Threshold-Related Throughput – a New Criterion for Evaluation of Sensor Network Performance

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***Abstract*. Energy efficient and power aware protocols are of utmost importance in Sensor Networks. The most popular criteria so far, for evaluating performance of energy-aware protocols are *lifetime* and *throughput*. One of the main contributions of the present paper is to show that very often those criteria provide insufficient indications of the algorithm performance. Here we propose a new criterion, named threshold-related throughput, which provides a much better measure of the algorithm performance. The other main contribution of the paper is an extensive investigation of a large variety of routing protocols and routing cost metrics, activated on a variety of Sensor Network topologies and initial energy configurations. The work studies the performance of these protocols and compares them using the new criterion.**

I. INTRODUCTION[1]

A. Overview

The research interest in different aspects related to deploying and further exploitation of Wireless Sensor Networks (WSNs) has been increasing in the last few years. A sensor network can be quickly and easily deployed and thus is suitable and very attractive for many environmental, commercial and military applications. A general-purpose sensor network is commonly a dense network that consists of a large number of energy-constrained nodes; it is likely to be deployed in difficult access regions and to be remotely operated by only a few operators. One can conclude therefore that energy becomes the most critical resource. As a result, conserving energy should be a primary requirement of the protocols designed for such networks. The present work addresses an important problem related to sensor network management – the problem of online message routing in a general-purpose sensor network. Heuristic energy aware routing algorithms whose routing objective is to maximize network lifetime can be found in [1], [2], [4], [6], [8]. The routing metrics suggested in the above works try to maximize network lifetime by maximizing minimal residual energy [2], minimal residual link capacity [1] or by minimizing total and maximal battery cost [4]. Works [3], [5] address the online routing problem, where neither the sequence of future generated packets nor the originated packet rates are known in advance. The routing objective of the algorithm proposed in [3] is to maximize the total number of messages sent over the network (network capacity). The objective of the algorithm proposed in [5] is to maximize network lifetime. Performance of routing algorithms was widely studied and evaluated by means of simulations.

In this paper, we present the results of an extensive investigation of a large variety of routing protocols. We have studied a variety of schemes and methods for evaluating and comparing the protocols. We show that the most popular criteria - *lifetime* and *throughput* - currently used in the literature, are often not sufficient for good evaluation of algorithm performance. We introduce a new method named *Threshold-Related Throughput* that provides a much more reliable indication of the algorithm performance.

B. Network Model

A sensor network can be modeled as a directed graph $G(V,L)$, where V is the set of nodes and L is the set of directional links. Every device j in the network, possibly with exception of several energy unconstrained base stations, has a finite initial energy E_j accumulated in its battery. The residual energy of node j at time t is denoted by $E_j(t)$. A node in a sensor network may be engaged in different kinds of activity, and thus its energy is consumed by several modules, like sensor and signal processing devices, computation and radio units, etc. The radio unit is considered to be the main consumer of energy resources. Therefore, we concentrate on energy dissipation when a node transmits and receives packets.

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The amount of energy consumed by some node j for directly transmitting a packet to another node k is denoted by e_{jk}^{tx}. This parameter is called the packet transmission energy cost of the link $(j,k)\in L$. The energy consumed by a receiving node is denoted by e_{k}^{rx} and is referred to as the receiving energy cost. Generally, the transmission energy is a function of the packet length and of the distance between transmitter j and receiver k, while the receiving energy is a distance independent parameter. In our model, we assume that all packets are of equal length. A more detailed discussion of several approaches to the modeling of the energy consumption process can be found in [9].

When a data packet travels via on a multi-hop path, it is received by each hop for further transmission to the next one. The energy cost e_{jk} of forwarding a packet from node j to the next hop k is the sum of the energies consumed by node j during receiving and transmitting the packet.

We say that node j is connected to node k at time t by a directional link (j,k), if the residual energy in j at this time denoted by $E_j(t)$ is equal to or greater than the packet transmission cost and the residual energy in k is equal to or greater than the packet receiving cost. In other words, node j is connected to node k if at least one packet can be transmitted directly by j and received by k.

We assume that once the battery charge has been depleted, it cannot be replenished. A node is said to be *isolated* or *dead* if there are no active nodes in its transmission range. Such a node cannot forward any packets, whether originated by it or received from other nodes and therefore cannot participate in the routing process. Therefore such nodes and all their incoming links should be removed from the set of nodes V and the set of links L respectively.

The path or route, denoted by p, connecting source node s with destination node d is defined as a sequence of nodes (hops), where the first and the last elements are s and d respectively. Alternatively, the path can be defined as a sequence of links, where the first element is some outgoing link of node s and the last element is some incoming link of node d.

The next step is to define the cost metric function for each link in the graph and the method used for calculation of a multi-hop path cost. Let $C_{jk}(t)$ be the cost (weight) of a link (j,k) at time t and $C_p(t)$ be the cost of a path p at time t. The selection of a proper cost function is one of the greatest challenges in developing routing algorithms. In this paper, we focus on the *on-line* routing problems, namely situations when, neither the sequence of future packets nor the generation rates of packets, is known in advance.

II. ENERGY-AWARE ROUTING

In this section, we shall briefly discuss several approaches to energy-aware routing. A more detailed discussion can be found in [9]. The algorithms can be divided into four groups, according to the methods and rules they use for calculating and comparing routing paths: *minimum total cost routing*, *min-max cost routing*, *max-min cost routing* and *hybrid cost routing*. Within each group, algorithms differ by the link cost function. The groups differ by the scheme for computing the cost of the entire path and by the method for comparing the quality of the path.

The action of the routing algorithm is defined as follows. For a given routing packet, the algorithm provides the best route from a source node to a destination node according to some criterion if such a route can be found or rejects the packet if no feasible route exists.

Consider a path p connecting the source node R_0 with the destination R_{m+1} and containing m additional intermediate nodes R_j, $j=1,2,\ldots,m$:

$$p = \{(R_0, R_1),(R_1, R_2),...,(R_m, R_{m+1})\}, \tag{1}$$

Let $C_{j,j+1}(t)$ be the cost of the link $(R_j,R_{j+1})\in p$. Let P be a set of all possible paths (routes) from source to destination. Let $\hat{p}$ be the best route from a source to a destination according to some criterion.

A *minimum total cost routing* algorithm minimizes the total cost of forwarding the packet along the entire route. In the other words, the route $\hat{p}$ selected by a minimum total cost routing algorithm can be written as follows:

$$\hat{p} = \underset{p\in P}{argmin}\, C_p(t), \tag{2}$$

where $C_p(t)$ is the total cost of the route $p\in P$ calculated as the sum of the link costs along the route p:

$$C_p(t) = \sum_{\forall(R_j,R_{j+1})\in p} C_{j,j+1}(t). \tag{3}$$

The minimum cost routing algorithms investigated in the present paper use cost functions that depend on forwarding energy e_{jk} only (MTER[1]), residual energy of the node $E_j(t)$ only (MBCR [3]) or on some combination of the above-mentioned parameters (MREPsum, MREPcupsum [1], CMAX [2]), as shown in section IV. Generally, cost functions that depend only on the transmission cost or only on the residual energy do not provide good measures for the solution of the energy efficient routing problem. In addition, the cost function used by the CMAX algorithm appears to be sensitive to the implementation of the shortest path algorithm. In order to eliminate this drawback we have modified it somewhat. The modified metric is referred as MCMAX (Modified CMAX). A more detailed discussion of the advantages and disadvantages of the various algorithms can be found in [9].

In contrast to the algorithms from the previous group, *min-max cost routing algorithms* are oriented to minimize the maximal cost of links in the routing path rather than the total path cost. In other words, when some min-max cost routing scheme is used, the cost of the route p is computed as follows:

$$C_p(t) = \max_{\forall(R_j,R_{j+1})\in p}\left(C_{j,j+1}(t)\right), \tag{4}$$

and the selected route $\hat{p}$ is as in (2).

The main problem of all min-max algorithms is their sensitivity to the implementation of the shortest path algorithm responsible for selecting a proper route. The min-max cost of a path is equal to the maximal link cost among the links composing it. Therefore, adding a number of less expensive links to the path does not increase its cost. This fact shows that very inefficient routes containing several redundant nodes might be selected. A more detailed discussion can be found in [9].

Like the minimum total cost algorithms, min-max cost algorithms investigated by us utilize cost functions that depend on the residual energy of the node $E_j(t)$ [3] and the forwarding energy cost e_{jk} [1].

The third scheme is called *max-min cost routing*. According to the max-min approach, the cost of the path p is given by the link with minimal cost, i.e. the path bottleneck:

$$C_p(t) = \min_{\forall(R_j,R_{j+1})\in p}\left(C_{j,j+1}(t)\right). \tag{5}$$

A max-min algorithm routes packets along the path $\hat{p}$ with maximum minimal link cost (widest bottleneck):

$$\hat{p} = \underset{p\in P}{argmax}\, C_p(t). \tag{6}$$

The hybrid cost routing [3-5], is some combination of the three previous routing techniques. Each algorithm in the group applies its own methods and rules. A more detailed discussion can be found in [9].

III. PERFORMANCE EVALUATION

In the previous section, we have introduced a number of routing algorithms that use energy-aware routing metrics. The next question is to find a good scheme to evaluate the performance of the various algorithms and to compare them. Only in very few and simplistic cases it is possible to perform an exact mathematical analysis of the algorithms. Therefore, we have performed extensive simulations that allow us to give a proper answer to this problem.

The other big challenge is to select a good criterion for comparison of the algorithm performance. The most popular criteria found in the literature so far are *lifetime* and *total network throughput* (*capacity*).

Two quite different definitions of *lifetime* can be found in the literature. According to first one, the network lifetime is the period until the first network node depletes its batteries' resources and hence becomes dead. In other words, network lifetime [6-8] is defined as the time of the first node failure due to battery depletion.

A second definition appears in [1], [2], [4] and defines the lifetime as the period until the first packet cannot be delivered to its destination. In order to avoid ambiguity, we shall use here for this definition the term – *time of first packet loss* – instead of lifetime. One can intuitively conclude that there is certain dependence between these two definitions, although they are definitely not equivalent.

Let us now discuss the two measures introduced above. When the first node fails, it does not necessarily mean that some kind of "system failure" happens. For example, one can think of a situation when some active node *j* exhausts its battery, turns off its equipment and disappears from the network. However, there are other nodes in its near environment, which can fulfill *j*'s duties, so the node's disappearance is almost unnoticed by other nodes. Note that a sensor network might consist of a large number of nodes and maybe only part of them is actually needed for successful network transmissions. The remaining nodes may be used in order to improve the network reliability. They may be in the energy saving (sleep) state most of the time and wake up from time to time in order to check if their active participation is desired. This discussion shows that there might be situations when the first node failure may not be very critical. On the other hand, the first packet loss is a more critical event. It shows that from now on, packets may be rejected because of lack of energy. However, given the nature and possible size of sensor networks, it seems that loss of a certain percentage of packets is acceptable. Anyway, it seems that the events defined by both measures are too early and so do not reflect the global network behavior. Simulations show that even after the above-mentioned events have occurred in a large sensor network, the amount of data which still can be transmitted over the network and delivered to destination can be very significant and thus should not be neglected.

Note that instead of the time of first node failure or the time of first packet loss, the corresponding throughputs measured at the corresponding time instants can be used for performance evaluation. However, like in the previous case, both measures are taken too early and thus ignore the later network behavior.

The next criterion, named *expiration sequence*, extends the concept of lifetime of an individual node to all nodes in the network. The expiration sequence is the sequence of nodes sorted in increasing order of their expiration time [3], [5]. On the one hand the latter criterion contains much more information about network behavior than lifetime, and therefore seems more reliable. On the other hand, both the network lifetime and the expiration sequence criteria refer only to nodes lifetime and do not take into account the amount of delivered and rejected data; therefore they do not sufficiently express the "routing efficiency" of the algorithm. Although we have no strict definition of routing efficiency, we believe that a good criterion should refer to both rejected and delivered packets.

Another criterion widely proposed in the literature is *network throughput*. Both the *average* [6], [7] and the *total* [2], [5] *throughput* (*capacity*) are used for performance evaluation and comparison of routing algorithms. The average throughput is defined as the rate of data received at the destination nodes, while the total network throughput is defined as the number of packets successfully delivered to their destinations, until no more packets can be delivered.

Observe that when measuring the total throughput, we measure only the number of delivered packets, but not the efficiency of service provided by the algorithm. For example, we do not ask questions like "How many packets were rejected until the last successful packet was delivered to its destination?" Intuition suggests and the results received from simulations concur, that the number of packets rejected by all algorithms discussed in the previous section is larger than the total throughput achieved by them. Therefore, the total throughput criterion hardly gives a good indication of the actual network performance.

From the above discussion appears that a more general measure of the algorithm performance than *lifetime* and *throughput* is required. Measuring only throughput takes us too late in the progress of the network behavior, the time when absolutely no packet can be sent. The other extreme is when lifetime is measured, namely the time (or the corresponding throughput) when the first node fails or the first packet is rejected. Given the nature and possible size of sensor networks, it seems that failure of small number of nodes or loss of a certain percentage of packets can be tolerable.

Let us now summarize the above discussion. We need a new criterion that contains the information about the network behavior at different stages of the algorithm execution and refers to both delivered and lost packets. In order to accommodate these thoughts, we introduce in this paper the terms: *packet loss ratio* at time *t* and *threshold-related throughput*. The number of packets offered to the network until time *t* is the sum of delivered and rejected packets up to that time. The *packet loss ratio* at time *t*, denoted by $\rho(t)$, is defined as the ratio of the number of rejected packets and the number of offered packets up to time *t*. The *threshold-related throughput* corresponding to some threshold θ, $0 \leq \theta \leq 1$, is defined as the total number of delivered packets (throughput) until the first time when the packet loss ratio exceeds threshold θ. With these definitions, one can easily see that lifetime is the threshold-related throughput corresponding to $\theta = 0$, while total network throughput is the threshold-related throughput corresponding to θ close to 1, since loss of any number of packets is permitted.

We assert in order to perform a thorough evaluation of algorithm performance one should measure the threshold-related throughput for a wide range of threshold values and observe the algorithm performance at different stages during its execution.

To provide a specific example, it is asserted in many references (e.g. [1], [2], [3]) that the lifetime (the time of the first node failure or alternatively the time of the first packet loss) of the MTER (Minimum Transmitting Energy Routing) algorithm is significantly less than that of other schemes, and therefore the other scheme is preferable. This conclusion does not take into account that for any non-zero value of loss ratio threshold θ, the MTER algorithm obtains better threshold-related throughput (see next section), which makes it more attractive than the other schemes.

IV. SIMULATIONS AND RESULTS

A number of algorithms discussed above have been selected in order to evaluate their performance with respect to a number of comparison criteria. Performance of algorithms was widely studied under different conditions.

For each simulation scenario, we generated ten different network topologies and for each network, we have produced ten different packet sequences. The originating and the target nodes of each packet are uniformly distributed among all appropriate sources and destinations. All algorithms perform a single shortest path computation for each packet. A discrete (slotted) time system was used for the sake of simplicity. We assume a packet is produced at the beginning of each time slot and is delivered to its destination within the current slot. If no feasible path from source to destination can be found, the packet is rejected. Regular and modified versions of the Bellman-Ford algorithm [1] have been used in the simulations in order to compute minimum and min-max cost paths respectively.

The following parameters were measured for each of the compared algorithms:

1. *Lifetime*: the time slot in which the first node becomes dead.
2. *Total network throughput* (*capacity*);
3. *Threshold-related throughput* as a function of the threshold θ, namely the number of packets successfully delivered to their destinations until the first time when the loss ratio exceeds θ. Ten values from 0 to 0.9 with a step of 0.1 were selected for θ.

In this set of simulations, we have studied the performance of several routing algorithms for homogeneous sensor networks, consisting of nodes with identical initial battery power. The performance of the following algorithms was studied:

1. MTER (Min Transmitting Energy Routing) [1]:
$$C_{jk}(t) = e_{jk}\,; \tag{7}$$
2. MBCR (Min Battery Cost Routing) [3]:
$$C_{jk}(t) = 1/E_j(t)\,; \tag{8}$$
3. MREPcapsum (Min Residual Energy Path) [1]:
$$C_{jk}(t) = e_{jk}/E_j(t)\,; \tag{9}$$
4. MREPsum [1]:
$$C_{jk}(t) = 1/(E_j(t) - e_{jk})\,; \tag{10}$$
5. CMAX (Capacity MAXimization) [2]:
$$C_{jk}(t) = e_{jk} \cdot (\lambda^{a_j(t)} - 1)\,,\ a_j(t) = 1 - E_j(t)/E_j\,; \tag{11}$$
6. Modified CMAX (MCMAX) (suggested here):
$$C_{jk}(t) = e_{jk} \cdot \lambda^{a_j(t)}\,,\ a_j(t) = 1 - E_j(t)/E_j\,; \tag{12}$$
7. MMBCR (Min-Max Battery Cost Routing) [3];
$$C_{jk}(t) = 1/E_j(t)\,; \tag{13}$$
8. MREPmax [1]:
$$C_{jk}(t) = 1/(E_j(t) - e_{jk})\,. \tag{14}$$

For the CMAX algorithm and its modified version referred as MCMAX, we experimented with different values of λ and found that the algorithm performance is relatively insensitive to the value of λ, as long as it is large enough, so $\lambda = 100{,}000$ was used.

The packet route is determined in the first six algorithms using min cost and in the last two algorithms by using min-max methods.

A. Scenario I.

The network consists of fifty nodes, randomly distributed on a 40×40 square-units area. In this scenario packets are generated between all possible source-destination pairs; neither the sequence of future packets nor the origination rates of the packets are known in advance.

The energy consumed by node *j* in transmitting a unit length packet to a neighboring node *k* is computed according to the following formula:

$$e_{jk} = max\{0.001, 0.001 \times d_{jk}^{3}\}, \qquad (15)$$

where d_{jk} is the physical distance between the nodes. A similar energy consumption model was used in [1], [2], [4].

Three values of the initial energy – 8, 15 and 30 units – were used. Nodes are declared dead as soon as there are no active neighbors in their transmission range. It is assumed that packets are not allowed to be sent to any dead node; therefore, if there is such a packet at the current time slot, it is discarded. In our simulations, the only restriction to the transmission range is the residual energy.

Due to lack of space, we present here explicitly only a small part of the simulations results. Comprehensive results, together with relevant figures and data tables can be found in [9]. The threshold-related throughput measured for ten different values of loss ratio threshold is depicted in Fig. 1–3.

For small values of initial energy (8 and 15 units), the MREPcapsum algorithm yields the best results in terms of threshold-related throughput, measured for any loss ratio threshold. When the initial energy of nodes is 30 units, both the MREPcapsum and MCMAX routing algorithms yield very similar results and outperform all other algorithms. Observe that the first packet loss (Fig.4) always occurs earlier in the MTER algorithm than in the MREPmax algorithm. However, for any given positive value of the loss ratio threshold, MTER achieves larger throughput (Fig.1–3). A similar situation can be observed while comparing the performance of CMAX versus MREPsum routing algorithm in Fig.2. One can conclude that, as said before, lifetime does not provide reliable indication of actual algorithm performance.

Note that in the given scenario, death of first node (minimal node lifetime) and first packet loss are most of the time very close events (Fig.4,5). However, as indicated above, these criteria do not provide sufficient information of the algorithm behavior.

Observe that in two simulations (initial energy of 8 and 15 units) the MTER algorithm achieves the maximal total network throughput among all compared algorithms (Fig.6). On the other hand, both the MREPcapsum and the MCMAX routing algorithms achieve better performance in terms of threshold-related throughput, measured for a wide interval of loss ratio threshold values. Again, the threshold-related throughput appears to be a much more reliable comparison criterion, because it provides actual indication about the algorithm behavior during its execution than the throughput does.

B. Scenario II.

In this part, we examine the performance of routing algorithms in a different configuration that appears often in ad-hoc, disaster recovery and sensor networks. Fifty nodes are randomly distributed on a 40×40 square-unit area. Four energy unconstrained sink nodes are positioned outside the area, at distance of 2 units from the area bound. All traffic is destined to these four sinks. Three different values of initial energy – 8, 15 and 30 units – were selected. We used the same energy consumption and slotted time model as in the previous set. A packet is originated by a randomly selected source at the beginning of each time slot. During the current slot, this packet has to be delivered to any one of four possible destinations. Packets that cannot be delivered are rejected and their source is declared dead.

For this scenario, we developed an additional routing scheme, named MTTR, as follows. A node that generates a packet sends it directly, with no help from intermediate nodes, to the closest sink. Only if no direct transmission is possible to any of the sinks because energy is low, the packet is sent on a multi-hop route. The route is selected as the minimum transmitted energy route to any node from which direct transmission to a sink is possible. It is shown in [9] that for the used energy consumption model, the MTTR routing algorithm reaches the upper bound derived in [9] on total throughput for any arbitrary generated packet sequence.

MTTR and each of the other algorithms previously mentioned was executed three hundred times: ten different packet sequences were simulated in each of ten randomly generated networks for three possible values of the nodes' initial energy. The main conclusions drawn for the previous simulation scenario are valid for this one as well. The best performance was obtained by the MREPcapsum and the MCMAX routing algorithms for a wide range of network topologies, packet generation sequences and initial node energy values.

The average results received from simulations can be found in Fig.7–12. The threshold-related throughput of compared algorithms measured for ten different values of the loss ratio threshold is depicted in Fig.7–9. One can see that for all values of initial energy both the MREPcapsum and the MCMAX routing algorithms yield the best performance among all compared algorithms. The MTER algorithm brings very similar results for any non-zero value of loss ratio threshold. However, as in the previous model, the first packet loss of the MTER algorithm occurs quite early.

Compare now the lifetime of MTER algorithm vs. that of MREPsum (Fig.10,11), the total throughput of MTTR algorithm vs. MCMAX algorithm (Fig.12) and their threshold-related throughput measured for any positive value of loss ratio threshold (see Fig.7–9). One can see that neither lifetime nor total throughput give enough information about algorithm behavior during its execution. The threshold-related throughput appears to be a much more reliable one, because it provides actual indication about algorithm's behavior at different stages of its execution.

V. CONCLUSIONS

The following conclusions were drawn based on the simulations results. The criteria *lifetime*, *time of first packet loss* and *total throughput* do not provide sufficient information about the algorithms behavior. Using those measures as comparison criteria sometimes does not yield a comprehensive view of algorithm performance. The threshold-related throughput criterion proposed in this paper provides a much better indication of the algorithm behavior. Using threshold-related throughput criterion we have evaluated the performance of and have compared a variety of routing algorithms. The best performance was obtained by the MREPcapsum and MCMAX routing algorithms for a wide range of network topologies, packet generation sequences and initial node energy values.

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APPENDIX – FIGURES

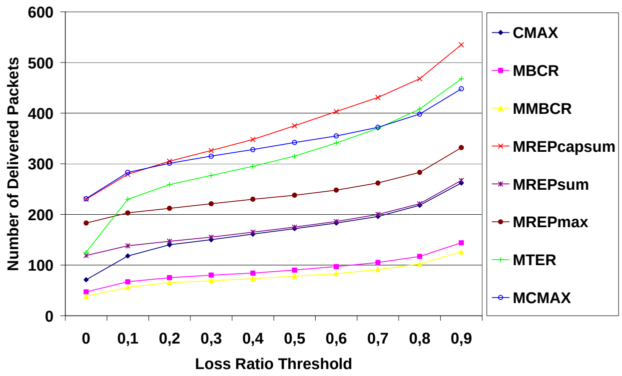

Fig. 1. Threshold-related throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 8 units (Scenario I)

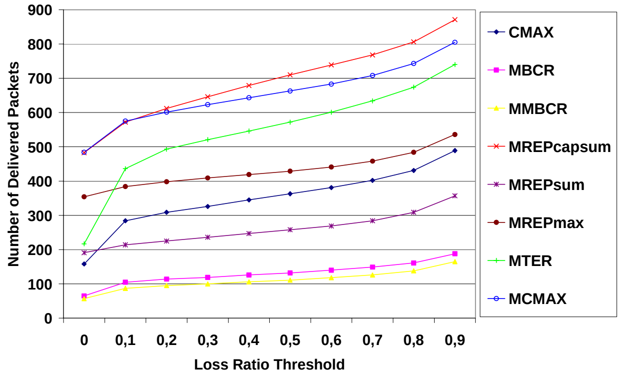

Fig. 2. Threshold-related throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 15 units (Scenario I)

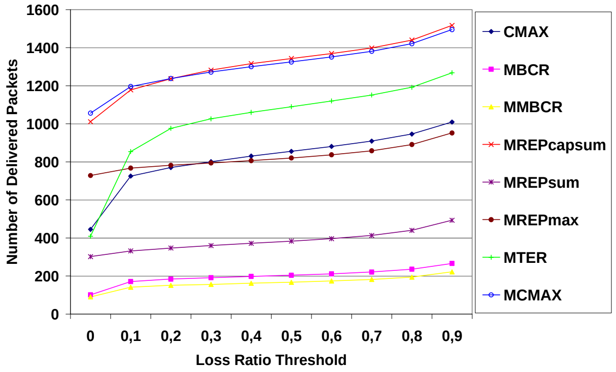

Fig. 3. Threshold-related throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 30 units (Scenario I)

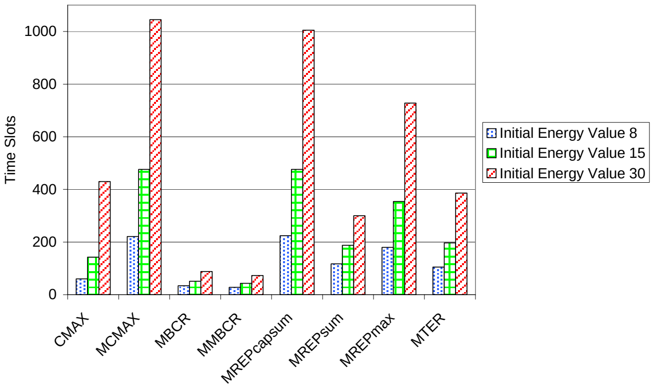

Fig. 4. Minimal node lifetime (Scenario I)

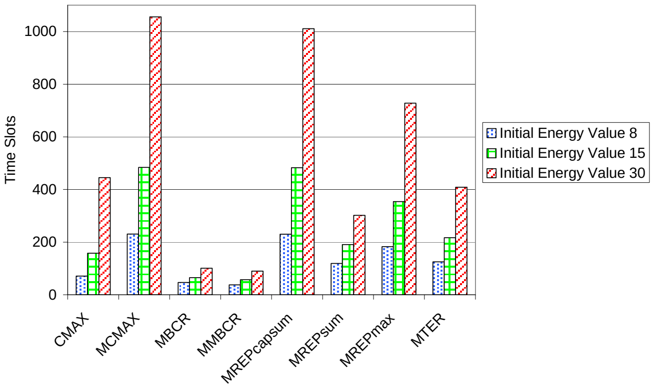

Fig. 5. Time of first node failure (Scenario I)

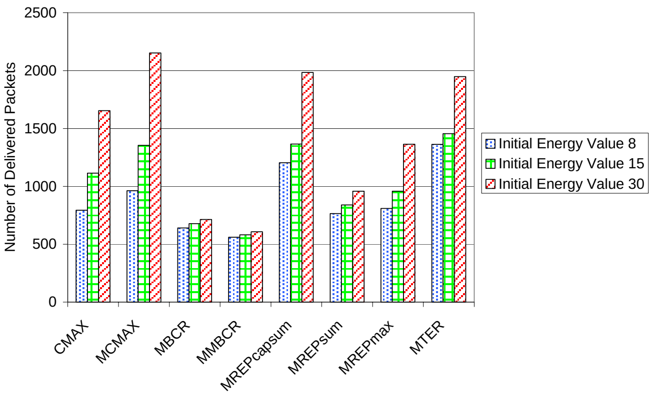

Fig. 6. Total network throughput (capacity) (Scenario I)

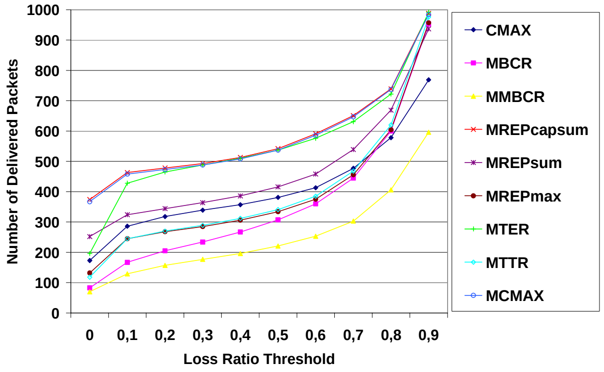

Fig. 7. Threshold-related Throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 8 units (scenario II)

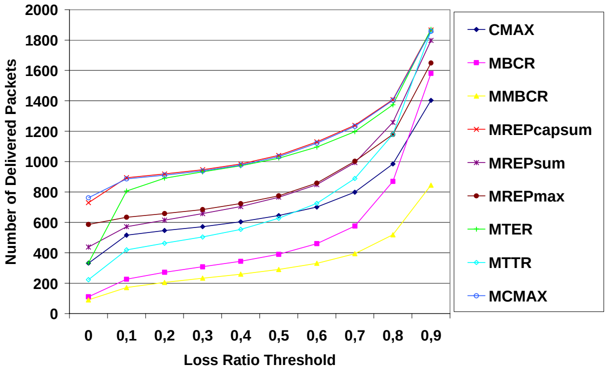

Fig. 8. Threshold-related Throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 15 units (Scenario II)

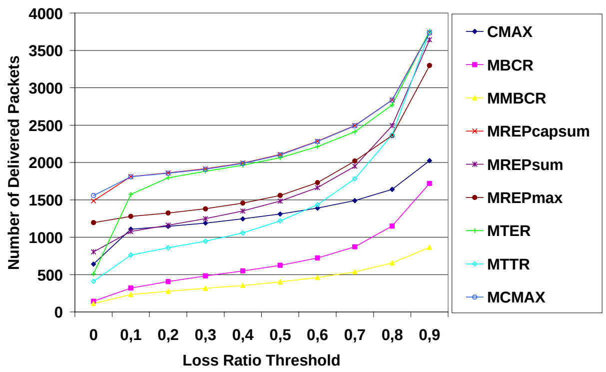

Fig. 9. Threshold-related Throughput of compared algorithms measured for ten values of loss ratio threshold when the initial value of energy was 30 units (Scenario II)

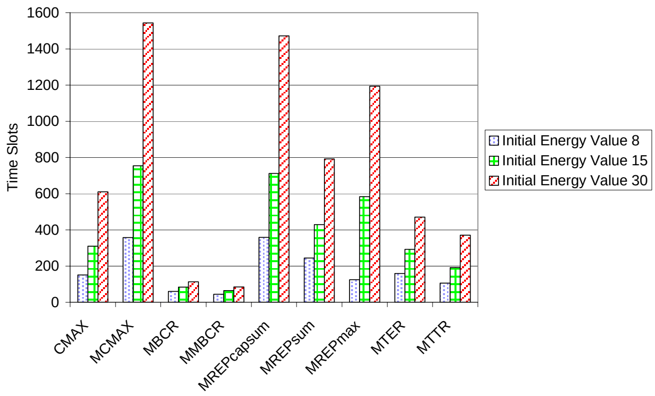

Fig. 10. Minimal node lifetime (Scenario II)

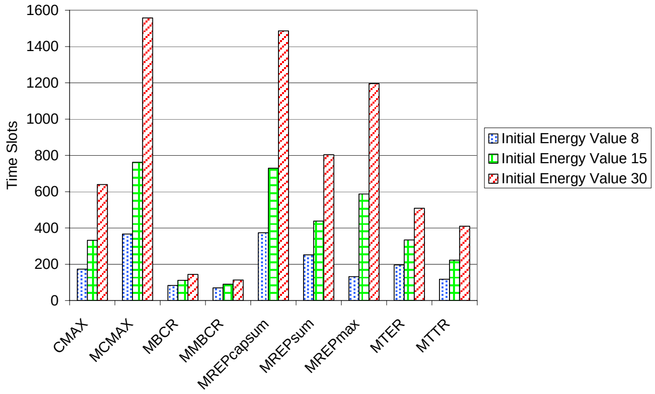

Fig. 11. Time of first node failure (Scenario II)

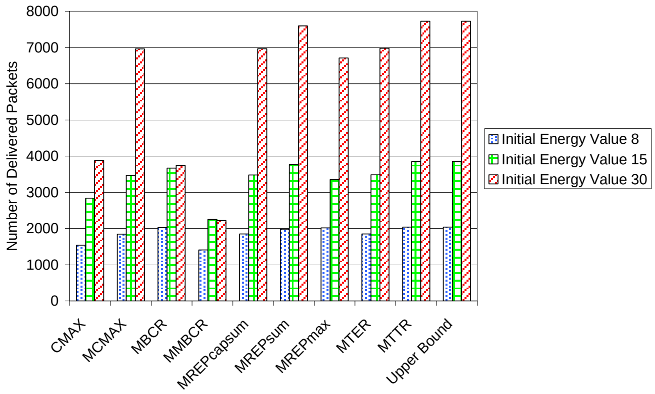

Fig. 12. Total network throughput (capacity) (Scenario II)