Maximizing Lifetime of Heterogeneous Wireless Tunable Camera Sensor Networks Ensuring Barrier Coverage

Nguyen Thi My Binh, Huynh Thi Thanh Binh,
Nguyen Hong Ngoc, Mai Dang Quan Anh and Nham Do Hai Ninh

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*,+Nguyen Thi My Binh, +Huynh Thi Thanh Binh, +Nguyen Hong Ngoc, +Mai Dang Quan Anh, +Nham Do Hai Ninh
*Hanoi University of Industry, Hanoi, Vietnam; +Hanoi University of Science and Technology, Hanoi, Vietnam
*binhntm79@gmail.com, +binhht@soict.hust.edu.vn, +ngocnguyen.nd97@gmail.com, +anhmdq@gmail.com, +bonbit09@gmail.com

Abstract—**Barrier coverage in wireless camera sensor networks (WCSNs) has drawn the attention of research community since it promises an extremely potential in applications involve movement detection and surveillance. Energy-efficiency is an important issue in WCSNs because battery resources are limited. Mechanisms that conserve energy resources are highly desirable, as they have a direct impact on network lifetime. How to prolong lifetime of wireless sensor networks has been examined by academic community. However, most prior researches worked on the problem have not obtained good solutions and under the assumption that sensor nodes are homogeneous as well as omni-directional sensing coverage. This paper thus investigates an optimizing lifetime in heterogeneous WCSNs with ensuring strong barrier coverage problem named MLBC-HWCSN. We formulate the MLBC- HWCSN problem, and then devise the Modify Maximum Flow Algorithm (MMFA) including three stages: constructing the flow-network, finding the maximum flow and refining the solution to solve this problem. Experimental results on extensive instances have been proven that the proposed algorithm is suitable for the MLBC-HWCSN problem and more efficient than existing algorithm.**

Index Terms—**Maximizing the network lifetime, barrier coverage, heterogeneous wireless tunable camera sensor networks, max flow, Edmond-Karp algorithm, Dinitz algorithm.**

I. INTRODUCTION

Wireless camera sensor networks (WCSNs) have drawn the attention of research community, because they can gather much richer information of the environment in the forms of images or videos than conventional scalar sensors. WCSNs promise an extremely potential in applications involve movement detection, such as surveillance battlefield and intrusion detection. Recently, the barrier coverage problem in (WCSNs) has drawn the attention of research community, due to WCSNs can gather much richer information of environment in the forms of audio, image, video than conventional scalar sensor (e.g. temperature, humidity) [1]–[3]. Most prior solutions to the problem aimed at finding as many barrier sets as possible to enhance coverage for the region of interest, which did not consider the power conservation and energy-efficiency.

Conserving energy and prolonging battery lifetime of WSNs become importance, because battery resources are limited. Mechanisms that conserve energy resources are highly desirable, as they have a direct impact on network lifetime. Network lifetime can be defined as the continuous interval time from the network setup time to the time that the deployed network cannot provide adequate coverage, e.g. the coverage degree is less than a predefined threshold. It is no sense in discussing the network lifetime if the coverage degree is not feasible. For the barrier coverage, in case one barrier is form, the network lifetime is determined by the sensor with the least energy belonging to the barrier. If no barrier can be constructed, the network lifetime is zero even though each node has available energy. Therefore, an excess of sensors are often deployed to obtain a high coverage probability and extend prolong the network lifetime. Since each sensor node is usually energy-limitation and is hard to recharge or battery replacement with hostile or inaccessible environments in many scenarios, how to maximize the network lifetime through efficient algorithms becomes vital and is highly desirable. Therefore, in this paper, we investigate the problem of maximizing the network lifetime ensuring barrier coverage by heterogeneous wireless camera sensor networks (HWCSNs) with tunable orientations under the random deployment strategy, called MLBC-HWCSN.

A HWCSN includes two or more various types of camera sensor nodes with functionality and battery energy difference. Camera sensor nodes are always directional sensing coverage models. The WCSN is also called the wireless directional sensor network (WDSN), which possesses some unique characteristics, such as limited sensing angle, directional sensing, communicating range, and line of sight. These features cause the majority of existing coverage control theories and methods of traditional omni-directional wireless sensor networks can not be directly applied to WDSNs [4]. Furthermore, the motivation in real life behind the HWCSN is the need of extra battery energy and more complex hardware is necessary to be embedded in some cluster heads, hence this reducing the overall cost of hardware for the remaining sensor network. This paper focuses on HWCSN regarding different lifetime and types of sensors in which some camera sensors can rotate around their central (Figure 1 demonstrates a turnable sensor) while other can not.

Although the maximizing barrier coverage lifetime problem in WSNs has examined by the academy community, most these studies had not achieved good solution or assumed that sensor nodes were homogeneous and/or omni-directional sensing coverage. In addition to, the motivations have considered for

HWCSN, we are the first to study the optimizing lifetime strong barrier coverage in heterogeneous wireless tunable camera sensor networks. The main contributions of this paper are as followed:

- Establish the maximizing the network lifetime problem of heterogeneous wireless camera sensor networks ensuring barrier coverage with some camera sensors be able to tunable around their central (hereinafter MLBC-HWCSN problem).
- Proffer an efficient method called MMFA for solving the problem.
- Analysis, evaluate and compare the experimental results and show that our method outperforms the previous methods for most cases regarding quality solution and computation time.

The rest of the paper is organized as follow. Related works are presented in section 2. Preliminaries and formulation for the optimizing lifetime of strong barrier coverage in heterogeneous wireless camera sensor networks is discussed in Section 3. Section 4 introduces proposed algorithm. Section 5 gives our experiments along with computational and comparative results as well as conclusion in section 6.

II. RELATED WORKS

Barrier coverage in WSNs has received extensive attentions by academy community in recent years, because of its advantage for security applications. The barrier coverage problem can be classified into two subproblems [5], [6] as find penetration paths and build intrusion barriers, which have been explored and examined in different aspects.

For finding penetration path, the researchers have been attracted to the minimal exposure path (MEP) problem [7]–[9]. The object of the MEP problem is to find a penetration path having minimal exposure value from a source point to a destination point in the sensing field. The knowledge of MEP in the sensor field is very useful, because the MEP is a good performance metric, which can be used to measure the quality of surveillance system or coverage quality of the sensor network [10]. Furthermore, the MEP can be used in optimizing, managing and maintaining quality of coverage of the deployed WSNs.

For building intrusion barriers, a series of front research results have been published [11]–[18]. Kumar et. al. [11] introduced the notion of k-barrier coverage of a belt region using wireless sensors. The authors also proposed efficient algorithms for quickly determining, after deploying the sensors, whether a region is k-barrier covered. In [12], the authors presented an efficient distributed algorithm to construct strong sensor barriers on long strip areas of irregular shape without any constraint on crossing paths. In [15], the authors established a tight lower-bound for the existence of barrier coverage under line-based deployments. They then considered sensor deployment along multiple lines and shown how barrier coverage is affected by the distance between adjacent lines and the random offsets of sensors. These results illustrated that sensor deployment strategies had directly impacted on the barrier coverage of WSNs. Distinctive deployment strategies may result in significantly different barrier coverage. Therefore, in the deploying and planning of WSNs, the coverage goal and possible sensor deployment strategies must be carefully and jointly considered. In [13], the barrier coverage model was proposed for applications in which sensors are deployed for intrusion detection. This paper focused on a strong barrier coverage problem in wireless directional sensors networks (WDSNs). They then proposed efficient centralized algorithms and a distributed algorithm to solve the problem. Simulation results extrapolated that the provided algorithms can be obtained close-to-optimal solutions and consistently outperform a simple greedy algorithm. In [14], the concept of local barrier coverage (LBC) was provided. Chen et. al. shown that LBC guarantees the detection of all movements whose trajectory was confined to a slice of the belt region of deployment. They then demonstrated that LBC can be used to design localized algorithms by developing a novel sleep-wakeup algorithms for maximizing the network lifetime.

Regarding maximized network lifetime ensuring strong barrier coverage in WSNs, in the literatures [19]–[24], have delved into an optimizing lifetime of strong barrier coverage with various assumptions. In [19], the sleep-wakeup problem is to determine a sleeping schedule for sensors such that the lifetime of the network is maximized while maintaining the desired quality of monitoring. Although the maximizing lifetime problem is proved to be NP-hard in full coverage model, Kumar et al. were the first proposing a polynomial time algorithm which utilizing the concept of multi-route network flows and proved its optimality to solve the sleep-wakeup problem for a specific class of applications, where a senor nodes were deployed as a smart barrier for detecting moving objects as in intrusion detection. In [20], the authors focused on the problem: how sleep-wakeup schedule can be used for omni-directional individual sensor nodes so that the redundancy is appropriately exploited to maximize the network lifetime? They then proposed algorithms can obtained an optimal solution on both homogeneous and heterogeneous sensor lifetime. Experimental results shown that when an optimal number of sensor nodes had been deployed randomly, statistical redundancy can be exploited to expire the network lifetime by up to seven times, and the assumption of homogeneous lifetime can result in severe loss of the network lifetime. In [23], the authors studied the problem of maximizing the coverage lifetime of a barrier by mobile sensors with limited battery powers, where the coverage lifetime is the time until there is a breakdown in coverage due to the death of a sensor. They investigated two variants which are the fixed radii problem and the variable radii problem. They then designed parametric search algorithms for both problems for the case where the final order of the sensors was predetermined and for the case where sensors were initially located at barrier endpoints. In [24], Han et. al. introduced the problem of maximizing WSNs lifetime with homogeneous tunable directional sensors, which is the most relevant to our work. The authors show that the maximum lifetime problem is equivalent to an Integer Programming Problem (ILP), which is a NP-hard. Thus, a heuristic algorithm is proposed to achieve a preferable solution, called Two-round maximum flow algorithm (TMFA). Although the algorithm is then proved experimentally to offer near-optimal solutions of the maximum lifetime problem in experimental circumstances, it still consumes much time, there thus is room for improvement. The research [24], which is the most relevant to ours, but the problem in [24] focused on homogeneous wireless sensor networks while we considered heterogeneous wireless camera sensor networks. We then proposed an efficient algorithm to solving the maximize the network lifetime of HWCSNs with ensuring barrier coverage.

III. PRELIMINARIES AND PROBLEM FORMULATION

A. Preliminaries

Sensor model describes how each sensor works in the deploying environment of WSNs. In this problem, the deployed sensors are turnable camera sensors which are modeled as nodes that contain multiple sectors represent the sensing orientations of sensors. Some definitions will be covered in the following to formulate the model.

Definition 1: Turnable camera sensor
The sensing region of a turnable camera sensor s is a sector represented by a tuple $(P, R, \alpha, \vec{W}d)$, where P is the location of the camera sensor, R is the sensing radius of the sensor, α is the sensing angle, and the working direction $\vec{W}d$ or also called the sensing orientation. The turnable camera sensor also has ability to change the sensing orientation among a set of m fixed directions. Figure 1 illustrates a turnable camera sensor. It is assumed that the energy consumption in rotating the sensor is negligible. The sensor has a lifetime, indicating the amount of time units it can operate and obtain information about the sensing field. The sensor can be scheduled to be turned to a certain orientation at a certain time. At the same time, it can also be scheduled to turn on or off for sleeping mode and we assume that the energy consumption when sleeping of a sensor is negligible.

Definition 2: Strong barrier coverage
A general WSN is said to be archiving strong barrier coverage if for every penetration path through the sensor field from a boundary to the opposite one, the intruder is crossed and being sensed by at least one sensor of the WSN.

Definition 3: Lifetime of the WCSN
The lifetime of the WCSN is the amount of time the network can provide continuous strong barrier coverage given the ability to rotate as well as turning on and off of each camera sensor individually.

To achieve the most out of a WCSN, it is necessary to set up a schedule for the camera to turn on, off and rotate to a certain orientation at a certain time so that the total lifetime of the WCSN is maximum. This problem is called the maximum lifetime for ensuring strong barrier coverage in HWCSN (MLBC-HWCSN).

B. Problem Formulation

We consider a WCSN with n heterogeneous turnable camera sensors: $S = s_1, s_2, \ldots, s_n$ deployed uniformly randomly inside a belt region B. The MBC-HWCSN problem can be formulated as a set of inputs and output as following.

Input

- W, H: the length and width of the sensing field
- $S = s_1, s_2, \ldots, s_n$: the set of turnable camera sensors
- n: number of sensors
- $P_i = (x_i, y_i)$: the position of the i-th sensor
- R_i: sensing radius of the i-th sensor
- α_i: half the sensing angle of the i-th sensor
- m_i: the number of possible orientations of the i-th sensor
- V_i: the set of possible orientations of the i-th sensor
- L_i: the lifetime of the i-th sensor

Output:
The maximum lifetime of the WCSN satisfying the strong barrier coverage.

IV. PROPOSED ALGORITHMS

In order to solve the MLBC-HWCSN problem presented above, an approach based on ILP has been proposed to find the exact solution. However, due to the fact that ILP is a NP-Completed problem, the complexity of the algorithm is rather high. Thus, we proposed an approximation algorithm called modified maximum flow (MMFA) to tackle this problem. The MMFA can achieve an acceptable solution in a short amount of time and includes three stages: constructing the flow-network, finding the maximum flow and refining the solution.

A. Constructing the Flow-Network

The EDBG proposed in [24] meets some critical issues as mentioned in section II. To overcome these issues, a directed network graph generated from a WSN called Flow-Network is proposed. From the WSN provided as input, a Flow-Network is constructed by the following four steps:

1) A source vertex S and a sink vertex T are added to the Flow-Network. The source vertex corresponds to the left boundary while the sink vertex corresponds to the right boundary.
2) For each sector of each sensor, e.g. sector a of sensor s, two corresponding vertices: a_{in} and a_{out} are added to the Flow-Network. An edge from a_{in} to a_{out} with capacity equals to the lifetime of sensor s is added to the Flow-Network. We call this edge the corresponding edge of sector a.
3) For every two overlap sectors that belong to two different sensors, e.g. sector a and b, add an edge from vertex a_{out} to vertex b_{in} and an edge from vertex b_{out} to vertex a_{in}. Both edges have capacity of positive infinity.
4) For each sector that overlap the left boundary, e.g. sector a, a edge from S to a_{in} with capacity of positive infinity is added to the Flow-Network. Similarly, if a overlap the

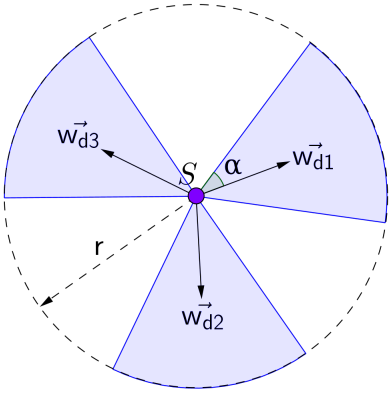


Fig. 1. Illustration of the turnable camera sensor model

right boundary, a edge from a_{out} to T with capacity of positive infinity is added to the Flow-Network.

In this case, the problem can not be modeled to the traditional capacity-on-edges maximum flow problem. As the lifetime of each sensor is limited, this problem is more likely related to the capacity-on-vertices maximum flow problem. Therefore, each sector is represented as two vertices in the Flow-Network, an inner vertex and an outer vertex. Edges toward the sector are connected to the inner vertex while edges direct from the sector are coming out of the outer vertex. An edge with capacity equals the lifetime of the sensor directs from the inner vertex to the outer vertex will ensure the constraint that the flow goes through a sector is not greater than the lifetime of it. Also, different from EDBG, in Flow-Network, we added both edges of both directions in order to give more accurate solution.

As an illustration for this stage, Figure 2 (a) shows the deployed WSN which includes two sensors: S_1 and S_2. Sensor S_1 have lifetime t_1 and two sensing orientations correspond to two sectors a and b; sensor S_2 have lifetime t_2 one sensing orientations corresponds to sector c. Figure 2 (b) shows the corresponding Flow-Network constructed from above steps. Each sector (a, b and c) has its inner vertex and outer vertex which edge between them has capacity equals the lifetime of the corresponding sensor. Other edges are added with capacity of positive infinity.

B. *Finding the maximum flow*

From the Flow-Network, we need to find the maximum flow on the network using Ford-Fulkerson method. A famous implement of Ford-Fulkerson method which is Edmond-Karp algorithm is used in [24]. Edmond-Karp algorithm which bases on choosing shorted path on number of edges as the residual path have the complexity of $O(VE^2)$. In this problem, as the number of edges is often much higher that the number of vertices, we will apply Dinitz algorithm to solve the maximum flow problem (the complexity of Dinitz algorithm is $O(V^2E)$.

C. *Refining the solution*

With the Flow-Network constructed above, it can be easily seen that the maximum flow on this network correspond to the maximum lifetime of an alternate WSN where each sector is an independent sensor with independent lifetime. Since each sector has its independent lifetime that equals to the lifetime of its container sensor, the total lifetime of all the sectors of a sensor combine is higher that the lifetime of the sensor. Therefore, in this case, it must have an additional constraint that: the total flow goes through all sectors of a sensor is not higher that the lifetime of the sensor. In which, the flow goes through a sector equals the flow goes through the corresponding edge of the sector. This stage is proposed in order to find the approximate correct maximum lifetime value of the input WSN. There are two steps:

1) For each sensor, check if the total flow goes through it sectors is higher than its lifetime. If it is, go to step 2.
2) Reduce the flow goes through each sector until the constraint is satisfied. The operator can be done by find a path that goes through the corresponding edge of the sector and then reduce the flow along the path.

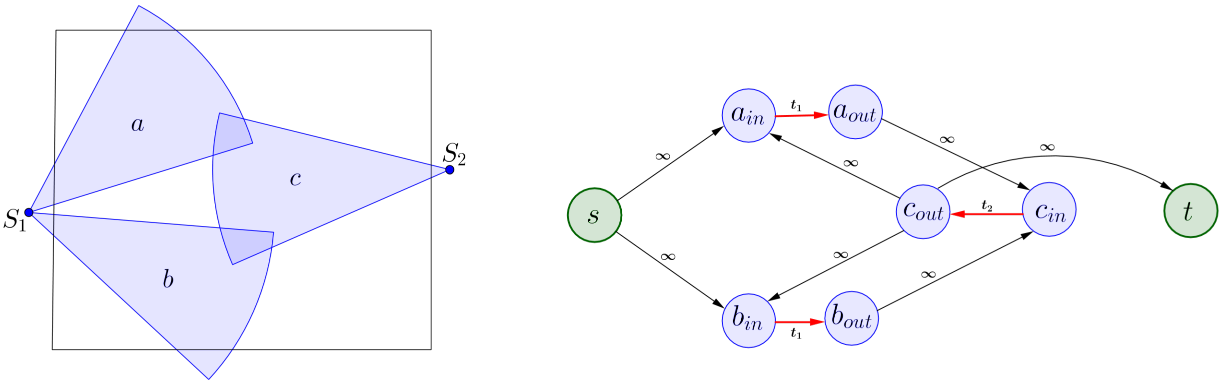
As an income, the maximum flow after this stage maybe different depends on which order do we iterate the sensors. However, the result satisfy all the constraints of the problem so it can be accepted as a solution.

V. EXPERIMENTAL RESULTS

A. *Data setting*

In this section, topologies are generated for simulation of the proposed algorithm. We built a dataset includes of four different scenarios:

- *Changing the number of sensors*: the number of sensing orientations is 4, the sensing radius is $40m$, the sensing angle is 45 degree and the number of sensors is changed from 50 to 400 with an increment of 50.
- *Changing the number of sensing orientations*: the number of sensors is 200, the sensing radius is $40m$, the sensing angle is 45 degree and the number of sensing orientations is changed from 1 to 8 with an increment of 1.



(a) The deployed WSN

(b) The corresponding Flow-Network constructed

Fig. 2. Illustration of constructing the Flow-Network from a WSN

- *Changing the sensing radius*: the number of sensors is 200, the number of sensing orientations is 4, the sensing angle is 45 degree and the sensing radius is changed from $20m$ to $80m$ with an increment of $5m$.
- *Changing the sensing angl*e: the number of sensors is 200, the number of sensing orientations is 4, the sensing radius is $40m$ and the sensing angle is changed from 10 degree to 80 degree with an increment of 10 degree.

The size of the region are fixed at $W = 300m$ and $H = 150m$. The lifetime of sensor is randomly generated in range $1, 2, 3$. For each topology, the coordinates of sensors are uniformly distributed in the region. The sensing orientations are also randomly generated in range $[0, 2\pi]$.

B. Computation results

In this subsection, we simulate MMFA and TMFA [24] on the scenarios generated above and analyze the output. Figure 3, 4, 5, 6 illustrate the result of simulation on each scenario.

From overall observation, for the solution on maximum lifetime value, MMFA gives slightly better value compared to TMFA in some topologies. The reason behind this is that the Flow-Network is more accurate than EDBG since it calculates both directions of the edge instead of just one direction in EDBG. Therefore, in some particular case, MMFA can find more valid barriers than TMFA can. In term of computational time, MMFA gives much shorter computational time compared to TMFA. This result is expected since MMFA uses Dinitz algorithm to find the maximum flow while TMFA uses Edmond-Karp algorithm. Statistics on topologies show that the number of vertices is thousands while the number of edges can easily reach millions. This outcome makes significant difference between using Dinitz and using Edmond-Karp as maximum flow algorithm.

Analyze on each scenario, it can be seen that, as the number of sensors increases, the number of sensing orientations increases, the sensing radius increases and the sensing angle increases, the maximum lifetime value tends to increase as well. It can be safe to assume this conclusion since the maximum lifetime value is affected by the randomize factor.

VI. CONCLUSION

This paper investigates the maximizing the network lifetime of heterogeneous wireless turnable camera networks ensuring strong barrier coverage problem named MLBC-HWCSN. This problem plays an important role to maintain energy-efficiency of wireless sensor networks. The MLBC-HWCSN is an optimization problem and transformed into ILP which is a NP-Complete [24]. We thus devise the approximate algorithm called modified maximum flow (MMFA) for solving the MLBC-HWCSN problem. The MMFA can obtain an acceptable solution in a short amount of time and includes three stages: constructing the flow-network, finding the maximum flow and refining the. We conduct extensive instances to analysis, evaluate and compare. Experimental results show that the proposed algorithm is suitable for the MLBC-HWCSN problem and surpass the prior algorithm.

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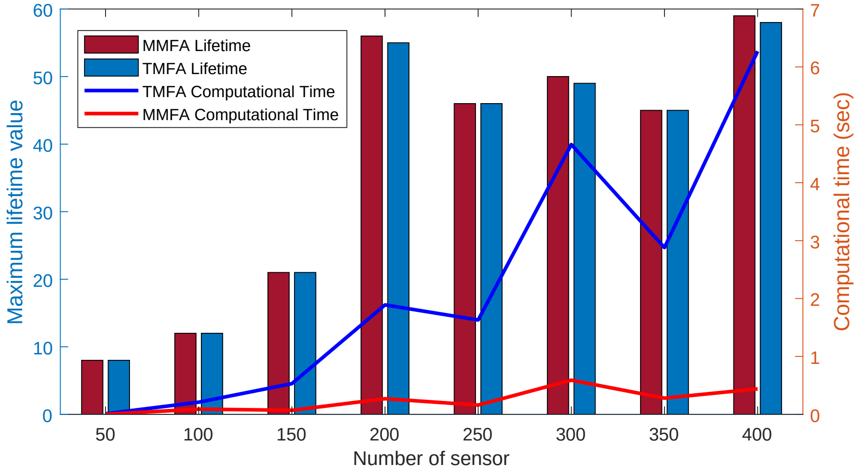

Fig. 3. Maximum lifetime and computational time by MMFA and TMFA when changing the number of sensors

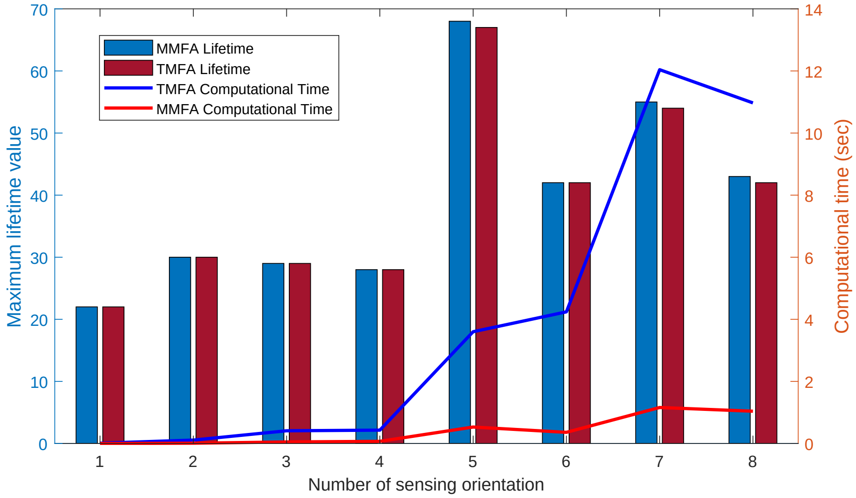

Fig. 4. Maximum lifetime value and computational time by MMFA and TMFA when changing the number of sensing orientations

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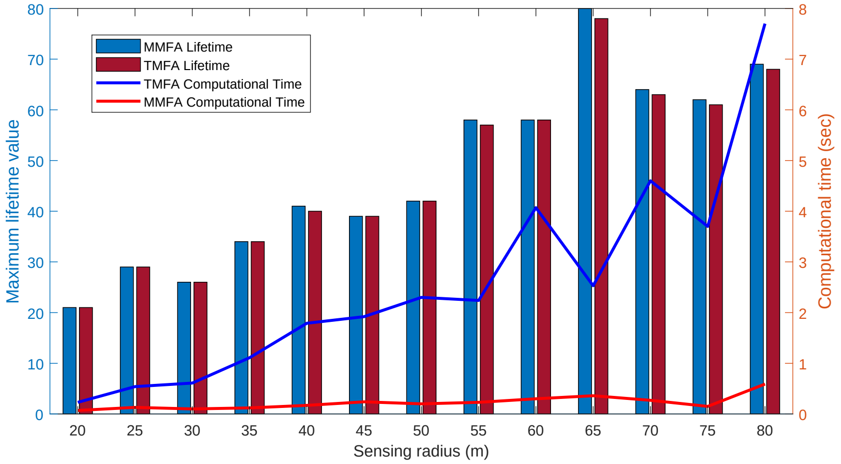

Fig. 5. Maximum lifetime value and computational time by MMFA and TMFA when changing the sensing radius

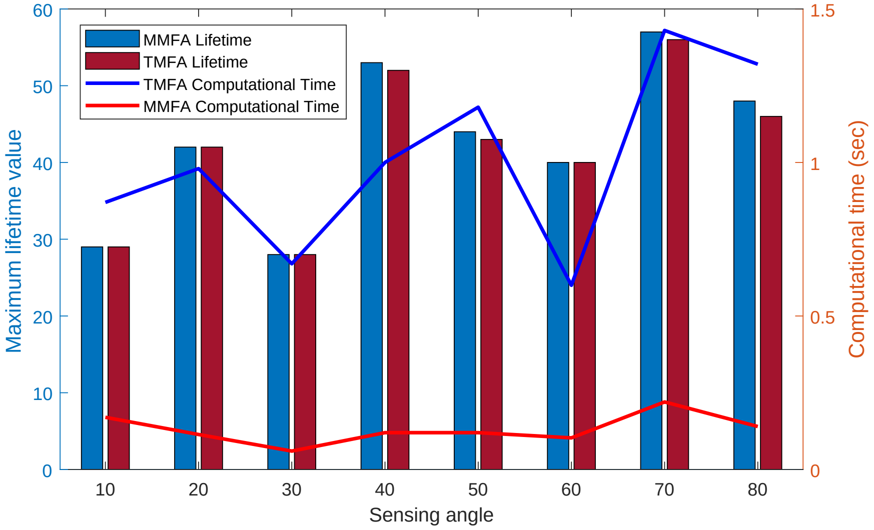

Fig. 6. Maximum lifetime value and computational time by MMFA and TMFA when changing the sensing angle

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