Efficient Minimum-cost Bandwidth-constrained Routing in Wireless Sensor Networks^{+}

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***Abstract*— A critical issue in the design of routing protocols for wireless sensor networks is the efficient utilization of resources such as scarce bandwidth and limited energy supply. Many routing schemes proposed in the literature try to minimize the energy consumed in routing or maximize the lifetime of the sensor network without taking into consideration limited bandwidth of wireless links. This can lead to congestion, increased delay, packet losses and ultimately to retransmission of packets, which will waste considerable amount of energy. This paper presents a routing protocol, which minimizes the total cost of routing while guaranteeing that the load on each wireless link does not exceed its capacity. The protocol is derived from a combinatorial optimization problem, known as the minimum-cost flow problem in the operations research literature. Because we use polynomial-time minimum-cost flow algorithms, the protocol is highly scalable. The proposed protocol is compared with the maximum lifetime bandwidth constrained routing protocol [1] (formulated as an Integer Linear Program). Simulation results indicate that the proposed protocol achieves longer lifetimes, delivers more number of messages and has higher residual energy than the maximum lifetime bandwidth constrained routing protocol for the test example.**

I. INTRODUCTION

Wireless sensor networks, designed to monitor and/or control the surrounding environmental phenomena, have the potential to revolutionize many applications. A sensor network consists of sensor nodes and one or more base stations. Sensor nodes generate, process, and forward data (via intermediate sensor nodes) to base stations. Among the major design challenges in the design of sensor networks is the efficient utilization of resources available to sensor nodes such as scarce bandwidth and limited energy supply. Addressing these issues at the routing layer is very important due to the significant amount of energy consumed in transmitting high volume of data generated by the sensor nodes.

A. Motivation

The conventional way of routing in sensor networks is to route packets on the minimum-cost path from the source to the destination. The minimum-cost shortest path tree (rooted at the base station) connecting all nodes can be constructed to identify the minimum-cost paths from sensor nodes to base stations. Routing the data packets towards the base station on these minimum-cost paths is efficient provided the rate of information generation is low or the channel bandwidth is sufficiently high. However, if the nodes generate data constantly and bandwidth is limited[1], then routing data on the minimum-cost paths can overload wireless links close to the base station. A routing protocol that does not take the wireless channel bandwidth limitation into consideration might route the packets over highly congested links and paths. This will lead to increase in congestion, increased delay and packet losses, which in turn will cause retransmission of packets thereby increasing energy consumption.

This paper presents Minimum-Cost Bandwidth-Constrained Routing (MCBCR) protocol, which finds routes for transferring data from sensor nodes to base stations while guaranteeing that the load on a channel does not exceed its capacity. The proposed protocol is compared with the Maximum Lifetime Bandwidth Constraint Routing (MLBCR) [1] protocol. Simulation results indicate that the proposed protocol outperforms MLBCR protocol.

B. Objectives

In MCBCR, resource rich base stations are responsible for finding routes. Therefore, system wide floodings to discover new routes are avoided and sensor nodes are spared from maintaining huge routing tables, topology-related information and traffic-states. Since the base stations have the global view of the sensor network, routes computed at the base stations are more efficient. MCBCR can be solved in polynomial-time. Therefore, MCBCR is fast and is scalable. MCBCR avoids congestion, minimizes end-to-end delay and improves QoS by routing the data traffic such that the traffic on a wireless channel does not exceed its capacity.

II. RELATED WORK

Routing protocols for sensor networks have drawn the attention of many researchers. Chang and Tassiulas [1] define the routing problem as an optimization problem where the objective is to maximize the lifetime of a network (i.e. time until the first battery drains-out). Their model has been extended by Zussman and Segall [2] to account for the nodes

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[1] As per the IEEE 802.15.4 standard, there can be as many as 65,536 nodes in the network and the raw data rate can be 20, 40 or 250 Kb/s per node.

processing and transmitting limitations. Our work is closely related to the work of Chang and Tassiulas [1].

A cluster-based energy-efficient protocol is proposed by Heinzelman, et al. [3] and a minimum-cost forwarding protocol is proposed by Ye, et al. [4]. He, et al. [5] have developed a stateless protocol for real-time communication in sensor networks. Routing with the objective of maximizing the total number of messages successfully carried is addressed by Kar et al. [6]. Optimizing the network lifetime when the message sequence is not known is addressed by Li, et al. [7]. Gandham, et al. [8] deploy multiple mobile base stations to prolong the lifetime of sensor networks. The major difference between MCBCR and other protocols is that MCBCR takes into consideration the capacity of the wireless channel while making routing decisions.

III. SYSTEM MODEL

The following assumptions are made about the system model.

1) A sensor network consists of sensor nodes and base stations.
2) Sensor nodes are deployed in an ad-hoc basis for unattended operation and they are static. (No mobility.)
3) Sensor nodes can estimate and control the rate at which data packets are generated. All the data packets are of the same size.
4) Sensor nodes can communicate with other sensor nodes and base stations within their radio transmission range using a MAC protocol. The MAC protocol determines the mean rate at which a sensor node can transmit data to its neighbor over a wireless channel. This rate is the channel capacity.
5) Sensor nodes can dynamically control their radio signal power.
6) Sensor nodes can estimate the energy level of their batteries at any time and estimate the energy consumed in transmitting and receiving one unit of data.
7) Multiple base stations are deployed and their locations are fixed and known a priori.
8) Base stations have sufficient hardware, sufficient software and constant power supply. All the base stations can communicate with each other without interfering with the rest of the sensor network.
9) All the base stations are homogeneous. Thus, the sensor node can send data packets to any base station.
10) The predominant traffic in the network is data traffic from sensor nodes to base stations.

Properties 5 and 6 are desirable for energy efficiency and are optional in our MCBCR protocol.

IV. MINIMUM-COST BANDWIDTH-CONSTRAINED ROUTING

A. Problem formulation

The sensor network under consideration is modeled as a directed graph $G(V, A)$ where $V = V_s \cup V_b$ where V_s represents the set of sensor nodes and V_b represents the set of base stations.

Let $N_i \subset V$ be the set of nodes, called the *neighbor set* of node i, that can be directly reached by node i in one hop. A is the set of all directed links (i, j) where $i \in V$, $j \in V$ and $j \in N_i$. Each directed link (i, j) has an associated cost per packet c_{ij} and a capacity u_{ij} expressed in number of packets per unit time. Let d_i represent the rate at which the data packets are generated at the sensor node i per unit time. Let C_{max} denote the maximum magnitude of any link cost. Let U_{max} denote the maximum magnitude of any d_i or the maximum magnitude of finite link capacity (whichever is greater). The energy required to transmit one data packet from node i to its neighbor j is represented by T_{ij}. The energy required to receive one data packet at node i from its neighbor j is represented by R_{ij}. It is assumed that only one node, to which the packet is intended, will consume the energy in receiving it. Other nodes, which are neighbors of the transmitter node, will be in the sleep mode or will be communicating with their other neighbors when a packet not destined for them is being transmitted. The flow of packets from node i to its neighbor j over wireless link (i, j) is represented by f_{ij}. Each sensor node i has an initial battery energy BE_i and a residual battery energy RE_i at a time instant where RE_i is normalized to its initial energy. $0 \leq RE_i \leq 1$.

The objective is to deliver all the data packets generated by sensor nodes to base stations in the most cost-effective manner without exceeding the link capacities. Formally, the problem can be stated as follows.

$$Obj = Min \sum_{(i,j) \in A} c_{ij} f_{ij}$$

Subject to

$$\sum_{\{j:(i,j) \in A\}} f_{ij} - \sum_{\{j:(j,i) \in A\}} f_{ji} = d_i \qquad \forall i \in V_s, \tag{1a}$$

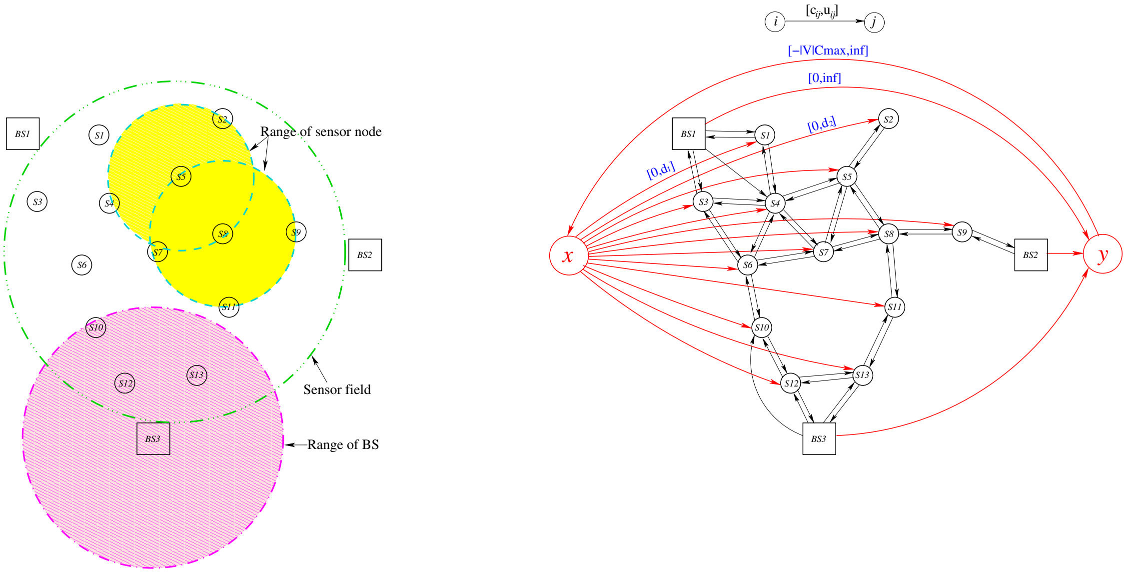
$$\sum_{\{k:k \in V_b\}} \Big(\sum_{\{j:(k,j) \in A\}} f_{kj} - \sum_{\{j:(j,k) \in A\}} f_{jk} \Big) = - \sum_{\{i:i \in V_s\}} d_i, \tag{1b}$$

$$0 \leq f_{ij} \leq u_{ij} \qquad \forall (i, j) \in A, \tag{1c}$$

$$f_{ij} \in Z^+ \qquad \forall (i, j) \in A. \tag{1d}$$

The first set of constraints (1a) ensures flow conservation at each sensor node. The second constraint (1b) ensures that base stations receive all the packets generated by all the sensor nodes. The flow of packets on a link must not exceed its capacity and this is ensured by the third set of constraints (1c). The fourth set of constraints (1d) ensures that the (packet) flow values are integers.

Fig. 1a shows an example of a deployed sensor network. The radio transmission ranges of sensor nodes 5 and 8, and base station 3 are shown by shaded circles. The connectivity graph induced by radio transmission ranges of sensor nodes and base stations is shown in Fig. 1b. The additional nodes x and y and links attached to them in Fig. 1b. are explained in the next subsection.



(a) Deployed Sensor Network

(b) Transformed Graph G'

Fig. 1. Minimum-cost Circulation

B. Solution

The above defined problem is similar to the *minimum-cost flow* problem, known in the operations research literature [9]. We will convert the above problem into *the minimum-cost circulation* problem as follows (see Fig.1b).

1) Add a super source x, and a super sink y, to the graph $G(V, A)$.
2) Add directed links (x, i), connecting the super source x to sensor node i, for all $i \in V_s$. Set costs of these links to 0 and the capacities to d_i.
3) Add directed links (j, y) connecting the base station j to the super sink y, for all $j \in V_b$. Set costs of these links to 0 and the capacities to infinity.
4) Add a directed link (y, x) connecting the super sink y to the super source x. Set the cost of the link (y, x) to $-|V|C_{max}$ and the capacity to infinity.
5) The modified graph is defined as $G'(V \cup \{x, y\}, A \cup A')$, where $A' = \{(x, i) : i \in V_s\} \cup \{(j, y) : j \in V_b\} \cup \{(y, x)\}$.

The minimum-cost circulation problem can be solved efficiently using well-known minimum-cost flow algorithms [10], [11], [12]. An advantage of the minimum-cost flow algorithm is the integrality of flows. If all link capacities and expected data rates of nodes are integers, then the minimum-cost flow algorithm can find paths with integral flow values.

C. Analysis of the solution

Pushing more flow from x to y will decrease the overall cost of the flow due to fact that the link from y back to x has sufficiently large negative cost. It is clear that the maximum flow is bounded from above by $F = d_1 + d_2 + ... + d_{|V_s|}$ because F is the maximum possible flow going out of x, the super source. There are two possibilities that have to be analyzed.

Case 1: $\sum_{\{i:i \in V_s\}} f_{xi} = \sum_{\{i:i \in V_s\}} d_i$

In this case, all the links of the form (x, i), $i \in V_s$ are saturated. The maximum-flow is restricted by the capacities of these links. Consider a link $(x, 1)$ having the capacity d_1. Since all the (x, i) links are saturated, the input flow at node 1 must be $d_1 + \sum_{\{j:(j,1) \in A\}} f_{j1}$ and the output flow must be equal to the input flow (flow conservation). There must be paths from node 1 to base stations which carry the flow $d_1 + \sum_{\{j:(j,1) \in A\}} f_{j1}$. The same argument holds for other nodes.

Case 2: $\sum_{\{i:i \in V_s\}} f_{xi} < \sum_{\{i:i \in V_s\}} d_i$

In this case the maximum flow is restricted by the capacities on the actual links ($(i, j) \in A$) of the network. The minimum-cost flow algorithm will identify the paths from the sensor node i to the base stations which carry the flow d'_i, where $0 \leq d'_i \leq d_i$, $\forall i \in V_s$. The flow on the links (x, i) would be d'_i, $\forall i \in V_s$.

In case 2, the sensor network cannot support the data rate of some nodes. The base station can instruct those nodes to lower their data rates. Alternatively, the base station can instruct a few sensor nodes in the densely populated regions to lower their data rates. The intuition behind this idea is that lowering the data rate of some nodes in densely populated areas is better than leaving pockets of areas of the sensor field unattended.

If the channel capacities are infinite then the paths identified by the MCBCR are the minimum-cost paths from sensor nodes to their nearest base stations. In reality, wireless channels have very limited bandwidth. This might force some packets to take longer paths than the minimum-cost path they would have taken if sufficient bandwidth were available.

D. Running-time complexity

The complexity of MCBCR protocol is bounded by the complexity of the minimum-cost flow algorithm. Let

$|V \cup \{x,y\}| = n$ and $|A \cup A'| = m$. The running time of some of the best known minimum-cost flow algorithms are $O(nmlog(n^2/m)log(nC_{max}))$ [10], $O(nm(loglogU_{max})log(nC_{max}))$ [11] and $O((mlogn)(m + nlogn))$ [12].

E. Load Balancing

The nodes can be prevented from being overloaded by setting a limit on the number of packets a sensor node can handle per unit time. Also, if a contention-based MAC protocol is used, then the nodes have limited capacities. The set of constraints in (2) can be added to ensure that sum of incoming and outgoing packets through a sensor node does not exceed its capacity. Let P_i represent the maximum number of packets node i can handle per unit time, called the *node capacity*.

$$\sum_{\{j:(i,j)\in A\}} f_{ij} + \sum_{\{j:(j,i)\in A\}} f_{ji} \le P_i \quad \forall i \in V_s, \tag{2}$$

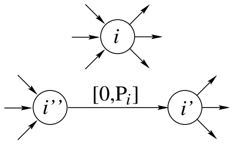


Fig. 2. Node splitting

1) Split each node $i \in V$ into two virtual nodes i' and i'' (Fig.2). The input flow into node i corresponds to the input flow into node i'' and the output flow from node i corresponds to the output flow from node i'.
2) For each link $(i,j) \in A \cup A'$, do the following: Replace (i,j) by a link (i',j'') of the same cost and capacity. Add a link (i'',i'). Set the cost of link (i'',i') to zero and capacity to P_i for each node $i \in V_s$. The information generated by node i is assumed to be generated at node i''.

The above mentioned transformation will cause node i'' to receive all the input flow of node i. The output flow of node i will be sent by the node i'. The link (i'',i') will carry the flow from input to the output which is restricted by its capacity P_i. The appropriate value of P_i will limit the data traffic handled by a node which, in turn, will limit the energy consumed, memory, processing power needed and delay (caused by a node).

V. MAXIMUM LIFETIME BANDWIDTH CONSTRAINT ROUTING

Chang and Tassiulas [1] have presented Linear Programming (LP) formulation of energy conserving routing in sensor networks where the performance objective is to maximize the network lifetime (i.e. to maximize the time until the first battery drains-out among all the sensor nodes.) We extend their LP formulation to include channel bandwidth constraints, node capacity constraints and impose the integrality of the flow values. Formally, the problem can be stated as follows where l denotes the lifetime of the network.

$$Obj = Max \quad l$$

Subject to

$$\sum_{\{j:(i,j)\in A\}} f_{ij}\cdot l - \sum_{\{j:(j,i)\in A\}} f_{ji}\cdot l = d_i \cdot l \quad \forall i \in V_s, \tag{3a}$$

$$\sum_{\{k:k\in V_b\}} \Big(\sum_{\{j:(k,j)\in A\}} f_{kj}\cdot l - \sum_{\{j:(j,k)\in A\}} f_{jk}\cdot l \Big) = - \sum_{\{i:i\in V_s\}} d_i \cdot l, \tag{3b}$$

$$\sum_{\{j:(i,j)\in A\}} f_{ij}\cdot l + \sum_{\{j:(j,i)\in A\}} f_{ji}\cdot l \le P_i \cdot l \quad \forall i \in V_s, \tag{3c}$$

$$\sum_{\{j:(i,j)\in A\}} T_{ij}\cdot f_{ij}\cdot l + \sum_{\{j:(j,i)\in A\}} R_{ji}\cdot f_{ji}\cdot l \le BE_i \quad \forall i \in V_s, \tag{3d}$$

$$0 \le f_{ij}\cdot l \le u_{ij}\cdot l, \quad f_{ij} \in Z^{+} \quad \forall (i,j) \in A, \tag{3e}$$

$$0 < l. \tag{3f}$$

The first set of constraints in (3a) ensures flow conservation at each sensor node. The second constraint in (3b) ensures that base stations receive all the packets generated by sensor nodes. Sum of incoming and outgoing packets through a sensor node must not exceed its capacity which is ensured by the third set of constraints in (3c). The fourth set of constraints (3d) ensures that the total energy consumed by a sensor node over the lifetime must not exceed total available energy. The constraints in (3e) and (3f) ensure that the flow of packets on a link does not exceed its capacity, the flow values are integers and the network lifetime is positive.

If the integrality of flow variables is not required then the above problem can be transformed into an LP problem by replacing each occurrence of $f_{ij}\cdot l$ by a new variable $\overline{f_{ij}}$. Resulting non-integer values of flow variables can be rounded to integers which will result in sub-optimal routing of packets, decreasing the lifetimes of nodes. Alternatively, a packet can be fragmented into multiple packets, but this option is very expensive due to the overheads involved. Therefore, we restrict the flow variables to integers in our model. In order to linearize constraints, divide both sides of constraints involving variable l by $l > 0$ and replace $1/l$ with a new variable. Maximizing the lifetime (l) is equivalent to minimizing the $1/l$ in the transformed problem. Note that the resulting ILP formulation needs to be solved once in the beginning, and whenever a forwarding node dies thereafter.

VI. COMMUNICATION COST MODEL

If the transmitter is capable of adjusting its signal power level (depending on the distance of the intended receiver from the transmitter) such that the power consumed in transmission is minimized, the transmission energy model is called variable. In constant transmission energy model, the transmitter transmits at the same power level irrespective of the distance between the transmitter and the intended receiver.

In our work, we assume that constant amount of energy is consumed in internal processing of a packet whereas the energy consumed in an amplifying the signal to achieve acceptable signal to noise ratio at a receiver is proportional to the square of the distance between transmitter and the intended receiver [3]. In the variable transmission energy model used in simulations, the cost of transmitting a packet from node i to j is given by

$$T_{ij} = (\mathit{Size}) \times (10.0 + 0.1 \times \mathit{Dist}_{ij}^2) \times 10^{-9} \qquad \mathit{EnergyUnits}$$

where Size represents the size of a packet in bits and Dist_{ij} represents actual distance between neighbors i and j in meters.

In the constant transmission energy model used in simulations, the cost of transmitting a packet from node i to j is given by

$$T = (\mathit{Size}) \times (10.0 + 0.1 \times \mathit{Range}^2) \times 10^{-9} \qquad \mathit{EnergyUnits}$$

where Range denotes the transmission range of a sensor node in meters.

The cost of receiving a packet is the same in both the models and is given by

$$R = (\mathit{Size}) \times (10.0) \times 10^{-9} \qquad \mathit{EnergyUnits}$$

The performance of the MCBCR protocol depends on the link cost function used to evaluate routes. The following cost function [1] is used in simulations:

$$c_{ij} = (T_{ij} + R_{ji})^{\alpha} / {RE_i}^{\beta} \qquad \forall (i,j) \in A$$

Where α and β are non-negative weighting factors. If $\alpha = 1$ and $\beta = 0$, then MCBCR protocol will minimize the total energy consumed in routing. If $\beta = 0$, then the minimum-cost circulation problem needs to be solved once in the beginning and whenever a forwarding node dies thereafter. If $\beta \neq 0$, then the minimum-cost circulation problem needs to be solved periodically to account for the residual energy of sensor nodes. Let γ denote the time interval between periodic routing updates.

VII. SIMULATION RESULTS

The performances of MCBCR and MLBCR are compared using randomly generated sensor network topologies. 100 sensor nodes are randomly distributed in a sensor field of size 100 m × 100 m. Four base stations are deployed on the periphery of the sensor field, one in the middle of each side of the square field. The transmission range of each sensor node is 25.0 meters. The transmission range of each base station is 50.0 meters. The routes are computed at one of the base stations and are distributed to the sensor nodes. The size of each data packet is 500 bits and the size of each routing packet is 200 bits. The node capacity of each sensor node is 40.0 Kbps and the link capacity of each wireless link is 10.0 Kbps. The rate of information generation is 1 packet/second. Each sensor node is equipped with initial energy of 1.0 EnergyUnit.

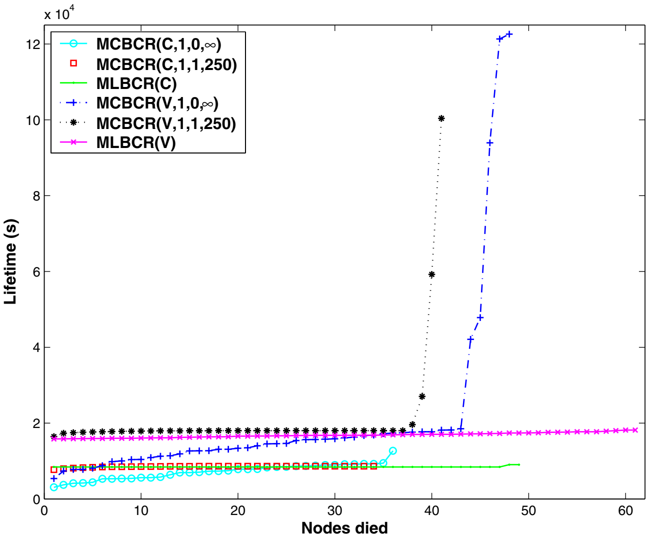


Fig. 3. Lifetimes of sensor nodes

MLBCR protocols under constant and variable transmission energy models are denoted by MLBCR(C) and MLBCR(V) respectively. MCBCR(C,α,β,γ) and MCBCR(V,α,β,γ) denote MCBCR protocols under constant and variable transmission energy models respectively where the last three parameters inside the parenthesis are input parameters. If $\beta = 0$ then $\gamma = \infty$ which means the routing information is updated only when a sensor node dies. If $\beta \neq 0$ then the routing information is updated when the time elapsed since the last routing update is γ or when a sensor node dies, whichever occurs first. We compare following protocols.

1) MCBCR(C,1,0,∞), 2) MCBCR(C,1,1,250), 3) MLBCR(C) 4) MCBCR(V,1,0,∞) 5) MCBCR(V,1,1,250) 6) MLBCR(V).

Fig.3 shows the time when the batteries of sensor nodes drain-out. Note that the network becomes disconnected when all the sensor nodes which can directly transmit packets to base stations have died. In MLBCR(C) and MLBCR(V) the lifetimes of individual sensor nodes are close whereas in MCBCR(C,1,0,∞) and MCBCR(V,1,0,∞) the lifetimes of individual sensor nodes vary significantly. MLBCR balances the energy consumed by a few heavily loaded sensor nodes close to base stations by adjusting the flow of packets through them. The flow of packets through lightly loaded sensor nodes can be sub-optimal which significantly increases the total energy consumed in routing. Therefore, in MLBCR, many sensor nodes die in a short period of time and the total number of sensor nodes that die when the network becomes completely disconnected is very high, lowering the residual energy of the network as shown in Fig. 4.

MCBCR(C,1,0,∞) and MCBCR(V,1,0,∞) minimiz the total energy consumed in the routing, so heavily loaded nodes die quickly and lightly loaded nodes die very late. MCBCR(C,1,1,250) has the highest residual energy and the least number of nodes are dead. In MCBCR, a few sensor nodes live a long time compared to most other nodes because they are located in such a position that routing packets of other nodes through them is either very expensive or is not feasible. For example, routing packets through a node located very close to a base station is very expensive because the energy consumed in processing and receiving packets is very

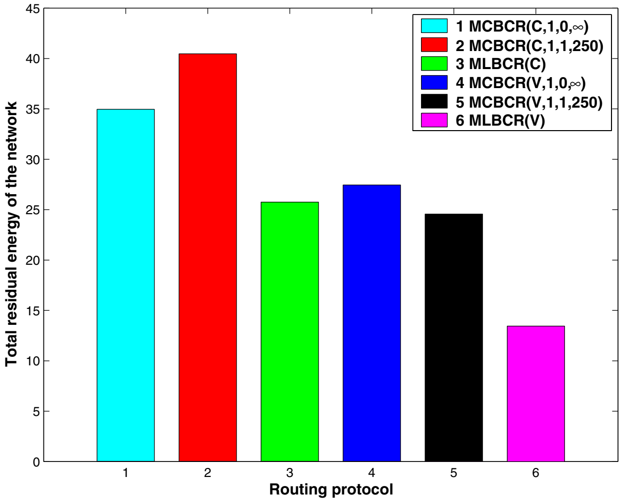


Fig. 4. Residual energy of the network

high compared to energy saved by an amplifier.

MCBCR(C,1,1,250) and MCBCR(V,1,1,250) balance the energy consumption by periodically updating routes. As the residual energy of a sensor node decreases, the cost of using outgoing links from that sensor node increases. Note that lifetimes of most sensor nodes in MCBCR(V,1,1,250) are longer than those in MLBCR(V). The following example (Fig.5) explains why periodic MCBCR performs better than MLBCR.

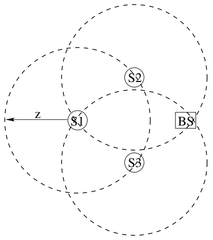


Fig. 5. MCBCR v/s MLBCR

In the above scenario (Fig.5), the life of the forwarding node (either 2 or 3) will be very short compared to that of non-forwarding nodes. If the responsibility of forwarding packets of node 1 is equally shared between nodes 2 and 3 then the time until the first battery drains-out can be increased. MCBCR(C/V,α,$\beta \neq 0$,γ) can achieve this effect by periodically toggling the responsibility of forwarding between nodes 2 and 3.

Fig. 6 shows the total number of messages received until the network becomes completely disconnected. The number of messages received in variable transmission energy models is more than double the total number of messages received in constant transmission energy models because the lifetimes of nodes in former are more than double the lifetimes of nodes in later. The total number of messages received in MCBCR(C,1,0,∞), MCBCR(C,1,1,250) and MLBCR(C) are almost the same because the lifetimes of nodes in all the three models are very close. MCBCR(V,1,0,∞) receives the highest total number of messages followed by MCBCR(V,1,1,250) because in both schemes, a few lightly loaded sensor nodes last a long time.

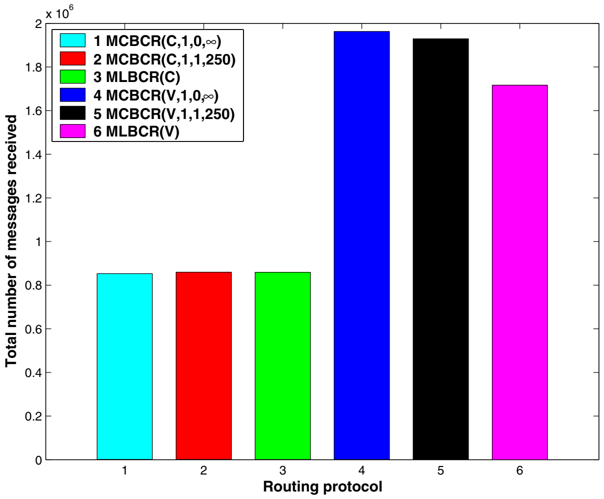


Fig. 6. Total number of messages received

The lifetimes of nodes in a variable transmission energy model are more than double the lifetimes of nodes in a constant transmission energy model (See Fig.1). Clearly, equipping sensor nodes with power control transmitters can increase lifetimes of sensor nodes. The energy consumed in processing and receiving a packet is independent of the distance between the transmitter and the receiver. Therefore, actual increase in the lifetime depends on the energy saved in an amplifier. In our model, the energy saved by a power control transmitter is proportional to $Range^2 - Dist_{ij}^2$ where $Dist_{ij}$ is the actual distance between neighbors i and j. If the transmission range is increased then the ratio of lifetimes in the variable transmission energy model to lifetimes in the constant transmission energy model should also increase. We compared the lifetimes of nodes in MCBCR(V,1,1,250) to the lifetimes of nodes in MCBCR(C,1,1,250) when the transmission range of the nodes was increased to 50.0 meters. Simulation results showed that lifetimes of nodes in MCBCR(V,1,1,250) were more than three times of those in MCBCR(C,1,1,250). However, if the energy consumed by the amplifier is less than the energy consumed in processing and receiving a packet, increase in lifetimes due to power controlled transmitters can be very little.

The impact of changes in transmission range on the lifetimes of sensor nodes in MCBCR(V,1,1,250) and in MCBCR(C,1,1,250) are shown in Fig.7 and Fig.8 respectively. Clearly, the number of dead nodes when the network becomes completedly disconncted increases with increase in transmission range. Lifetimes of nodes in the variable transmission energy model increase with increase in the transmission range (see Fig.7). Increasing the transmission range increases the connectivity which can add energy efficient routes and decrease the number of hops a packet has to traverse to reach a base stations. Better connectiviy can help balance the energy consumption among sensor nodes resulting in increased lifetimes of nodes. As shown in Fig.8, lifetimes of nodes in

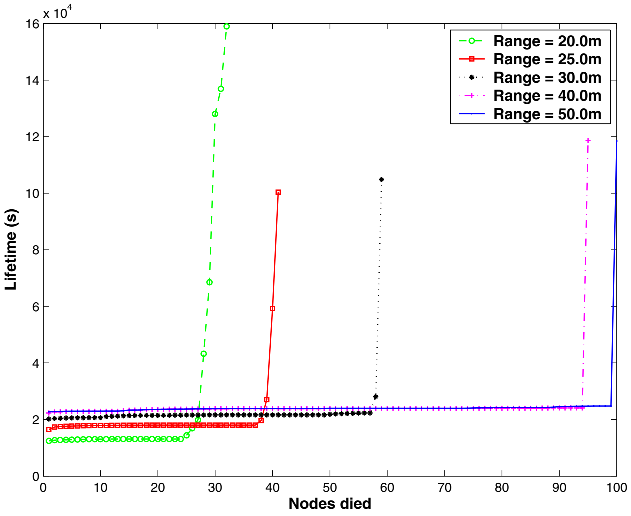


Fig. 7. Lifetimes of sensor nodes in MCBCR(V,1,1,250)

a constant transmission energy model initially increase with increase in the transmission range and then they decrease with further increase in the transmission range. A similar trend is observed in [8]. In this case, increasing the transmission range can add energy efficient routes and save energy and at the same time, energy consumed on existing routes also increases because the transmission energy is proportional to the square of the transmission range. Initially, when the transmission range is low, the energy saved by the addition of energy efficient routes is more than the increased energy consumtion due to increased transmission range, so the lifetimes of nodes increase. Later on, increase in energy consumption due to increase in transmission range is more than the energy saved by the addition of energy efficient routes, so the lifetimes of nodes decrease.

A. *Comparison of MCBCR with MLBCR*

MLBCR is formulated as an ILP which is an NP-hard problem whereas MCBCR can be solved in polynomial time. The MLBCR problem becomes infeasible if sufficient bandwidth is not available to support data rates of all the active sensor nodes. Even if sufficient bandwidth is not available, the MCBCR problem can be solved and the solution can be used to identify nodes whose data rates cannot be supported. MCBCR can be implemented in a distributed fashion. Simulation results indicate that MCBCR achieves longer lifetimes, delivers more number of messages and has higher residual energy compared to MLBCR in the test network.

VIII. CONCLUSION AND FUTURE WORK

MCBCR is a simple, scalable and efficient solution to the minimum-cost routing problem in wireless sensor networks. Simulation results have shown that MCBCR protocol gives good performance. The future version of the protocol will address variable data rate, data aggregation, types of service, bandwidth reservation and mobility management issues.

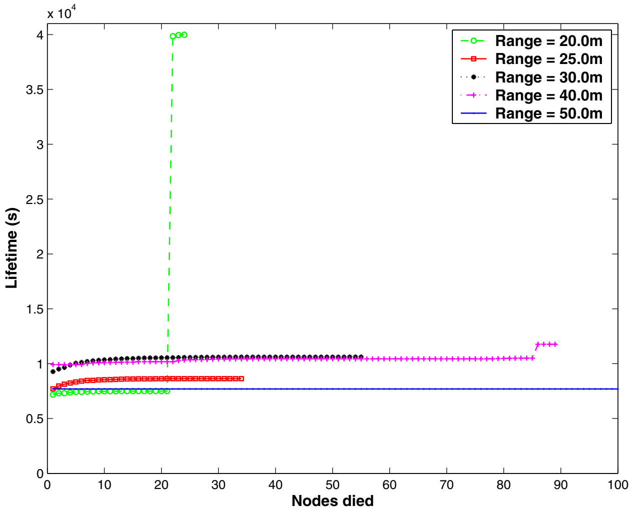


Fig. 8. Lifetimes of sensor nodes in MCBCR(C,1,1,250)

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