Continuous energy-efficient monitoring model for mobile ad hoc networks

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***Abstract*—The monitoring of mobile ad hoc networks is an observation task that consists of analysing the operational status of these networks while evaluating their functionalities. In order to allow the whole network and applications to work properly, the monitoring task has become of considerable importance. It must be carried out in real-time by performing measurements, logs, configurations, etc. However, achieving continuous energy-efficient monitoring in mobile wireless networks is very challenging considering the environment features as well as the unpredictable behavior of the participating nodes. This paper outlines the challenges of continuous energy-efficient monitoring over mobile ad hoc networks. We propose two strategies that can reduce the energy consumption and extend the lifetime of the monitoring system. We also formulate the continuous monitoring problem decision as a Markov Decision Process (MDP). The experimental results obtained by simulations, clearly show that our proposals can reduce significantly the energy consumption and increase the whole network lifetime.**

***Index Terms*—Mobile ad hoc network (MANet), efficient-energy monitoring, Markov decision process.**

I. INTRODUCTION

Mobile ad hoc networks are formed in order to provide diverse applications or services under normal or abnormal conditions. To benefit correctly from all provided services while controlling the fundamental network characteristics, monitoring becomes very demanding. This activity is achieved by observing participating nodes and links, the communications between neighbor nodes, and by storing and processing the collected data [1].

Managing the energy consumption of participating nodes in these networks can be considered as a key issue in maintaining continuous and energy-efficient monitoring since a participating node that drains its energy, will not perform its monitoring tasks. This can raise various concerns especially in disaster and hostile environments. The unavailability of some monitoring data as well as the absence of management nodes can cause a significant degradation of performance since users of this monitoring system do not benefit from a suitable and an appropriate service. Additionally, dangerous effects may even occur in hostile environments.

Several monitoring approaches exist in the literature and rely on different mechanisms to fulfill this requirement. Nevertheless, there is no performance evaluation to indicate which of these approaches can achieve the best energy consumption performance. In this paper, we aim to show how to optimize the monitoring process in order to reduce the energy consumption and thus to extend the monitoring system lifetime. We first propose two data collection energy efficient strategies for the monitoring process. Second, an infinite horizon time Markov Decision Process (MDP) is proposed in order to derive efficient decision policies that prevents to disable the current monitoring system. The simulation results show the effectiveness of our approach.

The structure of the paper is as follows. Section II is devoted to the problematic of energy limitation in ad-hoc mobile networks. Section III describes previous work in the area of continuous efficient-energy monitoring. Section IV is dedicated to the presentation of our directions and strategies. In section V, we formulate the monitoring model based on MDP. Simulation results are given in section VI. Finally, in section VII, we conclude this paper by the presentation of some future works.

II. BACKGROUND AND MOTIVATION

Mobile nodes can perform monitoring tasks, in addition to other specific/dedicated applications. This activity that allows to repeatedly report the recent updates of the nodes (normal and abnormal), can lead to additional drain on their batteries. The reasons are numerous. First, monitoring essentially consists of collecting, storing and analysing data, and sending alerts in the presence of anomalies. These tasks decrease the energy budget of the participating nodes. Moreover, the sending of these data collection can cause excessive collisions of messages. Secondly, monitoring systems try to handle voluntary or involuntary disconnection of participating nodes by relying on different mechanisms such as delegation and retransmission of monitoring data or alerts. However, this can generate extra communication-cost. Then, global positioning systems can be used to approximate the link expiration time or to localize any mobile node, which is computationally costly for resource utilization. Furthermore, Monitoring systems can also integrate security and privacy functionalities in order to protect monitoring data. Furthermore, they can implement fault tolerant services, which increase the overhead and the energy consumption. In addition, monitoring systems dedicated to disaster, hostile and unstable environments can involve specific installations and integrate emergency mechanisms which are expensive. Moreover, they can require that the monitoring system of any participating node must be always enable since the location, the frequency and the kind of the disaster cannot usually be predicted. Participating nodes can also be dispersed across long paths which generates a high communication overhead caused by the periodic reporting of states.

However, the impossibility of recharging their batteries can affect the performance of monitoring systems. This may impact the overall operation of the network especially in disaster environments and military areas. On the one hand, we can end up with a monitoring area without management nodes. On the other hand, we can have difficulty to obtain and keep up-to-date a global snapshot of the environment. This can lead to generate inappropriate decisions. In addition, several attacks or events cannot be always detected.

To this end, any monitoring system must take into consideration the energy limitation in order to guarantee the continuity of the monitoring tasks. This is can be achieved by addressing mechanisms and strategies that reduce energy depletion in mobile ad hoc network and so that extend the monitoring system lifetime.

III. RELATED WORK

As previously exposed, monitoring is a significant energy-consuming activity in mobile ad hoc networks. Consequently, different techniques have been proposed in order to reduce energy consumption of the monitoring process. Next we will detail some of these approaches while highlighting their advantages and drawbacks.

A. *Efficient-energy election of management nodes*

Management nodes are usually elected to handle the monitoring activity on behalf of neighborhood nodes. In [1] and [2], [29] the authors reviewed and analyzed several monitoring approaches and the underlying algorithms of election. Among these algorithms, only those cited in [2], [3], [7], [8], [9] and [10] use the energy budget of participating nodes as one of the considered criteria to elect management nodes. However,to our knowledge, there is no study in the literature which evaluates the reliability of the proposed algorithms in relation to energy requirements.

Finally, authors in [2] and [19] propose that, in order to reduce its energy consumption, the current management node can directly delegate part of its monitoring tasks to some others mobile nodes.

B. *Construction of virtual topology and routing protocols*

Constructing a virtual topology attempts to decrease the energy consumption by limiting the number of links between participating nodes as well as distributing the control and the storage loads. Several virtual topologies (cluster, MPR, CDS, etc.) have been proposed to meet the requirements of monitoring in mobile ad hoc network [2] [3].

Routing protocols can be used to achieve all communications between participating nodes as exposed in [11] [3] or to choose the best path to the sink with energy reserve as in [12].

C. *Optimization of data collection*

Several types of data can be collected from each participating node in the network based on the application domain. The specific characteristics of the application need to be translated into a number of relevant factors that need to be taken into account when developing approaches for monitoring this network. According to the monitoring area, we can classify the data collection strategies into two categories. The first one, distributed collection (DiC strategy) allows each node to collect information about its neighbors. The approaches [22] and [23] use this strategy for collecting data. The second one, decentralized collection (DeC strategy). In this strategy management nodes are elected and each management node can collect data only from its managed nodes. This strategy is adopted by several approaches as in [24] and [25].

The monitoring data can be locally analyzed and stored or sent to the corresponding management node. In the last one, the data can be sent either periodically or on demand and by trigger. For this last case, data are sent whenever a participating node finds a significant change in its observed state or a management send a query requesting the data. This can reduce the traffic of network by avoiding useless communication. Nevertheless, some events may not be easily detected.

In this context, in the literature three strategies have been proposed in order to reduce the energy consumption needed for data collection. The first strategy consists on reducing the size of data collections by excluding some nodes from the process ([13] and [2]). However, this strategy may affect the network performance due to the unavailability of some data or services. The second strategy aims to reduce the distance between the management node and some distant managed nodes [19]. Finally, the objective of the third strategy is to reduce the size of the collected data. In [20] and [27], the authors propose to aggregate data into messages in order to decrease the energy consumption. Nevertheless, this strategy can be only applied in hierarchical architectures.

D. *Hardware energy saving*

In [16], the authors propose to integrate two hardware techniques into a wireless network monitoring system to reduce the total energy consumption of heterogeneous resources. The first technique aims to decrease the power consumption of processors through dynamic voltage and frequency scaling. The second one (dynamic power management) allows to manage power consumption of peripherals and dynamic random access memory in order to automatically deactivate (if its power consumption is high) or activate the hardware component or switch it into energy-saving state. However, these proposed energy-saving techniques can have negative influences on monitoring system performance as the deactivated hardware component cannot perform monitoring tasks during idle periods.

As we can notice, every approach tries to decrease the energy consumption and increase the monitoring system lifetime by relying on different mechanisms. Each adopted mechanism presents its advantages and limitations. In the following, we propose two strategies to optimize the data collection energy consumption and a continuous monitoring decision approach based on Markov Decision Process in order to ensure an energy efficient continuous monitoring.

IV. OPTIMIZATION OF DATA COLLECTION

In this section, we propose to improve the data collection task in order to keep the monitoring system functioning as long as possible. In this way, we propose the two following strategies:

- *Reducing the distance between the management nodes and its managed nodes*. The long distance between managed nodes and their management node can lead to the depletion of their energy. So, a monitoring system must avoid this situation that lowers the network lifetime. We propose an appropriate network arrangement based on the coordinates of the participating nodes. Initially, each management node determines the smallest distance between it and its managed nodes. Then, it asks its managed nodes to move to the appropriate position for reaching this smallest distance. Considering this strategy, the adopted data collection model (called *CbRD*), which is based on the reduction of the distance between the management nodes and its managed nodes, can also be used to balance the energy consumption between the managed nodes.
- *Decrease the number of managed nodes*. When monitoring is distributed over the network nodes without relying on a virtual topology, we say that *equivalent* or *semi-equivalent* management nodes can appear. Two management nodes are equivalent (resp. semi-equivalent) if they fully (or partially) cover the same area. This means that, they manage common neighbors or supervise the same area. As we can notice, not all these management nodes can be crucial at the same time to supervise the networks. In order to reduce the total energy consumption of management nodes and to extend the lifetime in such networks, we propose a new saving energy strategy (called *CbRMN*) that allows reducing the number of both management nodes and managed nodes. In fact, only one equivalent management node having maximum energy level will be enabled (it will replace the other management nodes). In the same way, semi-equivalent management nodes must not supervise the same participating nodes.

In addition to these strategies, monitoring systems must also adapt their functionalities to the available resources of the current participating nodes in order to prevent to disable the current monitoring system. Therefore, in the following we propose to use a solid mathematical model to achieve this adaptability.

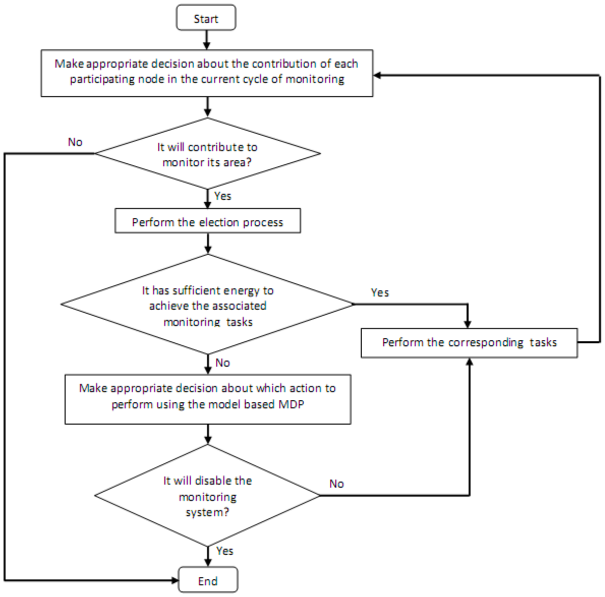

Fig. 1. Continuous monitoring

V. CONTINUOUS MONITORING DECISION PROBLEM

A regular participating node can properly contribute in monitoring process only if it has more residual battery power than the energy required to perform its monitoring tasks. Otherwise, it can make its strategic decision about the activation of its monitoring system. Thus, it can disable its monitoring system or perform either lightweight monitoring or prediction-based monitoring. Markov Decision Processes (MDPs) [6] use unified and mathematical framework to formulate optimization problems which can be resolved while making sequential decisions under uncertainty. In this way, the continuous monitoring decision problem can be modeled by a MDP, which is a discrete-time state-transition system. This model is presumed to be integrated to the used monitoring system and it will be executed by each participating node as illustrated by the diagram flow chart in figure 1.

A. Elements of the Markov Decision Process

In the following, we will identify the four elements of the proposed infinite horizon MDP which are: the state set S, the action set A, the transition function T and the reward function R. Typically, a participating node which is in a state $s \in S$ can enter into the state $s' \in S$ by executing the chosen action $a \in A$. Thereafter, it will obtain a reward r depending on the reward function R.

1) State space: In the following, we adopt the DeMM monitoring model (Decentralized Monitoring Model that integrates the DeC strategy, see section III.D). We can define the set of probable states of each participating node as $S = \{s1, s2, s3, s4, s5\}$ while also considering some proposed improvement cited in section IV.

- The initial state $s1$ indicates that the current participating node has not sufficient residual energy to perform its monitoring tasks.

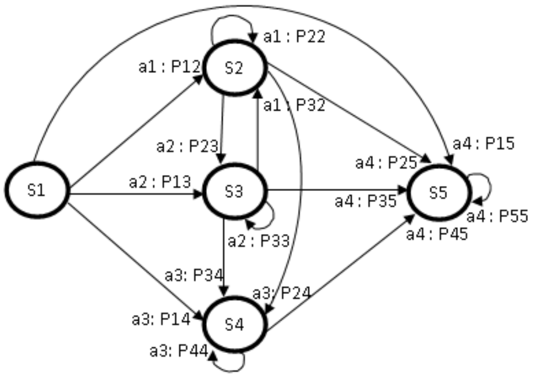

Fig. 2. The proposed MDP model

- The state $s2$ referred to lightweight-monitoring mode (called $mode1$). This mode consists in decreasing the number of managed nodes. It reflects the chosen monitoring mode which will occurred when the participant node decides to perform the action $a1$.
- The state $s3$ referred to lightweight-monitoring mode (called $mode2$). This mode consists in decreasing the volume of collected and transmitted data. This state will be reached when the action $a2$ has been taken by the participant node.
- The state $s4$ referred to the prediction-based monitoring. It represents the state where the participant node will move on by performing the action $a3$.
- The state $s5$ occurs when the current participating node disables its monitoring system.

2) Action space: A participating node is capable to make a decision about which strategic action to perform thanks to the MDP model based which chooses autonomously an allowed action from a limited set of potential actions $A = \{a1, a2, a3, a4\}$:

- The action $a1$ designates that the current participating node decides to activate the lightweight-monitoring $mode1$ while decreasing the number of managed nodes (i.e. controlled neighbors).
- The action $a2$ shows that the current participating node decides to activate the lightweight-monitoring $mode2$ while diminishing the amount of the transmitted data (resp. the collected data).
- The action $a3$ specifies that the current participating node decides to activate its prediction model.
- The action $a4$ indicates that the current participating node decides to shutdown its monitoring system.

3) Transition function: $T(s_i|s_j, a_k)$ is the transition function, which indicates the probability of mapping a state s_i providing an action a_k to a state s_j. In our context, it represents the current participating node state mapping between $s1, s2, s3, s4$ and $s5$ while executing its corresponding actions (see figure 2). Hence, the different transition probabilities can be defined as displayed in table I.

TABLE I
TRANSITION PROBABILITIES

	s1	**s2**	**s3**	**s4**	**s5**
s1	0	P12	P13	P14	P15
s2	0	P22	P23	P24	P25
s3	0	P32	P33	P34	P35
s4	0	0	0	P44	P45
s5	0	0	0	0	1

Let $P(s_i|s_j, a_k)$ be the transition probability that is calculated as follows :

- $P(s_{i\in\{1,2,3,4\}}|s5, a_k) = 1$ if the current participating node has not sufficient residual energy to perform at least one of these actions $\{a1, a2, a3\}$. Otherwise, it will be equal to 0
- $P(s_{i\in\{1,2,3,4\}}|s_{j\in\{2,3,4\}}, a_k) = \frac{1}{|A_f|}$ if $a_k \in A_f$ that represents the set of the feasible actions. Otherwise, it will be equal to 0.

4) Reward Function: $R(s_i, a_k, s_j)$ is a reward function specifying the predictable immediate reward that a participating node will get when performing the action a_k in state s_j. It is defined as the sum of two rewards $R(s_i)$ and $R(s_j)$. The first reward is obtained when being in the current state s_i, whereas the second one will be received when moving to another state s_j by performing the action a_k. In order to optimize the monitoring system performance, the cost of mapping $R(s_j)$ is calculated related to the participating node condition as well as the network behavior :

$$R(s_i, a_k, s_j) = R(s_i) + R(s_j), where\ R(s_j) = G_j - E_j - L_j \tag{1}$$

The gain G_j is obtained by mapping the state s_i to s_j. E_j designs the needed energy to map the state s_i to s_j. The fact of executing the allowed action a_k can reduce the overall network performance by the value noted by L_j.

5) Solving MDP: A policy π is a mapping which relates to a state s_t and a given action a_t (i.e. $a_t = \pi(s_t)$). The aim of our proposed MDP is to find an optimal policy π^* to maximize the reward function.

$$V^*(s) = maxV_{\forall\pi}(s)\pi^*(s_i) = argmax_{a_k\in A}\sum_{s_j\in S} P(s_i|s_j, a_k)V^*(s_j) \tag{2}$$

The infinite horizon value function discounting $V_\pi(s)$ is defined as :

$$V_\pi(s) = \lim_{T\longrightarrow\infty} E_{\pi,s}\left\{\sum\nolimits_{t=1}^{T} \gamma^{t-1} r_t\right\}, \gamma \in [0, 1] \tag{3}$$

The proposed MDP model can be resolved using the policy iteration algorithm [28]. This method aims to compute an optimal policy while evaluating a sequence of feasible policies.

VI. PERFORMANCE EVALUATION

The performance evaluation is achieved by a set of simulations developed using the Matlab programming language. We used the model proposed by Heinzelman et al. [21] to estimate the energy consumption. The simulation settings and parameters are listed in table II. Our goal is to evaluate two of the proposed strategies presented in section IV (i.e. CbRD and CbRMN) that aim to optimize the collection of data as well as the previously proposed model. Both evaluations are based on energy consumption and monitoring system lifetime.

TABLE II
SIMULATION PARAMETERS

Parameters	**Values**
Network size	50-500
Territory scale	100m*100m
Communication range	20
Mobility model	Random WayPoint
Hello frequency	2s
Collection frequency	3s
Initial energy	3j

1) Data collection optimization: We have compared two proposed strategies which are based on the decrease of the number of managed nodes (CbRMN) and the reduction of the distance between a management node and its managed nodes (CbRD) with the distributed (DiC) and decentralized (DeC) collection respectively. Figure 3 represents the average number of managed neighbors as well as the energy consumption in term of the number of nodes.

As we may notice, the CbRMN proposed strategy consumes less energy than the DiC strategy. This phenomenon is explained by the fact that management nodes can monitor less number of neighbors while avoiding the common once. Nevertheless, the Dic strategy can give a complete sight on the monitoring area. The efficiently of this strategy highly depends on the honestly of participating nodes (mobile nodes must participate in the monitoring process without any malicious or selfish attention). Hence, the following question arises: which monitoring type a user can adopt? Efficient monitoring or energy-efficient monitoring? The latter can ensure the monitoring efficiencies in terms of the availability of monitoring service, whereas the first type can ensure efficient monitoring satisfying quality of service constraints.

Figure 4 shows the energy consumption as a function of number of node for the CbRD startegy. As one can see, our strategy CbRD can decrease the consumption of energy compared to the DeC strategy while reducing the distance between the management nodes and their managed nodes. The movement of some managed nodes does not add high energy consumption. This is explained by the fact that these nodes are capable of moving over a small distance through the same area coverage. Furthermore, the movement of any managed node can significantly reduce its energy consumption during data collection. Energy consumption can also be ignored when considering the movement of people rather than the mobility of devices.

2) Performance evaluation of the monitoring model based on MDP: The proposed monitoring model based on MDP (MMDP) is validated via simulation and compared to decentralized monitoring model (DeMM). Our results illustrates that our proposed model can extend the monitoring lifetime as shown in figure 5. In contrast to the DeMM model, a participating node makes its decision to perform the most appropriate actions regarding to its remaining energy. This can lead to increase the number of monitoring cycles.

VII. CONCLUSION

Monitoring is a vital application for mobile network. When participating nodes run on rechargeable batteries having limited lifetime, the aspect of energy limitation must be considered at each monitoring phase. This is justified by the fact that some large-scale mobile ad hoc applications need to have macroscopic and real time monitoring data. In fact, we have proposed some strategies and recommendations that can reduce the energy consumption. Thought simulation, we have demonstrated that the proposals can reach a significant optimization in term of energy consumption. We have also proposed an infinite horizon MDP that can help participating nodes to make appropriate decisions about the activation of their monitoring system. Experiment result of the case study illustrate the effectiveness of this model in term of monitoring system lifetime. For future work, we investigate to extend the proposed MDP model to cover two other actions which can also increase the monitoring system lifetime. These actions designate for instance, the activation of the adaptive collection mode and the data compression mode. Moreover, we plan to evaluate the performance of the energy efficient routing based monitoring in terms of energy consumption and network lifetime.

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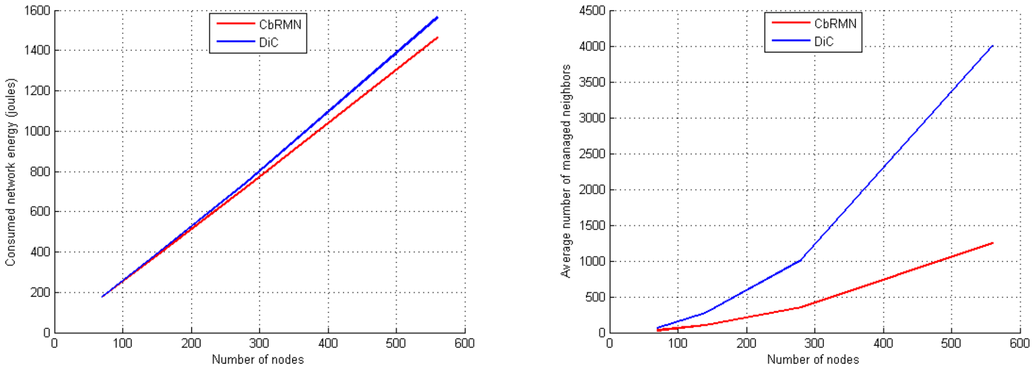

(a) a

(b) b

Fig. 3. [a] Network energy consumption [b] Average number of managed neighbors

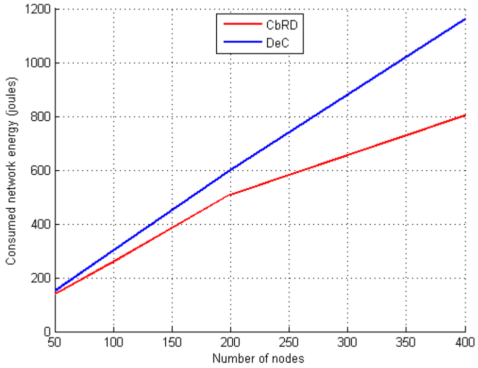

Fig. 4. Network energy consumption

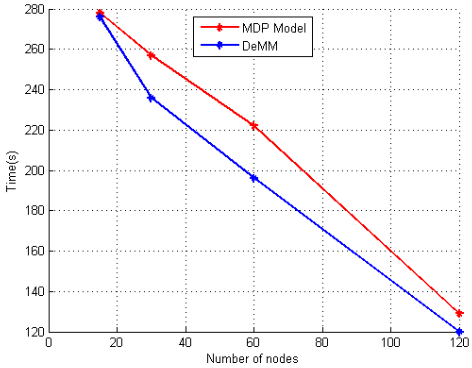

Fig. 5. Monitoring system lifetime

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