor Networks

Jingxian Wu* and Yahong Rosa Zheng†
*Dept. of Electrical Engineering, University of Arkansas, Fayetteville, AR 72701, USA
†Dept. of Electrical & Computer Eng., Missouri University of Science & Technology, Rolla, MO 65409, USA

Abstract— **This paper presents optimum multi-hop transmission strategies (MHTS) for energy constrained wireless sensor networks (WSNs). Nodes in a multi-hop WSN need to transmit their own information and to relay each other's information to a base station (BS), and there are usually multiple available paths between a node and the BS. The optimum MHTS derived in this paper answers three questions: 1) how should a node divide its limited energy between the transmission of the self-information and the relay-information? 2) whether a single path or a combination of multiple paths should be used to route the information from a node to the BS? and 3) if multi-path routing is used, how should a single data stream be divided among the multiple paths? The answers to these questions are obtained by minimizing the energy per bit, or equivalently, by maximizing the amount of information delivered to the BS under certain energy constraints. Two different scheduling strategies are considered, the fair equal information strategy that requires all the nodes deliver the same amount of information to the BS, and the unfair maximum information strategy that maximizes the total amount of information delivered to the BS. The optimum MHTS for these two strategies are derived, with either convex optimization or analytical expressions, under a per node energy constraint and a total energy constraint, respectively.**

I. Introduction

Energy efficient communication is one of the most formidable challenges faced by the development of wireless sensor networks (WSNs) for applications such as structure health monitoring (SHM), environment monitoring, and biomedical sensing. To match the life cycle of the monitored objects, WSNs are often expected to operate uninterrupted over a long period of time under the constraints of extremely limited battery capacity or small energy scavenging devices.

There have been considerable efforts devoted to energy efficient communications for wireless networks during the past decade [1]–[11]. Existing low energy/low power wireless network technologies can be roughly divided into three categories. The first category uses cluster-based hierarchical routing [1]–[4], such as low-energy adaptive clustering hierarchy (LEACH) [1], and power efficient gathering in sensor information systems (PEGASIS) [2], which provide localized control and balanced power consumption. Many of the hierarchical routing schemes are designed in conjunction with data fusion algorithms to exploit the spatial data redundancy in the network [1], [4]. The second category relies on joint routing-scheduling to maximize the throughput among node pairs [5], or to reduce the activation time of the wireless nodes [6], [7]. The third category tries to extend or maximize the network lifetime by employing multi-path routing, where the data between a source-destination pair is delivered through multiple parallel paths to balance the energy consumption of the network [8]–[11].

Most of these energy aware techniques are developed from the perspectives of transmission scheduling or information routing, and many of them are developed heuristically [1], [8], [11]. They do not provide an answer to one of the most fundamental questions for an energy constrained network: what is the most efficient way to utilize the limited energy such that the energy required to transmit one bit is minimized? The answer to the above question lies in two aspects. First, a node not only needs to transmit its own information, but also to relay the information for other nodes. Therefore it is critical to determine how to divide the limited energy between the transmission of the self-information and the relay-information. Second, there are usually more than one multi-hop paths between a source and its destination. Which path(s) to choose and how to divide the information flow and limited energy among the multiple paths will have a significant impact on the energy efficiency of the entire network.

In this paper, we will answer the above questions by developing optimum multi-hop transmission strategies (MHTS) for a given WSN to minimize the energy per bit, or equivalently, to maximize the information delivered to the BS under certain energy constraints. We define an MHTS as an allocation of the limited energy between the self-information and the relay-information, and among the multiple transmission paths. It should be noted that the optimum MHTS is different from multi-path routing, which does not specify the energy allocation among the multiple paths, and provides no guidelines on the choice between the self-information and the relay-information.

Two different transmission strategies are considered during the identification of the optimum MHTS. The first strategy strives to ensure the fairness among the nodes by requiring that all the nodes deliver an equal amount of self-information to the BS, and it is called the equal information (EI) strategy. The second strategy tries to maximize the total amount of information delivered to the BS without considering fairness among the nodes, and it is denoted as the maximum information (MI) strategy. Both the EI and MI strategies are investigated, respectively, under a per node energy constraint, where each node has its own energy constraint, and a total energy constraint, where the total energy of all the nodes are limited. The optimum MHTS for a WSN under different fairness and energy constraints are identified, and the results provide valuable guidelines on the development of practical WSNs with extremely limited energy.

II. Problem Formulation

Consider a WSN with N sensor nodes and one BS. The coordinate of the n-th sensor node is $\mathbf{c}_n = [c_{n1}, \cdots, c_{nd}]^T \in \mathcal{R}^{d\times 1}$, where $d = 1, 2$ or 3 is the dimension of the monitored area. Information collected by all the sensor nodes is converged to the BS through single or multi-hop transmissions. Without loss of generality, the BS is assumed to be node 0 at the origin of the coordinate system with a coordinate $\mathbf{c}_0 = \mathbf{0}_d$, where $\mathbf{0}_d$ is a length-d all-zero vector.

The energy required to transmit one bit between a node pair, (m, n), through a one-hop transmission is assumed to be

$$E_{mn} = \left(\frac{l_{mn}}{l_0}\right)^{\alpha} E_0 \tag{1}$$

where α is the pathloss exponent, E_0 is the energy required to transmit a bit over a reference distance l_0, and $l_{mn} = \|\mathbf{c}_m - \mathbf{c}_n\|$ is the distance between nodes m and n, with $\|\mathbf{a}\| = \sqrt{\mathbf{a}^T\mathbf{a}}$ being the L_2-norm of the real vector $\mathbf{a}$. It is assumed in this paper that the distance between any transmission-receiving pair is always bigger than l_0.

In the multi-hop transmission, node m can be a potential next-hop relay for node n if $E_{nm} + E_{m0} < E_{n0}$, *i.e.*, the energy required for a direct transmission between node n and the BS (node 0) is bigger than the total energy when using node m as a relay between the two. From (1), the above energy relationship can be alternatively represented as $l_{mn}^{\alpha} + l_{m0}^{\alpha} < l_{n0}^{\alpha}$.

Define a set of nodes that contains all the potential next-hop relays for node n as

$$\mathcal{O}_n = \left\{m | l_{mn}^{\alpha} + l_{m0}^{\alpha} \le l_{n0}^{\alpha}, m \in \mathcal{N}_n\right\}, \tag{2}$$

where $\mathcal{N}_n = \{0, 1, \cdots, n-1, n+1, \cdots, N\}$. It should be noted that $0 \in \mathcal{O}_n$, $\forall n = 1, \cdots, N$, where 0 represents the BS.

For each node in the network, we can also define a previous-hop set, which contains all the nodes that can potentially use node n as its immediate next-hop, as

$$\mathcal{P}_n = \left\{m | n \in \mathcal{O}_m, m \in \mathcal{N}_n\right\}. \tag{3}$$

Lemma 1: In a network, there exists at least one node with an one-element next-hop set, $\{0\}$.

Proof: Proof by contradiction. Assume all the nodes have a next-hop set with more than one element. Assume node n has the smallest distance to the BS, *i.e.*, $l_{n0} \le l_{m0}, \forall m \ne n$. Based on the assumption, there exists at least one node $m \in \mathcal{O}_n$ with $m \ne 0$ and $m \ne n$. Thus $l_{n0}^{\alpha} \ge l_{m0}^{\alpha} + l_{mn}^{\alpha}$. This contradicts with the fact $l_{n0} \le l_{m0}$, given that $l_{mn} > 0$ for $m \ne n$. ■

Node n can choose one or more nodes from $\mathcal{O}_n$ as its next-hop based on certain optimization criteria. If more than one nodes are chosen as the next-hop for node n, then the total traffic from node n will be distributed among the multiple next-hop nodes. Let x_{nk}, $\forall k \in \mathcal{O}_n$, denote the number of bits transmitted from node n to node k through a one-hop transmission. The corresponding energy used for the one-hop transmission between nodes (n, k) is thus $x_{nk}E_{nk}$.

Based on the above notations, the total number of bits delivered by node n can then be expressed as

$$\sum_{k\in\mathcal{O}_n} x_{nk} = \sum_{m\in\mathcal{P}_n} x_{mn} + x_n, \tag{4}$$

where x_n is node n's self-information. In (4), the left hand side is the total number of bits transmitted by node n, and the right hand side is the total number of bits received and/or generated by node n.

The total energy consumption for node n can then be calculated by

$$E_n = \sum_{k\in\mathcal{O}_n} x_{nk}E_{nk}. \tag{5}$$

Definition 1: (MHTS) A member of the set, $\{x_{nk}E_{nk} | k \in \mathcal{O}_n, n = 1, \cdots, N\}$, which satisfies the constraints in (4) and (5) is defined as a multi-hop transmission strategy of a wireless network. ■

In this paper, the optimum MHTS is developed by considering different fairness constraints: the fair EI strategy, where all the nodes deliver exactly the same number of bits to the BS, *i.e.*, $x_1 = \cdots = x_N$, and the unfair MI strategy, where $x_T = \sum_{n=1}^{N} x_n$ is maximized. The optimum MHTS for a WSN with a per node energy constraint and a total energy constraint are discussed in the next two sections, respectively.

III. Optimum Multi-hop Transmission with a Per Node Energy Constraint

The optimum MHTS for a given WSN with a constraint on the maximum energy for each node, E_n, for $n = 1, \cdots, N$, is discussed in this section.

A. Equal Information Strategy

The EI strategy strives to ensure the fairness among the nodes by requiring all the nodes in the network deliver the same amount of information to the BS. Let $x = x_1 = \cdots = x_N$, then the optimization can be represented as

$$\begin{aligned} \text{maximize} \quad & x \\ \text{subject to} \quad & \sum_{k\in\mathcal{O}_n} x_{nk} = \sum_{m\in\mathcal{P}_n} x_{mn} + x, \\ & \sum_{k\in\mathcal{O}_n} x_{nk}E_{nk} \le E_n, \\ \text{and} \quad & x \ge 0 \end{aligned} \tag{6}$$

where E_n is the maximum energy for the n-th node.

This is a convex optimization problem and it can be alternatively represented in matrix format as

$$\begin{aligned} \text{maximize} \quad & x \\ \text{subject to} \quad & \mathbf{O}\mathbf{x} = \mathbf{P}\mathbf{x} + \mathbf{1}_N \cdot x \\ & \mathbf{R}\mathbf{x} \le \mathbf{e} \\ \text{and} \quad & x \ge 0 \end{aligned} \tag{7}$$

where $\mathbf{e} = \frac{l_0^\alpha}{E_0}[E_1, \cdots, E_N] \in \mathcal{R}^{N\times 1}$ is the normalized energy constraint vector, $\mathbf{1}_N$ is a length-N all-one vector, $\mathbf{x} = [\mathbf{x}_1^T, \cdots, \mathbf{x}_N^T]^T$, with $\mathbf{x}_n = [x_{nk}]_{k\in\mathcal{O}_n}$ being a length $|\mathcal{O}_n|$ column vector containing the numbers of bits forwarded by node n to the different next-hops, and $|\mathcal{O}_n|$ is the cardinality of the set $\mathcal{O}_n$. The matrices $\mathbf{O}$ and $\mathbf{P}$ are size $N \times \sum_{n=1}^{N} |\mathcal{O}_n|$ binary matrices. For the matrix $\mathbf{O}$, there are $|\mathcal{O}_n|$ consecutive ones on the n-th row, with the column index of the first non-zero element on the n-th row being $\sum_{u=1}^{n-1} |\mathcal{O}_u|$. All the other elements on the n-th row of $\mathcal{O}_n$ are zeros. For the matrix $\mathbf{P}$, the $(n, \sum_{u=1}^{m-1} |\mathcal{O}_u|+k)$-th element is 1 if the k-th element of $\mathbf{x}_m$ is x_{mn}, and 0 otherwise. The matrix $\mathbf{R}$ is a size $N \times \sum_{k=1}^{N} |\mathcal{O}_n|$ matrix. If we denote the k-th element of $\mathbf{x}_n$ as x_{nn_k}, then the $(n, \sum_{u=1}^{n-1} |\mathcal{O}|_u + k)$-th element of $\mathbf{R}$ is $l_{nn_k}^\alpha$.

The optimization problem described in (7) can be easily solved with standard convex optimization tools such as `cvx` [13].

The optimum MHTS for the 6-node network in Fig. 1 with $E_1 = \cdots = E_N = 100\frac{E_0}{l_0^\alpha}$ is shown in Table 1.

Table 1. The optimum MHTS for a network with EI and a per node energy constraint (values are percentage of E_n).

	BS	1	2	3	4	5	6
1	100						
2	56.8	43.2					
3		100					
4	61.0		39.0				
5	6.7		79.4	13.9			
6	40.9					59.1	

In Table 1, the row and column represent the transmitter and the next-hop receiver, respectively. The results are shown as the percentage of energy allocated to the (row, column) communication link by the corresponding transmitter. For example, node 1 allocates 100% of its energy to the (1, BS) link, and node 2 allocates 56.8% energy to the (2, BS) link, and 43.2% to the (2, 1) link.

With the MHTS given in Table 1, the optimum value of x is 12.8 bits, *i.e.*, each node can transmit 12.8 bits self-information with an energy constraint of $100\frac{E_0}{l_0^\alpha}$. Therefore, the total number of new bits delivered to the BS is $x_T^{\text{EI-EN}} = x \cdot N = 76.8$ bits.

We have the following observations from the result. 1) A node n does not transmit to all the nodes in its next-hop set $\mathcal{O}_n$. For example, $\mathcal{O}_6 = \{0, 1, 2, 3, 4, 5\}$, yet it only transmits to nodes 0 (BS) and 5. 2) Nodes that are close to the BS spend a large portion of its own energy to relay information for other nodes. For example, node 1 has a single direct path to the BS, and it only uses 12.8% of its total energy for self-information, and the remaining 87.2% of energy for relay-information. On the other hand, node 6 spend 100% of its energy transmitting its own information. 3) Most nodes have direct links to the BS in addition to other possible indirect links, even for node 6, which is the furthest from the BS. 4) The choice of the next-hop depends heavily on the geometric locations of the nodes. The nodes have a high tendency to choose its immediate neighbor as one of the desired next-hop nodes.

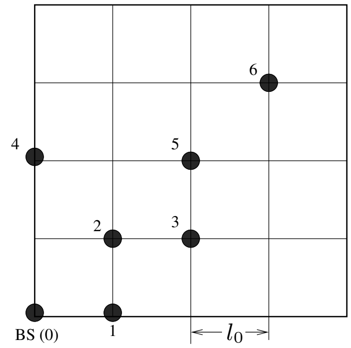

Fig. 1. A WSN with 6 sensor nodes and 1 BS.

Since the EI scheme strives to maintain the fairness among all the nodes, the nodes that are close to the BS spend the majority of its own energy relaying information for other nodes. The fairness is achieved at the cost of reducing the total amount of information transmitted to the BS.

B. Maximum Information Strategy

The target function of the MI strategy is to maximize $x_T = \sum_{n=1}^{N} x_n$, the total number of bits delivered to the BS.

Similar to (7), the problem can be formulated as a convex optimization problem as

$$\begin{aligned} \text{maximize} \quad & \mathbf{1}_N^T \mathbf{x}_0 \\ \text{subject to} \quad & \mathbf{O}\mathbf{x} = \mathbf{P}\mathbf{x} + \mathbf{x}_0, \\ & \mathbf{R}\mathbf{x} \leq \mathbf{e}, \\ \text{and} \quad & x_n > 0, \end{aligned} \tag{8}$$

where $\mathbf{x}_0 = [x_1, \cdots, x_N]^T \in \mathcal{R}^{N\times 1}$ contains the amounts of self-information for different nodes, and the rest of the definitions are the same as in (7).

Instead of directly performing convex optimization on (8), the optimum MHTS for a system with the MI strategy can be obtained analytically based on the following proposition.

Proposition 1: For a wireless network employing the MI strategy described in (8) and a per node energy constraint, all the nodes will transmit directly to the BS without using other nodes as relay.

Proof: Based on Lemma 1, we can always find a node, say n, that has a next-hop set, $\mathcal{O}_n = \{0\}$, and $n \in \mathcal{O}_m$ for some node m. When both m and n transmit directly to the BS, the numbers of bits delivered to the BS by the two nodes are $x_{m1} = \frac{\bar{E}_m}{l_{m0}^\alpha}$ and $x_{n1} = \frac{\bar{E}_n}{l_{m0}^\alpha}$, respectively, where $\bar{E}_m = \frac{E_m l_0^\alpha}{E_0}$ is the normalized transmission energy of the m-th node.

Consider the case that node m uses node n as a relay. Assume node m allocates $\beta\bar{E}_m$ for the (m, n) link, with $\beta < 1$, and use the remaining $(1-\beta)\bar{E}_m$ energy for the $(m, 0)$ link. In such a case, the number of bits delivered by node m to the BS is $x_{m2} = \frac{(1-\beta)\bar{E}_m}{l_{m0}^\alpha} + \frac{\beta\bar{E}_m}{l_{mn}^\alpha}$. Since node n can only transmit to the BS, the maximum number of bits that can be delivered by node n is fixed at x_{n1} due to its own energy limit. Thus the number of node n's self-information bits is $x_{n2} = \frac{\bar{E}_n}{l_{m0}^\alpha} - \frac{\beta\bar{E}_m}{l_{mn}^\alpha}$.

It is apparent that $x_{m1}+x_{n1} > x_{m2}+x_{n2}$. Therefore, m needs to transmit directly to the BS.

Assume node $m \in \mathcal{O}_p$, then the above argument can be easily extended to nodes p and m. Since node m needs to directly transmit to the BS, then the total number of bits transmitted by nodes p and m will be reduced if node p uses node m as its relay. Therefore node p needs to transmit directly to the BS. The above analysis can be applied recursively to all the nodes in the network, and this completes the proof. ■

Based on Proposition 1, we can directly have the optimum MHTS, where all the nodes act selfishly by allocating 100% of its energy for the transmission of their own information and there is no relay. The corresponding number of bits transmitted by the n-th node is thus

$$x_n = \frac{E_n}{E_0}\left(\frac{l_0}{l_{n0}}\right)^{\alpha}. \tag{9}$$

The total amount of information delivered to the BS can then be calculated by

$$x_T^{\text{MI-EN}} = \sum_{n=1}^{N}\frac{E_n}{E_0}\left(\frac{l_0}{l_{n0}}\right)^{\alpha}. \tag{10}$$

For the 6-node network in Fig. 1 with $E_1 = \cdots = E_N = 100\frac{E_0}{l_0^{\alpha}}$, we have

$$[x_1, x_2, x_3, x_4, x_5, x_6] = [100, 35.4, 8.9, 12.5, 4.4, 1.3], \tag{11}$$

and $x_T^{\text{MI-EN}} = 162.5$ bits, which is a $(x_T^{\text{MI-EN}} - x_T^{\text{EI-EN}})/x_T^{\text{EI-EN}} \times 100\% = 111.6\%$ increase over $x_T^{\text{EI-EN}}$ under the same energy constraint. The performance improvement is achieved at the cost of unfairness among the nodes. It can be seen that node 1 transmits the maximum amount of information (100 bits) and node 6 transmits the least amount (1.3 bits).

The above results are obtained with the analytical expressions in (9) and (10). We also verified the results by solving the convex optimization in (8), which yields the same result.

IV. Optimum Multi-hop Transmission with a Total Energy Constraint

The optimum multi-hop transmission strategies for a wireless network with a constraint on the total energy, $E_T = \sum_{n=1}^{N} E_n$, and various fairness conditions are discussed in this section.

A. Equal Information Strategy

The optimum MHTS with the EI strategy and a total energy constraint can be easily obtained by modifying (7), and the result is

$$\begin{aligned} &\text{maximize} && x \\ &\text{subject to} && \mathbf{Ox} = \mathbf{Px} + \mathbf{1}_N \cdot x, \\ & && \mathbf{rx} \le E_T, \\ &\text{and} && x \ge 0, \end{aligned} \tag{12}$$

where $\mathbf{r} = \sum_{n=1}^{N}\mathbf{R}_{(n,:)}$ is a row vector, with $\mathbf{R}_{(n,:)}$ being the n-th row of $\mathbf{R}$, and E_T is the total energy constraint.

In order to get a better understanding of the optimum MHTS satisfying (12), we have the following definition.

Definition 2: (Normalized Accumulated Energy) If $[n, r_1, \cdots, r_{k_n}, 0]$ is a possible multi-hop relay path between node n and the BS, then define the normalized accumulated energy (NAE) along this path as

$$\bar{E}_{n0} = l_{nr_1}^{\alpha} + \sum_{m=1}^{k_n-1} l_{r_m r_{m+1}}^{\alpha} + l_{r_{k_n}0}^{\alpha}. \tag{13}$$

■

We have the following proposition regarding the optimum MHTS for a network with the EI strategy and a total energy constraint.

Proposition 2: Consider a wireless network employing the fair EI strategy and operating under a total energy constraint. When there are more than one relay paths between a node n and the BS, the node n following the optimum MHTS will always choose the path with the smallest NAE. If there are two or more paths with the same smallest NAE between node n and the BS, then the node can choose any combination of these paths without affecting the optimality.

Proof: Assume each node will transmit x bits self-information to the BS. If all the nodes transmit by using the path with the smallest NAE, then the total energy consumption will be $E_{\text{opt}} = \frac{xE_0}{l_0^{\alpha}}\sum_{n=1}^{N}\bar{E}_{n0}^{\min}$, where $\bar{E}_{n0}^{\min}$ is the smallest NAE between the nodes n and 0. If any node, say node m, transmits by choosing the path with the NAE being $\bar{E}_{m0} > \bar{E}_{m0}^{\min}$, then the total energy required for the system will be $E' = E_{\text{opt}} + x(E_{m0} - E_{m0}^{\min})$. Therefore any deviation from the scheme described in the proposition will require more energy for the same amount of information, or transmit less information for a fixed total energy. ■

The result in Proposition 2 indicates that each node can choose just one node as its next-hop. When there are more than one paths with the same smallest NAE, using just one path or any combination of these paths leads to the same energy consumption.

The transmission strategy described in Proposition 2 can simplify the identification of the optimum MHTS, which can be solved without resorting to the convex optimization described in (12). Noting the fact that the transmission strategy described in Proposition 2 resembles a shortest path routing problem, we can find the optimum relay paths by using the well known Dijkstra algorithm. To simplify analysis, we will limit each node with one and only one next-hop and this restriction will not affect the optimality of the MHTS.

Once the optimum relay paths are identified with the Dijkstra algorithm, define $\mathcal{H}_n$ as the set of nodes that have node n on their optimum relay paths to the BS. Please note that $n \in \mathcal{H}_n$. The total energy consumption of the system can then be calculated as

$$E_T = x\sum_{n=1}^{N}|\mathcal{H}_n|E_{nn_h}. \tag{14}$$

where $n_h \in \mathcal{O}_n$ is the next-hop of n that is on the optimum path between nodes n and 0. The optimum value of x given E_T can then be solved by using (14).

Based on the transmission scheme described in Proposition 2, the optimum MHTS for the network in Fig. 1 with a total energy constraint of $E_T = 100\frac{E_0}{l_0^\alpha} \times 6$ is given in Table 2, and the corresponding optimum value of x is 27.7 bits. The total amount of information delivered to the BS is thus $x_T^{\text{EI-ET}} = 27.7 \times 6 = 166.2$ bits.

Table 2. The optimum MHTS for a network with EI and a total energy constraint (values are percentage of E_T/N).

	BS	1	2	3	4	5	6
1	166.2						
2		138.5					
3			83.1				
4			78.4				
5				55.4			
6						78.4	

The results in Table 2 are shown as the percentage of E_T/N. For example, node 1 consumes 166.2% of E_T/N for the (1, BS) link, and node 6 consumes 78.4% of E_T/N for the (6, 5) link. From the results in Table 2, it can be seen that each node has exactly one next-hop node. In this particular example, the next-hop node happens to be the node that has the shortest distance with the source node. The nodes that are closer to the BS need to relay information for those that are further away, thus they generally consume more energy.

Under the same total energy and the fair EI strategy, the total amount of information delivered under a total energy constraint increases $(x_T^{\text{EI-ET}} - x_T^{\text{EI-EN}})/x_T^{\text{EI-EN}} \times 100\% = 116\%$ over that with a per node energy constraint. Therefore, tremendous performance gain can be achieved by unevenly distributing energy among the nodes based on their geographical locations.

Please note that the above results are obtained by using the analytical method as in (14). They are also verified with the convex optimization in (12), which lead to the same result.

B. Maximum Information Strategy

The optimization for a wireless network that employs the MI strategy and operates under a total energy constraint is trivial. In this case, the maximum information can be achieved by allocating all the energy to the node that is closest to the BS. As a result, the wireless network degrades to a single transmitter-receiver link. This case does not have much practical value, yet we still present it here for completeness.

For the network in Fig. 1, the optimum MHTS with MI and a total energy constraint of $100\frac{E_0}{l_0^\alpha} \times 6$ is $x = 600$ bits, and the total amount of information delivered to the BS is thus $x_T^{\text{MI-ET}} = 600$ bits, the absolute maximum that can be achieved by this network, at the cost that only one node can deliver its information to the BS.

V. Conclusions

The optimum multi-hop transmission strategies for WSNs with multiple sources and one BS have been analyzed in this paper. The MHTS was optimized by minimizing the energy per bit, or equivalently, by maximizing the amount of successfully delivered information under certain energy constraints. Two different scheduling strategies, the fair EI strategy and the unfair MI strategy, were investigated under two different energy constraints, the per node energy constraint and the total energy constraint. The combination of the two scheduling strategies and the two energy constraints yield four different cases. The results showed that nodes in a network with the MI strategy acted selfishly and they used only one-hop direct transmissions, yet multi-hop transmissions were used by networks with the EI strategy, under both energy constraints. Among all the system configurations, EI with a per node energy constraint had the highest energy per bit, followed by MI with a per node energy constraint, EI with a total energy constraint, and MI with a total energy constraint. For the EI strategy, relaxing the energy constraint from per node to a total energy constraint resulted in a 116% increase in the total amount of information delivered to the BS.

References

[1] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Hawaii IEEE Intern. Conf. System Science*, vol. 2, pp. 1 - 10, Jan. 2000.

[2] S. Lindsey and C. S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in *Proc. IEEE Conf. Aerospace*, vol. 3, pp. 1125 - 1130, 2002.

[3] S. Bandyopadhyay, E. J. Coyle, "An energy efficient hierarchical clustering algorithm for wireless sensor networks," in *Proc. INFOCOM'03*, vol. 3, pp. 1713-1723, 2003.

[4] S. Pattem, B. Krishnamachari and R. Govindan, "The impact of spatial correlation on routing with compression in wireless sensor networks," *ACM Transactions on Sensor Networks*, vol. 4, Aug. 2008.

[5] M. Kodialam and T. Nandagopal, "Characterizing achievable rates in multi-hop wireless networks: the joint routing and scheduling problem," in *Proc. Intern. Conf. Mobile Computing and Networking MobiCom'03*, pp. 42-54, Sept. 2003.

[6] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," *Wireless Networks*, vol. 8, pp. 481-494, 2002.

[7] J. Zhang, H. Wu, Q. Zhang, and B. Li, "Joint routing and scheduling in multi-radio multi-channel multi-hop wireless networks," in *Proc. Intern. Conf. Broadband Networks BroadNets'05*, vol. 3, pp. 1109-1115, March. 2002.

[8] C. Schurgers, M. B. Srivastava, "Energy efficient routing in wireless sensor networks," in *Proc. Mil. Commun. Conf. MILCOM'01*, vol. 1, pp. 357-361, 2001.

[9] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Wireless Networks*, vol. 11, pp. 471-487, 2005.

[10] J. Zhu and S. Papavassiliou, "On the energy-efficient organization and the lifetime of multi-hop sensor networks," *Wireless Networks*, vol. 11, pp. 471-487, 2005.

[11] X. Hong, M. Gerla, and H. Wang, "Load balanced, energy-aware communications for mars sensor networks," in *Proc. of IEEE Aerospace 2002*, vol. 3, pp. 1109-1115, March. 2002.

[12] J. Wu, "Ultra-low power compressive wireless sensing for distributed wireless networks," in *Proc. IEEE Mil. Commun. Conf. MILCOM'09*, pp.1-7, Oct. 2009.

[13] M. Grant and S. Boyd, "CVX: Matlab Software for Disciplined Convex Programming, version 1.21," http://cvxr.com/cvx, Apr. 2011.