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Long Lifetime Routing in Unreliable Wireless Sensor Networks

Hamed Yousefi, Mohammad Hossein Yeganeh, Ali Movaghar

***Abstract*—Lifetime is the most important concern in wireless sensor networks due to limited battery power of sensor nodes. In this paper, we focus on designing an energy-efficient and energy-aware routing algorithm, LLR, to increase the operational lifetime of multi-hop wireless sensor networks in the presence of unreliable communication links. Our proposed protocol utilizes a parameter, *Broadcasting Delay,* in each node associated with the hop parameters passed by a route request packet to select long lifetime paths in the network. The key point in *Broadcasting Delay* formulation is that it includes both node and link specific parameters. We use two different scenarios: either the link layer reliability or the transport layer reliability is implemented. Simulation results reveal that the proposed algorithm can outperform other existing schemes in term of the network lifetime.**

I. Introduction

RECENT advancement in wireless communications, micro-electronics, and low power design shows gradually wide application perspective of Wireless Sensor Networks (WSNs) [1]. Considering that communication costs (transmission power) are usually more expensive than computing costs, Energy efficient routing algorithms are very important in multi-hop WSNs where the constituent nodes have batteries with limited energy. Several energy-aware routing protocols (e.g., [2]-[4]) define the link cost based on the power required to transmit a packet on it, and accordingly employ minimum cost routing algorithms to determine the "minimum total transmission energy" route from a source to the destination.

In many wireless ad-hoc scenarios, however, the metric of actual interest is the total operational network lifetime [5]-[15], not the transmission energy of individual packets. Through the energy aware routing mechanism, the residual energy on each node is the basis of the routing decisions. The main objective of these algorithms is to avoid the extinction of nodes due to exhaustion of their battery power.

However, none of the previous papers have considered the lossy property of the wireless links. They are often assumed to be reliable. This is clearly too optimistic since even under benign conditions, wireless communication links are unreliable and often unpredictable due to various factors like fading, interference, multi-path effects, and collisions [16]-[18]. If a poor path is chosen for data delivery, loss rate will be heavy and retransmissions will cause extra energy consumption, and consequently, less network lifetime.

Furthermore, more traffic also yields a higher collision probability and delivery delay. [19]-[22] have shown why energy spent in potential retransmissions, is the proper metric for reliable, energy-efficient communications.

In this paper, we present a new energy-efficient and energy-aware route selection algorithm called LLR (Long Lifetime Routing). Moreover, we show how power aware routing protocols must not only be based on node specific parameters (e.g. residual battery energy and the number of paths which the node is common among), but also consider the link specific parameters (e.g. link error rate and the packet transmission energy for reliable communication across the link) as well in each hop, to increase the operational lifetime of the network. To the best of our knowledge, it is the first work addressing these goals in an integrated manner. To make a special flooding mechanism, LLR combines these four factors together in one parameter, Route Request Broadcasting Delay, defined as the inverse of the idealized maximum number of packets that can be transmitted in each hop by the transmitting node over the link.

However, if a lot of minimum-energy routes share a node, the node's battery will be exhausted quickly. Therefore, LLR employs an energy reservation scheme to significantly decrease the probability of the common nodes selection.

We use two different scenarios: either the link layer reliability or the transport layer reliability is implemented. Simulation studies show how LLR leads to a longer network lifetime than alternative suggested algorithms due to the optimal path selection.

The remainder of the paper is organized as follows. Section II explains the proposed scheme and presents the specifications of LLR. Simulation results are presented and discussed in section III. Finally, Section IV concludes our work and discusses some future directions.

II. Protocol Overview And Properties

LLR is a distributed algorithm that provides a robust transmission environment based on the energy-efficient and energy-aware routing and energy-reservation mechanisms at the network layer. The algorithm comprises: Path Discovery stage, Path Reservation stage and Data Transmission stage.

However, the main idea of LLR protocol is to combine the broadcasting speed with four factors together to make a special flooding mechanism for the selection of long lifetime paths. All these factors are mixed and integrated into the notion of Broadcasting Delay. As the routing decision is made based on these factors, in the next section we will explain them and will formally define how to calculate the value of Broadcasting Delay in two different operating models:

H. Yousefi and A. Movaghar are with the Department of Computer Engineering, Sharif University of Technology, IRAN (e-mail: hyousefi@ce.sharif.edu, movaghar@sharif.edu).

M.H. Yeganeh is with the Department of Computer Engineering, Science and Research Branch, Islamic Azad University, IRAN (e-mail: m.yeganeh@srbiau.ac.ir).

a) **Hop-by-Hop Retransmissions (HBH):** where each individual link provides reliable forwarding to the next hop using localized packet retransmissions.

b) **End-to-End Retransmissions (E2E):** where the individual links do not provide link-layer retransmissions and error recovery but reliable packet transfer is achieved only via retransmissions initiated by the source node.

A. Calculation of Broadcasting Delay

As described earlier, Route Request Broadcasting Delay in each intermediate node is a key parameter to make decision during the routing. It contains four factors which are relevant to the residual node energy, the transmission energy on the link, link error rate, and the number of paths which the node is common among.

To formulate the Broadcasting Delay, Consider a simple path $P= v_1, v_2, \ldots, v_N$ from a source node S (v_1) to destination node D (v_N) consisting of N-1 intermediate nodes indexed as 2,…, N. Moreover, let us assume that B_i is the residual battery power at a certain instance of time at node i, $E_{i,i+1}$ is the transmission energy consumed in node i to transmit a packet over link (i,i+1) to node i+1, and $ler_{i,i+1}$ is the packet error probability associated with link (i,i+1). Here, $E_{i,i+1} = \alpha d_{i,i+1}^2$ where d is the distance between the receiver and the transmitter and α is a technology specific constant.

When a link layer reliability (Hop-by-Hop Retransmission) is implemented, the expected number of transmissions (including retransmissions as necessary) to reliably transmit a single packet across link (i,i+1) is calculated by $\frac{1}{1-ler_{i,i+1}}$. Hence, the expected energy requirement to reliably transmit a packet across the link is given by $E_{link(i,i+1)} = \frac{E_{i,i+1}}{1-ler_{i,i+1}}$ and it is calculated by $E_{path} = \sum_{i=1}^{N-1}\frac{E_{i,i+1}}{1-ler_{i,i+1}}$ for path P. Therefore, the maximum number of packets that node i can forward over the link (i,i+1) is clearly $\frac{B_i}{E_{link(i,i+1)}}$. However, it is possible that node i is common among k other paths and therefore it consumes some energy, E_{con}, for reliable data transmission on output links associated with those paths, where

$$E_{con}(i) = \sum_{m=0}^{k-1}\frac{E_{i,i+1}(m)}{(1-ler_{i,i+1}(m))} \tag{1}$$

Accordingly, we can define a **node-link Metric,** *Ability (i)* for the hop count i as:

$$Ability(i) = \frac{B_i}{E_{con}(i)+E_{link(i,i+1)}} \tag{2}$$

Finally Route Request Broadcasting Delay *(B Delay)* in each intermediate node i is calculated by:

$$B\,Delay_{HBH}(i) = \frac{1}{Ability(i)} = \frac{E_{con}(i)+E_{link(i,i+1)}}{B_i} \Rightarrow$$
$$B\,Delay_{HBH}(i) = \frac{\sum_{m=0}^{k-1}\frac{E_{i,i+1}(m)}{(1-ler_{i,i+1}(m))} + \frac{E_{i,i+1}}{(1-ler_{i,i+1})}}{B_i} \tag{3}$$

When a transport layer reliability (End-to-End Retransmission) is implemented, the expected number of transmissions (including retransmissions as necessary) to reliably transmit a single packet across link (i,i+1) is $\frac{1}{\prod_{j=i}^{N-1}(1-ler_{j,j+1})}$. Hence, the expected energy requirement to reliably transmit a packet across the link is given by $E_{link(i,i+1)} = \frac{E_{i,i+1}}{\prod_{j=i}^{N-1}(1-ler_{j,j+1})}$ and for path P is calculated by $E_{path} = \sum_{i=1}^{N-1}\frac{E_{i,i+1}}{\prod_{j=i}^{N-1}(1-ler_{j,j+1})}$. Therefore, the maximum number of packets that node i can forward over the link (i,i+1) is clearly $\frac{B_i}{E_{link(i,i+1)}}$. However, it is possible that the node i is common in k other paths and therefore it consumes some energy, E_{con}, for reliable data transmission on output links associated with those paths.

$$E_{con}(i) = \sum_{m=0}^{k-1}\frac{E_{i,i+1}(m)}{\prod_{j=i}^{hop(m)-1}(1-ler_{j,j+1}(m))} \tag{4}$$

where *hop(m)* is the number of hops in path m. Accordingly, we can define a **node-link Metric,** *Ability (i)* for the hop count i as:

$$Ability(i) = \frac{B_i}{E_{con}(i)+E_{link(i,i+1)}} \tag{5}$$

Finally, Route Request Broadcasting Delay *(B Delay)* in each intermediate node i is calculated by:

$$B\,Delay_{E2E}(i) = \frac{1}{Ability(i)} = \frac{E_{con}(i)+E_{link(i,i+1)}}{B_i} \Rightarrow$$
$$B\,Delay_{E2E}(i) = \frac{\sum_{m=0}^{k-1}\frac{E_{i,i+1}(m)}{\prod_{j=i}^{hop(m)-1}(1-ler_{j,j+1}(m))} + \frac{E_{i,i+1}}{\prod_{j=i}^{N-1}(1-ler_{j,j+1})}}{B_i}$$
(6)

The key point in these formulations is that the Broadcasting Delay includes both two node specific parameters and two link specific parameters.

By increasing $ler_{i,i+1}$, the Broadcasting Delay value will increase. Thus, by factoring the individual link error probabilities in the Broadcasting Delay, our algorithm avoids including poor quality links in the eventual transmission path, even if such links apparently incur lower transmission costs. Therefore the main advantage of using this parameter is a higher quality path selection which causes reduction of retransmissions, reduction of energy consumption and prolongation of the network lifetime.

By decreasing B_i, the Broadcasting Delay value will increase. Thus the selection probability of one node with little residual energy will decrease. It maximizes the total number of packets that may be ideally transmitted over network paths. Moreover, by providing a more stable transmission environment, LLR can reduce packet loss due to the frequent path breakdowns. Consequently, path requests will be reduced. Thus, more energy can be used to forward data, instead of being wasted on consecutive path discoveries.

By increasing $E_{i,i+1}$, the Broadcasting Delay value will increase. Thus the selection probability of one link with high energy consumption will decrease. Using this parameter can lead to providing the path with minimum energy consumption and consequently prolongation of the network lifetime.

By increasing E_{con}, the Broadcasting Delay value and consequently the selection probability of the common nodes will decrease. Moreover, the network operational time maximizes by balancing the energy draining rates among nodes. However, selecting common nodes can accelerate paths breakdowns and lead to lower path lifetime, more path discovery, and consequently wastage of network resources. The reduction of packet loss induced by buffer overflow and the reduction of the end to end packet transmission delay are other main advantages of using this parameter.

However, among several paths arriving in one node, we are interested in a path with minimum error rate and energy consumption on its links, maximum battery power on its nodes, and minimum number of common nodes with other paths. All of these factors that extremely impress network lifetime are considered in Broadcast Delay formulation. Thus, one path with lower value of Route Request Broadcasting Delay on its nodes indicates a better path.

B. Path Discovery Stage

The process starts at the sink by broadcasting a route request packet (label) to its neighbors. This stage is initiated when the sink receives an interest that carries an unknown source, or when the already established path is broken. A label carries the information of the source, one index, and a route table onto which intermediate nodes piggyback their IDs. The label index increases one unit in each new path discovery stage.

We suppose that there is one timer in each node for every source node. When an intermediate node receives a label, it does not broadcast it to its neighbors immediately. Before sending the label out, several actions must be undertaken. Thereafter, the node decides to transmit or discard the label according to the algorithm shown in Fig. 1.

The labels are flooded throughout the network until they reach the source node. The source waits until expiration of its timer. Thereafter, the path discovery stage finishes. It should be noted that there may be many potential label paths from the sink to the source. However, we are interested in one optimal (long lifetime) established path towards the source. Therefore, the source only selects one label which has been received with minimum path Broadcasting Delay.

C. Path Reservation Stage

LLR tries to ensure an equitable distribution of transmission costs among the constituent nodes. This is realized through path reservation. Path reservation is mainly concerned with energy. After the source retrieves the candidate-path from the label, it will generate a path reservation packet and unicast it along the retrieved path toward the sink. Every node on this path will increase its E_{con} by E_{link}. The path reservation is a key element of the Route Request Broadcasting Delay. It can prevent too many paths from sharing a few nodes. Once a node is reserved, its Broadcasting Delay becomes longer (*B Delay* increases), and so another path can potentially bypass this node to use other nodes with lower Broadcasting Delay. This also can reduce the effects of a broken node. If the broken node is only on one path, then only one new path discovery is employed.

```
1:If (label index already has been cached in the node)
2:   The received label is discarded;
3:Else{
4:   B Delay is calculated as in (3,6);
5:      If (it is the first time the node receives this index)
6:         Node timer is scheduled to B Delay;
7:      Else if (B Delay <  timer value){
8:               Node timer is rescheduled to B Delay;
9:                 The previous received label is discarded;
               }
10:     Else
11:          The received label is discarded;
12:     Steps 4-11 can be repeated for this label received from
        different paths until expiration of the node timer;
13:     The label index is cached in the node;
14:     The node ID is added to the label route table;
15:     The label is transmitted to neighbor nodes;
        }
```

Fig. 1. The routing decision algorithm in each intermediate node

However, if k paths share this node, then there will be k new attempts for the path discovery. The procedure of path reservation ends once the sink receives the path reservation packet.

D. Data Transmission Stage

LLR provides reliable packet delivery for unicast transmission. It uses two different operating models in different scenarios:

a) Hop-by-Hop Retransmissions (HBH)

b) End-to-End Retransmissions (E2E)

Reserved energy for a path will not be released unless the path is broken when one or more node/link failures occur on the reserved path. The failure is detected by the sender when it does not receive any ACK from the receiver within a time out period after a fixed number of attempts. In the event of a path failure, an error report will be generated and broadcast to both terminals of the broken path. The reserved energy, E_{link}, in the intermediate nodes will be released, and the old path will be removed from the route table of the terminals. Also, the sink will start a new path discovery once it receives this error report packet.

III. Performance Analysis

In this section, we evaluate the performance of our algorithm via simulation. We implemented a simulation framework using OMNeT++, an object-oriented discrete event network simulator [23]. Here, we compare the performance of 7 different routing schemes.

1. Our proposed algorithm, LLR, in which long lifetime paths are selected based on both two node specific parameters and two link specific parameters.
2. Min-hop routing as the conventional “energy-unaware” Internet routing algorithm.
3. Simple energy-aware routing protocol considering only the remaining energy levels of the nodes in route discovery.
4. Simple energy-efficient routing algorithm selecting the route based on only the minimum total transmission power.

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5. Simple energy-aware energy-efficient routing protocol which takes into account both total energy cost and residual energy when selecting the next hop, without considering the link reliability.
6. Reliable energy-efficient routing which selects the path corresponding to the minimum packet transmission energy for reliable communication, without considering the battery power of individual nodes.
7. Reliable energy-aware routing in which the cost associated with each hop is a function of the link error rate and residual battery energy.

A. Simulation Model

The same network setup is used to compare the routing schemes. Table I summarizes the network characteristics. We used a traffic scenario, where four source nodes at the upside left of the terrain send periodic data to the sink at the downside right.

Each intermediate node is equipped with a total amount of energy 0.5 J (node with minimum energy) or 1.5 J (node with normal energy) at the beginning of the simulation. We have divided up all the links into two categories: one with a normal error rate 2%, and the other with a high value of 30%. The percentage of network links with high error rate is considered 10% over simulations. If a packet loss occurs for any reason during the transmission, it will be retransmitted until it is delivered successfully to the sink.

TABLE I. NETWORK CHARACTERISTICS

Simulation Area (Terrain)	500×500 m^2
Number of Nodes	100
Node Deployment	Uniform
Radio Range	200 m
Bandwidth	200 kb/sec
Data Packet Size	50 B
Route Request Packet size	5 B

We use the following metrics to evaluate the performance of LLR and compare the results with the traditional schemes.

Lifetime: The network lifetime is defined as the smallest time that it takes for at least one node in the network to drain its energy [7]-[9].

Total Energy Consumption: The total energy expended by all nodes.

B. Simulation Results

We run the simulation by varying several parameters, including data rate, the percentage of network nodes with minimum energy, and time. Simulation results are obtained from 10 runs and results are averaged over the runs (with a 90% confidence level and 10% confidence intervals).

Figures 4 and 5 illustrate the network lifetime when varying the data rate from 20 to 100 in HBH and E2E manner, respectively. Here, the percentage of network nodes with minimum energy is set to 50%. Obviously, the network lifetime decreases with the increase in the data rate. We can see that, as expected, the min-hop algorithm performs the worst, since it not only fails to balance the workload among the intermediate nodes, but also uses large distance hops and consequently larger transmission energy. Furthermore, the plots effectively demonstrate the superior performance of algorithms 7 and 6 over the 3 and 4 as a result of selecting the low-error links and consequently, smaller energy expenditure on packet re-transmissions. Moreover, the scheme 5 outperforms 3 and 4 by taking into account both residual battery energy and packet transmission energy in node capacity measure. However, we can clearly see that the LLR expectedly performs better than the others. In contrast to other schemes, not only does LRR consider the node specific parameters (e.g. residual battery energy and the number of paths which the node is common among), but also the link specific parameters (e.g. link error rate and the packet transmission energy for reliable communication across the link) as well, to increase the operational network lifetime. Even if the residual battery energy and effective transmission energy for a single packet are identical on all hops, LLR performs better by selecting the path with minimum number common nodes using a path reservation mechanism and preventing quickly exhaustion of common nodes.

In E2E retransmission model, the results are generally similar to the case of HBH retransmission, except that the performance of HBH is better especially in the case of the schemes which consider reliability in route discovery. This can be explained by the effect of the number of retransmissions on energy expenditure and consequently, the network lifetime. Since any lost packet must be retransmitted from the source node in E2E manner that causes more energy consumption on intermediate nodes.

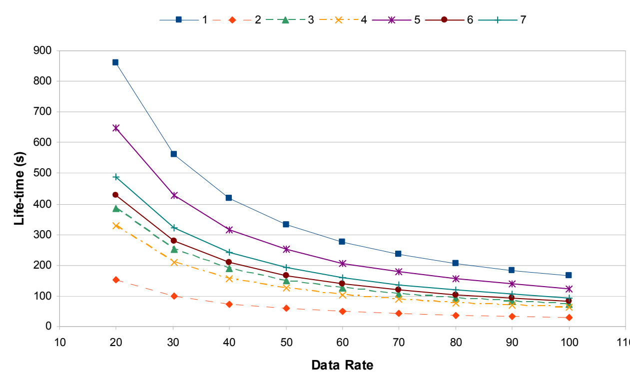

Fig. 2. Lifetime vs. Data Rate (HBH)

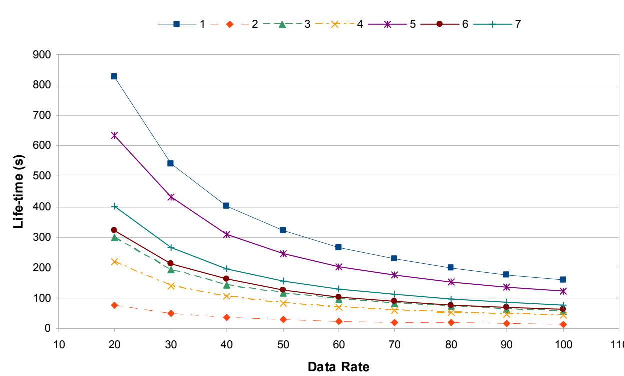

Fig. 3. Lifetime vs. Data Rate (E2E)

To study better, next we show how varying the percentage of network nodes with minimum energy from 10% to 50% affects the network performance, i.e., the network lifetime when the data rate is set to 20 packets per second (see Fig. 4, 5). Once again, it can be seen that the LLR algorithm present better lifetime than other routing protocols.

Figures 6 and 7 plot total energy consumption for the schemes in different time when the simulation duration is 200 seconds. In these scenarios, the data rate and the percentage of network nodes with minimum energy are set to 20 and 50%, respectively. Whereas the LLR algorithm obviously results in maximum network lifetime, we can clearly see that the Reliable energy-efficient routing results in the lowest total energy consumption among all the routing schemes.

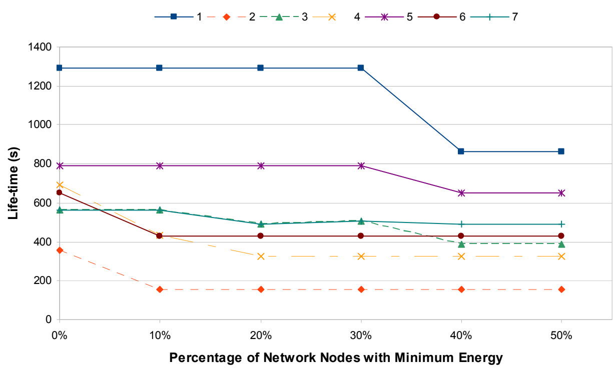

Fig. 4. Lifetime vs. percentage of nodes with minimum energy (HBH)

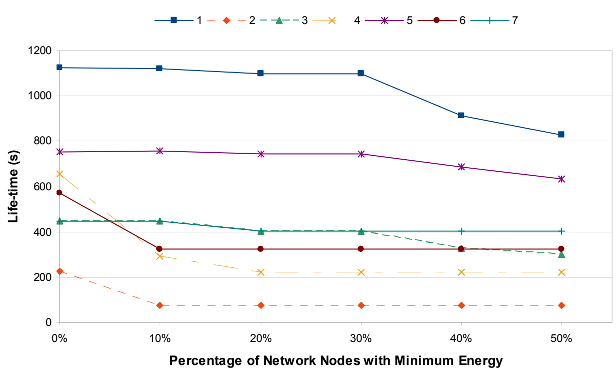

Fig. 5. Lifetime vs. percentage of nodes with minimum energy (E2E)

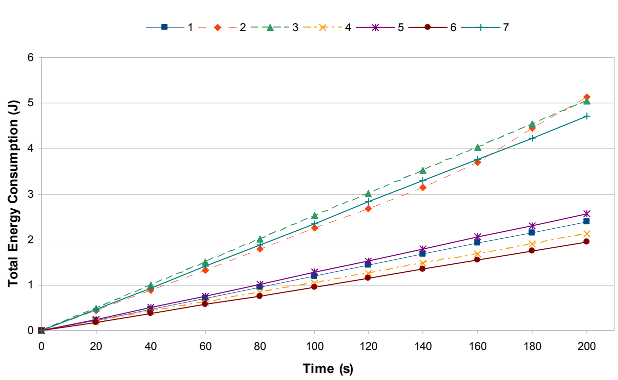

Fig. 6. Total energy consumption vs. percentage of nodes with minimum energy (HBH)

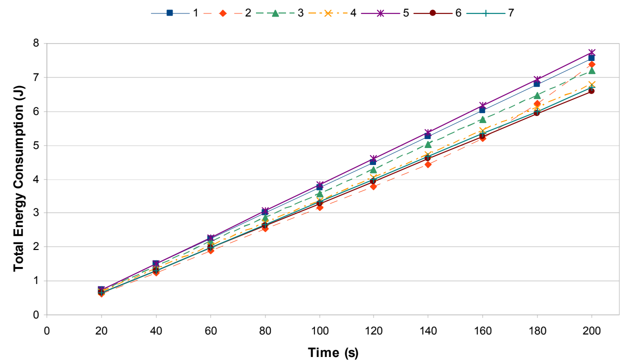

Fig. 7. Total energy consumption vs. percentage of nodes with minimum energy (E2E)

As expected, especially in a harsh environment characterized by extremely poor channel conditions, E2E manner will cause more energy consumption on intermediate nodes because the lost packets must be retransmitted from the source nodes which it causes more energy consumption on intermediate nodes.

Moreover, from the experiments made, it can be concluded that power-aware routing protocols must not only be based on the node specific parameters but also consider the link specific parameters to prolong the operational network lifetime.

IV. Conclusion

In this paper, we have presented a new power-aware algorithm for energy-efficient routing that increases the lifetime of multi-hop WSNs. In contrast to conventional power-aware algorithms, LLR identifies the capacity of a hop not only based on the residual battery energy and the number of paths sharing the associated node, but also the expected energy spent in reliably forwarding a packet on it. Our simulation experiments confirm that LLR outperforms other traditional routing schemes.

The algorithm could be modified to take into account some aspects that have not been addressed in this work, and that can be interesting subject of future research. For instance, studying a deadline-aware long lifetime algorithm can be considered as a future work.

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