Fixed Image Sensors and Mobile Camera Robots Interactions for Mission-Critical Surveillance Applications

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***Abstract*—This paper introduces mobile camera robots with camera rotation capabilities. The motivation behind mobile camera robots is that as they rotate their camera their real sensing range moves from a FoV coverage to a disk coverage, therefore allowing neighboring nodes to decrease their activity level, thus their energy consumption. As a sensing node's activity is based on a criticality or risk approach, we proposed 2 interaction behaviors between fixed image sensors and mobile camera robots to dynamically adapt the activity level without decrease the surveillance quality. The performance of the interaction models is evaluated through simulation. The results show that mobile camera robots can successfully help to increase the network lifetime but, depending on the number of deployed mobile camera robots, care must be taken with the interaction behaviors to not decrease the detection quality.**

***Keywords*-Sensor networks, video surveillance, pannable camera, mission-critical applications**

I. INTRODUCTION

We address mission-critical surveillance applications [1], [2], [3], [4], [5] where autonomous sensors can be thrown in mass and mobile robots deployed when needed for intrusion detection or disaster relief applications. This article focuses on visual information where both fixed sensors and robot nodes are equipped with miniaturized visual cameras. Mobile robots usually already have embedded cameras and the advantage of camera mounted on mobile robots is the possibility to provide 360^o visual coverage over a period of time, as the robot moves or when the camera is mounted on a rotatable axis, instead of the limited cone of vision of fixed image camera.

Fig. 1. A proof-of-concept of a image sensor in a beach rocket toy.

In the case of autonomous sensors, figure 1 shows a image sensor in a rocket-shaped case to be thrown from the air. The figure shows that it is possible to have the embedded camera set in the right position, and not upside-down, to start sensing and transmitting images.

Based on the criticality model we developed previously in [6], this article extends the work we conducted in providing high quality of detection in intrusion detection systems or search&rescue applications [7], [8]. Most previous works on visual mobility have been done in the context of smart cameras or network of robots [9]. The contribution of the paper is to study mobile camera robots (we use this term to refer to camera mounted on mobile robots) and fixed image sensors interaction schemes to further increase the network lifetime while providing a high detection quality. There have been previous works on various cooperation schemes between different elements of a sensor network, [10], [11], [12] to name a few, but our contribution here is, to the best of our knowledge, the first paper that investigates the possible cooperation of mobile camera robots under criticality-based scheduling where the detection quality must be kept high. In this paper, we propose simple interaction schemes that are evaluated through extensive simulation studies. We study the impact on the intruder's stealth time and show that the network lifetime can be increased without increasing dramatically the stealth time.

The paper is then organized as follows: Section II quickly presents the coverage model and the node's activity scheduling based on application's criticality level. We then present in section III the fixed image sensors and mobile camera robots interaction possibilities for increasing further the network lifetime. Performance results showing the network lifetime and the detection quality will be presented in section IV. The impact of our mobile camera robots cooperation schemes on network load and congestion will also be discussed in section V. We conclude in section VI.

II. ACTIVITY MANAGEMENT OF IMAGE SENSOR NODES

A. Image sensor model

An image sensor node v is represented by the Field of View (FoV) of its camera. In our approach, we consider a commonly used 2-D model of a image sensor node where the FoV is defined as a triangle (pbc). A sensor v is denoted by a 4-tuple $v(p, d, \overrightarrow{V}, \alpha)$. Here p is the position of v, d is distance pv (depth of view, DoV), $\overrightarrow{V}$ is the vector representing the line of sight of the camera's FoV which determines the sensing direction, and α is the angle of the FoV on both sides of $\overrightarrow{V}$ (2α can be denoted as the angle of view, AoV). The left side of figure 2 illustrates the FoV of a image sensor node in our model. The AoV (2α) is 30^o and distance bc is the linear FoV. By using simple trigonometry relations we can link bc to pv with the following relation $bc = 2\tan\alpha * pv$.

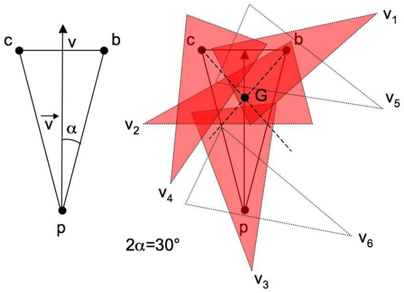

Fig. 2. Visual sensing and coverage model

We define the ith cover set $CO^i{}_v$ of a visual node v as a subset of visual nodes such that $\bigcup_{v' \in CO^i(v)}(v'$'s FoV area) covers v's FoV area. For instance, figure 2 shows that $\{v_1, v_2, v_3, v_4\}$ is one cover set of node v. Then CO_v is defined as the set of all the cover sets of node v.

In [15] we studied the problem of coverage by image sensors in randomly deployed WISN. We presented a model based on coverage of specific points of a sensor's FoV to find subsets of nodes that cover the FoV area of a given node. We evaluated various cover set construction strategies and we showed that some strategies perform better than others depending on the angle of view and whether the angle of view are homogeneous or not. Depending on the focus of the application, it is possible to choose a strategy to reduce the stealth time or to increase the network lifetime.

B. Criticality-based scheduling with Bezier curves

In randomly deployed sensor networks, provided that the node density is sufficiently high, sensor nodes can be redundant (nodes that monitor the same region) leading to overlaps among the monitored areas. Therefore, a common approach is to define a subset of the deployed nodes to be active while the other nodes can sleep. While this general scheme can serve as a guideline, practically deploying image sensor networks for mission-critical application requires advanced scheduling mechanisms to both capture relevant events with a high probability and provide longer network lifetime.

Our scheduling proposition works as follows. At initialization every sensor broadcasts its position p (we assume GPS capability) and its line of sight $\overrightarrow{V}$ in a single message to its neighbors and then constructs all possible covers, i.e. CO_v, that satisfy its local coverage objective (e.g. covering its FoV area) without exchanging additional messages [15]. Then, every node starts in active mode and waits to receive status packets from its neighbors. When a image node v receives the status of a neighbor v_x it adds v_x to its set A_v of active neighbors. Then it checks whether there is a $CO^i{}_v \in CO_v$ included in A_v, i.e. $\exists i, CO^i{}_v \subset A_v$. Every node orders their cover sets according to their cardinality (the number of nodes involved in the cover set), and gives priority to the covers with minimum cardinality. If a $CO^i{}_v$ is found, v goes in sleep mode after sending its decision to its neighbors. In the case where no $CO^i{}_v$ is satisfied, node v decides to remain in active mode and diffuses its decision.

Then, with visual sensor nodes, the frame capture rate is an important parameter that defines the surveillance quality. In [6], we proposed to link v' capture rate to the size of its cover set CO_v. The motivation is that nodes with more cover sets can capture at a higher rate, therfore acting as sentry nodes, since they can be replaced by one of their cover sets. In our approach we define two classes of application: high and low criticality applications. This criticality level can be represented by a concave and a convex shape as illustrated in figure 3 with the following interesting properties. **Class 1 "low criticality"**, does not need high frame capture rate. This characteristic can be represented by a concave curve where most projections of x values on the y-axis are gathered close to 0 (figure 3 box A). **Class 2 "high criticality"**, needs high frame capture rate. This characteristic can be represented by a convex curve where most projections of x values on the y-axis are gathered close to the max frame capture rate (figure 3 box B).

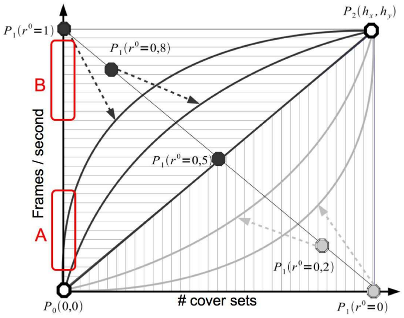

Fig. 3. The Behavior curve functions

We proposed in [6] to use a Bezier curve to model the 2 application classes. The advantage of using Bezier curves is that with only 3 points we can define a ready-to-use convex (high criticality) or concave (low criticality) curve: P_0, P_1, and P_2. $P_0(0,0)$ is the origin point, $P_1(b_x, b_y)$ is the behavior point and $P_2(h_x, h_y)$ is the threshold point where h_x is the highest cover cardinality and h_y is the maximum frame capture rate determined by the sensor node hardware capabilities.

As also illustrated in figure 3, by moving the behavior point P_1 inside the rectangle defined by P_0 and P_2, we are able to adjust the curvature of the Bezier curve, therefore adjusting the criticality level. According to the position of point P_1 the Bezier curve will morph between a convex and a concave form. Interested readers can refer to [6] for more details on the modified Bezier curves definitions. Let us denote by r^0 the criticality level which is between 0 and 1, 1 being the highest criticality level. We fixed maximum cover set cardinality to

12 and the maximum frame capture rate to 3fps.

We showed in [7], [8] that the risk-based dynamic scheduling approach succeeds in increasing the network lifetime while providing a low stealth time for intrusion detection systems. The purpose is to only set the surveillance network in an alerted mode (high criticality value) when needed, i.e. on intrusions. Sensor nodes start with an initial criticality level of $r^0_{min} = 0.1$. When a sensor node detects an intrusion, it sends an alert message to its neighbors and increases its criticality level to $r^0_{max} = 0.8$ for instance. Alerted nodes will then also increase their criticality level to $r^0 = 0.8$. Both the node that detects the intrusion and the alerted nodes will run at a high criticality level for an alerted period before going back to $r^0 = r^0_{min}$.

III. MOBILE CAMERA ROBOT AND FIXED IMAGE SENSOR INTERACTION

With mobile camera robots capable of 360^o coverage, the basic idea here, compared to the fixed camera case we studied previously in [7], is to decrease the criticality level (therefore reducing the frame capture rate) of alerted nodes when these nodes are close to mobile camera robots. In this case, the mobile camera robot with rotation capability will start rotating its camera (or moving itself), moving from a triangle-FoV to a disk-FoV as it rotates (or moves itself). The purpose of this paper is to study whether such cooperation can succeed in reducing further the energy consumption without decreasing the detection quality. We will also discuss issues related to reducing traffic loads on the network.

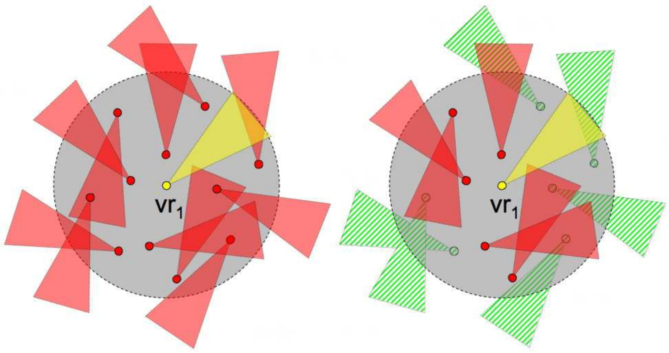

Fig. 4. A mobile camera robot with rotatable feature vr_1 interacting with fixed image sensors.

Figure 4 depicts a scenario where a mobile camera robot is put in alerted mode, either because it has detected an intrusion or because it has been alerted by other fixed sensor nodes. In the left part of the figure, the mobile camera robot vr_1 will indicate to its neighbors that it will start rotating its camera. All neighbors (fixed image sensors or mobile robots) whose position is within the radius of vr_1's DoV can then take predefined actions such as returning to the normal criticality level (e.g. $r^0 = r^0_{min}$, in red in the figure). The right part of the figure shows a variant of this behavior where only nodes whose FoV's center of gravity is within the radius of vr_1's DoV will return to the normal criticality level. The other nodes' status is kept unchanged so if they are in alerted mode they will just keep capturing at a high rate (nodes in green in the figure). We can see that in this latter case the number of nodes that return to normal criticality level is smaller, with the motivation of only disabling nodes whose FoV will be "correctly" covered by the mobile camera robot .

It is possible to define a wide range of variants. For instance, neighbor nodes could decrease their current criticality level by a given amount instead of going back directly to the minimum criticality level as described previously. Then another behavior for nodes whose center of gravity is outside the radius of the mobile camera robot's DoV is to decrease their criticality level in such a way to be at a higher criticality level than nodes covered by the mobile camera robot . In this way, several layers of various criticality levels will be defined in the neighborhood of each mobile camera robot. Also, it is very possible for each sensor node to schedule a "just-in-time" back to normal criticality event based on the mobile camera robot's FoV rotation prediction. As can be seen, there is room for many variants from simple ones to more complex ones with reinforcement behavior for example: a node decreases its criticality level each time it receives an indication of a different mobile camera robot,... In this paper, we will compare the following behaviors when the mobile camera robot is noted vr:

1) all nodes whose position is within the radius of vr's DoV go back to normal criticality level, i.e. $r^0 = r^0_{min}$.
2) all nodes whose FoV's center of gravity's position is within the radius of vr's DoV (they are "well-covered") go back to $r^0 = r^0_{min}$ AND nodes whose FoV's center of gravity's position is outside the radius of vr's DoV stay at the alerted criticality level ($r^0 = r^0_{max}$).
3) all nodes whose position is within the radius of vr's DoV go back to normal criticality level plus a security amount, i.e. $r^0 = r^0_{min} + S$. The motivation of S is to maintain for those alerted nodes a higher criticality level than normal operation mode.
4) all nodes whose center of gravity's position is within the radius of vr's DoV go back to normal criticality plus a security amount ($r^0 = r^0_{min} + S$) AND nodes whose FoV's center of gravity G (see figure 2) is outside the radius of vr's DoV stay at the alerted criticality level ($r^0 = r^0_{max}$).

It is worth noting that although the proposed approach here can appear as similar to a clustering approach where the mobile camera robot is the cluster head, our proposition is however different. In our approach, each node can be alerted and can be at different a criticality level if they want to do so. Then, if they receive a rotation indication from a neighbor node, they, once again, have all liberty to react in their own way to this indication. For sake of simplicity and for demonstrating that simple cooperation between fixed image sensors and mobile camera robots is beneficial we do not introduce more complex behavior on fixed image nodes that could use local information such as the number of current active neighbors, their energy level, the number of time they have been alerted in the past,. . .

IV. FAST EVENT DETECTION WITH MOBILE CAMERA ROBOT AND FIXED IMAGE SENSOR INTERACTIONS

For these sets of simulations, a total of 150 nodes (fixed and mobile) are randomly deployed in a $75m*75m$ area. We do not address here how the mobile nodes could be deployed from an initial position. Unless specified, all cameras have an 36^o AoV and we used the ”alternate point” strategy proposed in [15] to construct cover sets. Fixed image sensors start with an initial energy level of 100 units while mobile camera robots start with an initial energy level of 500 units. Each camera captures at a given number of frames per second (between 0.01fps and 3fps) according to the model defined in figure 3 and taking 1 picture consumes 1 unit of battery. Nodes with 12 or more cover sets will capture at the maximum speed. 2 deployment configurations of mobile robots will be compared: 15 mobile camera robots, noted 15MCR, and 8 mobile camera robots, noted 8MCR. Therefore the ratio of mobile camera robots are 10% and 5.3% respectively. Also, for behavior 3 and 4, S will take 3 different values: 0.2, 0.4 and 0.6. A mobile camera robot will start rotating when it is alerted and will perform 2 complete rotations. The time for a complete rotation is set to 5s and one complete rotation consumes 5 times the energy for taking 1 image.

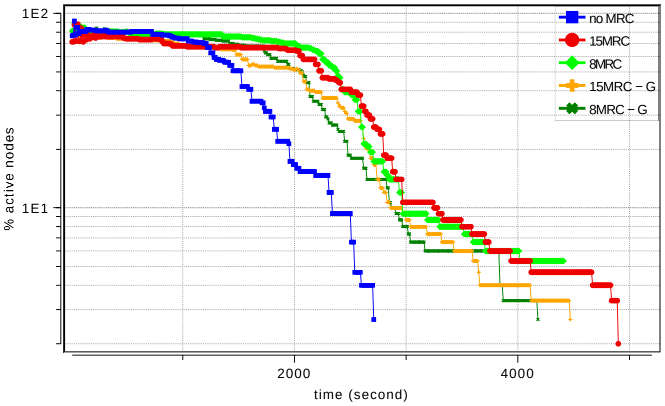

Fig. 5. Percentage of active nodes, behavior 1&2.

Figure 5 shows the percentage of active nodes and the network lifetime when comparing the no-MRC case to the interaction behaviors 1 and 2, both for 15MCR and 8MCR. The y-axis is shown in log scale and we will distinguish for the analysis 2 parts in the network lifetime: the first part is when the percentage of active nodes remains constant because most of fixed sensor nodes do have energy; the second part begins when the percentage of active nodes starts to decrease because of battery shortage in some nodes. In figure 5 we can see that introducing mobile camera robots that allows neighboring nodes to go back to normal criticality level is beneficial to the network lifetime. The more mobile camera robots, the longer the network lifetime. Behavior 2 where only nodes whose FoV's center of gravity is within the radius of vr's DoV go back to normal criticality level shows shorter network lifetime.

To judge the impact on the detection quality, figure 6 shows the mean stealth time of random intrusions introduced in the area of interest. The stealth time is the time during which an intruder can travel in the field without being seen. The first intrusion starts at time 10s at a random position in the field. The scan line mobility model is then used with a constant velocity of 5m/s to make the intruder moving to the right part of the field. When the intruder is seen for the first time by a sensor, the stealth time is recorded and the mean stealth time computed. Then a new intrusion appears at another random position. This process is repeated until the simulation ends (i.e. no more node with energy).

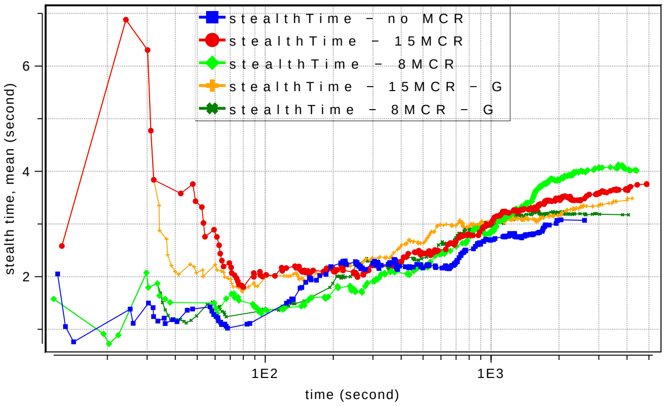

Fig. 6. Stealth time, mean [0, T], behavior 1&2.

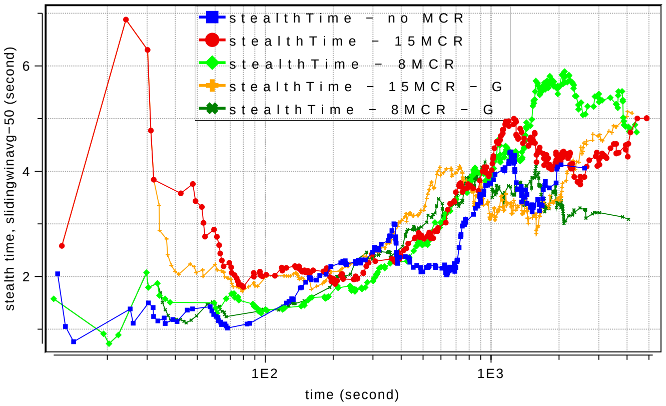

Fig. 7. Stealth time, sliding window avg(50), behavior 1&2.

In figure 6 (x-axis in log scale) having a higher number of mobile camera robots can decrease the detection quality if neighboring nodes go back to normal criticality level (behavior 1). This phenomenon is reduced when adding the center of gravity constraint. Figure 7 plots the same data with a sliding window averaging filter of 50 values to better show the variations of the stealth time. We can see that as the percentage of active nodes decreases due to battery shortage the detection quality is better when only ”well-covered” nodes are put back to normal criticality level. Figure 6 and 7 show that for 15MCR the stealth time is quite high at the beginning of the network operation. In all our simulation runs, this behavior is more or less accentuated but the 15MCR case always showed larger stealth time than the 8MCR case. Figure 8 compares in terms of percentage of active nodes and network lifetime the no-mobile camera robot case with interaction behavior 3 and 4, both for 15MCR and 8MCR. Regarding the network lifetime, a higher criticality security amount S reduces the network lifetime. The impact of using the center of gravity constraint or not is similar to the previous case shown in figure 5.

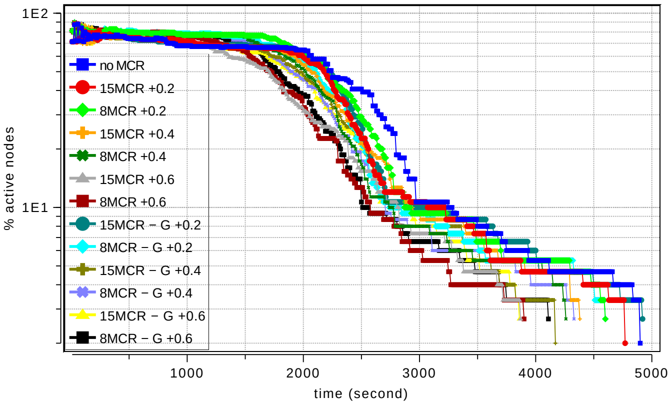

Fig. 8. Percentage of active nodes, behavior 3&4.

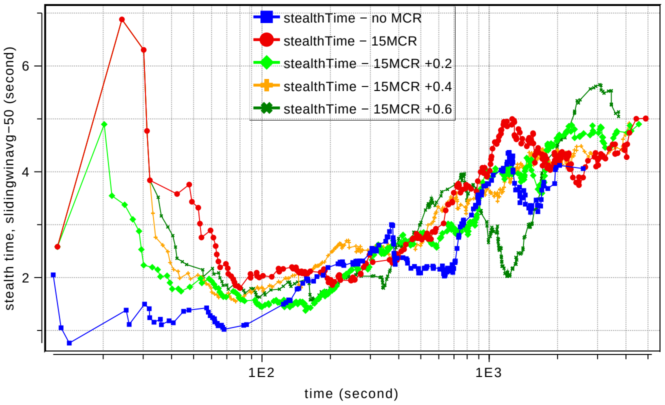

Fig. 9. Stealth time, 15MCR, sliding window avg(50), behavior 1&3.

Figure 9 and 10 show the detection quality by means of the stealth time. These 2 graphs compare behavior 1 (goes back to normal) and 3 (maintains a criticality security amount) for 15MCR and 8MCR respectively. The no-mobile camera robot case is shown for reference purpose. What can be seen is that the security amount is useful in the second part of the network lifetime, when there are few active nodes. At the beginning of the network activity, adding a security amount has no significant impact on the detection quality. These results may lead to an adaptive behavior where, as the network’s activity evolve over time, with less and less active nodes, it may be necessary to maintain the detection quality by introducing a security amount. Of course, this is mainly driven by the application’s needs.

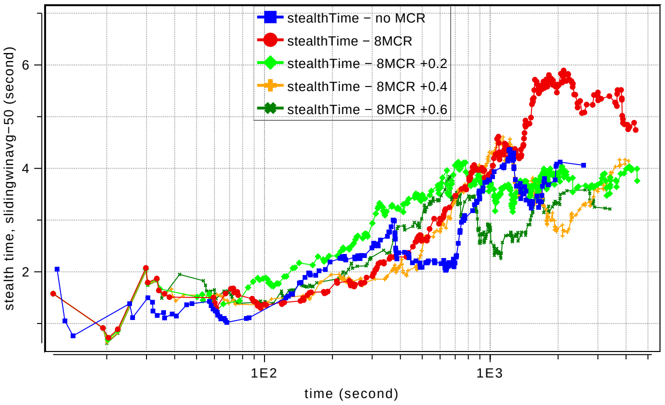

Fig. 10. Stealth time, 8MCR, sliding window avg(50), behavior 1&3.

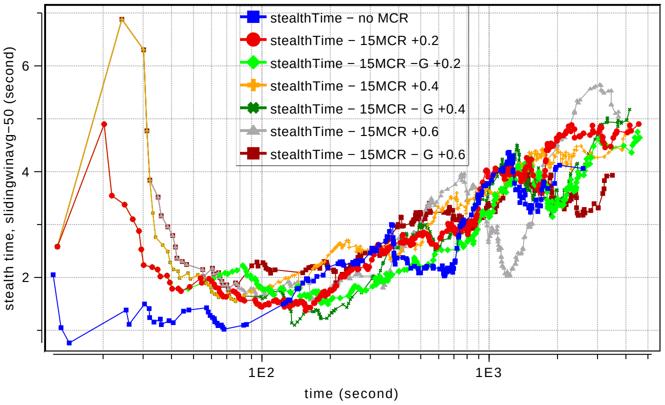

Fig. 11. Stealth time, 15MCR, sliding window avg(50), behavior 3&4.

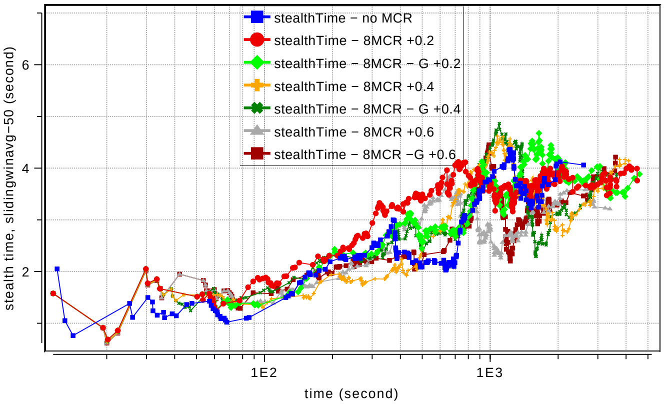

Fig. 12. Stealth time, 8MCR, sliding window avg(50), behavior 3&4.

Figure 11 and 12 compare behaviors 3 and 4 (similar to behavior 3 but adds the G variant), both for 15 and 8 mobile camera robots respectively. Once again, the no-mobile camera robot case is shown on these graphs for reference purpose. We can see that the impact of using point G as a filter to more carefully select the nodes to be put in sleep mode is much higher in the 15MCR case. Therefore, when the number of mobile camera robots is high for a given deployment scenario (which provides a longer network lifetime), it may be desirable to use behavior 4 in order to not decrease the detection quality, especially in the second part of the network lifetime.

V. DISCUSSION ON LOAD AND CONGESTION ISSUES

The results we showed in the previous section validate the idea of introducing mobile camera robots with visual disk coverage by rotation capabilities to further increase the network lifetime without decreasing dramatically the detection quality of the surveillance system. We want to highlight in this section that the cooperation between fixed image sensors and mobile camera robots has also a high impact on the transfer of urgent information between sensing nodes and the sink. By reducing the nodes' activity around a mobile camera robot during alert periods we can also decrease significantly the contention on the MAC layer. If a somewhat synchronized MAC layer is used for scheduling active and sleep periods of a node's radio module (such as TMAC [16] for instance), mobile camera robots can also contribute in increasing and/or predicting the sleep periods of neighboring nodes based on the camera's rotation time. Some MAC approaches create a source-to-sink "high-priority channel" by relaying the RTS/CTS control frame along the path from the source sensor node to the sink to reserve the shared medium [17]. In this case the rotation duration can be used as the minimum reservation time.

At the routing level, it is most likely that multi-path routing will be necessary for transporting the picture frames from the various camera nodes to the sinks [18]. However, even with an underlying multi-path routing protocol, it is quite difficult to find totally disjoint paths, or non-interfering paths, to the sink from a set of cameras (those that got alerted) that are usually geographically close each others [19]. Once again, by reducing the nodes' activity in the close neighborhood of a mobile camera robot during alert periods, we can reduce the traffic load at the network and above layers, therefore alleviating the problem of network congestion that dramatically increases the packet's drop probability in these very resource-constrained infrastructures. Moreover, neighboring nodes that reduce their activity can rather serve as relay nodes to the sink.

VI. CONCLUSIONS

This paper introduces mobile camera robots with camera rotation capabilities. We proposed 2 interaction behaviors between fixed image sensors and mobile camera robots to dynamically adapt the activity level without decreasing the surveillance quality: a back-to-normal criticality and a back-to-normal plus a security amount. The 2 behaviors can further be derived into 4 variants, depending on how the neighboring nodes of the mobile camera robot are selected: by taking into account a "coverage quality" criterion represented by whether the neighbor node's FoV's center of gravity is within the radius of the mobile camera robot's DoV or not. The first result from our simulations is that the security amount is useful in the second part of the network lifetime, when there are few active nodes. At the beginning of the network activity, adding a security amount has no significant impact on the detection quality. Secondly, when the number of mobile camera robots is high for a given deployment scenario, it is desirable to use the sensor's FoV center of gravity as a filter on neighbor nodes in order to not decrease the detection quality, especially in the second part of the network lifetime. The general result is that a simple form of interactions between fixed and mobile camera robots, coupled with a criticality-based scheduling of node's activity succeeds in increasing the network lifetime without decreasing the surveillance quality of mission-critical applications.

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