2-Hop Neighborhood Information for Cover Set Selection in Mission-Critical Surveillance with Wireless Image Sensor Networks

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***Abstract*—Mission-critical surveillance applications such as intrusion detection or disaster response have vital requirement in QoS. We consider a Wireless Image Sensor Network (WISN) with a scheduling of image sensor node's activity based on the application criticality level. Sentry nodes capable of detecting intrusions with a higher probability than others will alert neighbor nodes as well as activating cover sets member for image disambiguation or situation-awareness purposes. In order to optimize the performance of image transfer from multiple sensor nodes to the Sink we propose a 2-hop neighborhood information-based cover set selection to determine the most relevant cover sets. Then, in order to be consistent with our proposed approach, a multi-path extension of Greedy Perimeter Stateless Routing (called T-GPSR) wherein routing decisions are also based on 2-hop neighborhood information is proposed. Simulation results show that our proposal reduces packet losses, enabling fast packet delivery and higher visual quality of received images at the Sink.**

***Index Terms*—Image transmission, mission-critical, quality of service (QoS), 2-hop information, multipath routing, Wireless Sensor Networks (WSN).**

I. Introduction

Wireless Image Sensor Networks (WISN) where sensor nodes are equipped with miniaturized visual cameras to provide visual information is a promising technology for intrusion detection or search&rescue applications. These image sensors can be thrown in mass to provide accurate information in various geographical parts of an area of interest. Figure 1 shows the scenario of a random deployment of image sensor nodes which is typical of the kind of applications we want to address in this paper. The right part of the figure shows that the deployed network could be used for situation awareness in search&rescue applications for instance where images from remote nodes are collected at the sink node, displayed and possibly integrated into a GIS system.

In an another type of surveillance applications, Figure 1 also shows sensor nodes self-organizing themselves to designate a number of nodes to act as sentry nodes (nodes in black) to better detect intrusions and to trigger alerts [1], [2], [3]. Situation awareness and intrusion detection do not have the same criticality and it may be necessary to handle the sensor's activity accordingly. In previous works, we have proposed criticality-based scheduling of image sensor nodes to fulfill the requirements of a large variety of surveillance applications depending on their criticality level. This kind of scheduling approach can be used at a high level for scheduling these surveillance nodes.

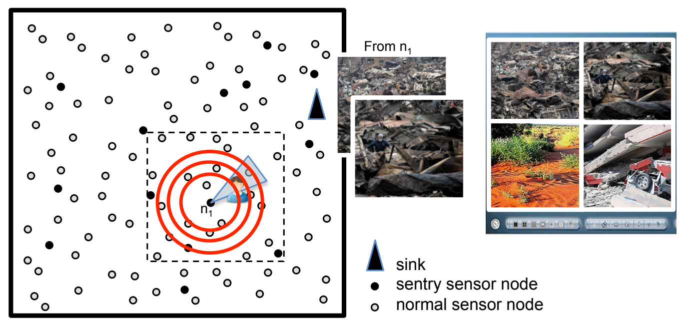

Fig. 1: Mission-critical intrusion detection system

Early surveillance applications involving WSN have been applied to critical infrastructures such as production systems or oil/water pipeline systems [4], [5]. There have also been some propositions for intrusion detection applications [6], [7], [8], [9] but most of these studies focused on coverage and energy optimizations without explicitly having the application's criticality in the control loop which is the main concern in our work. The authors in [10], [11], [12] did consider multimedia sensors but once again, the criticality of a surveillance application is not taken into account.

For instance, with image sensors, the higher the capture rate is, the better relevant events could be detected and identified. However, even in the case of very mission-critical applications, it is not realistic to consider that video nodes should always capture at their maximum rate when in active mode. 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. One obvious way of saving energy is to say that nodes that can be put in sleep mode are typically

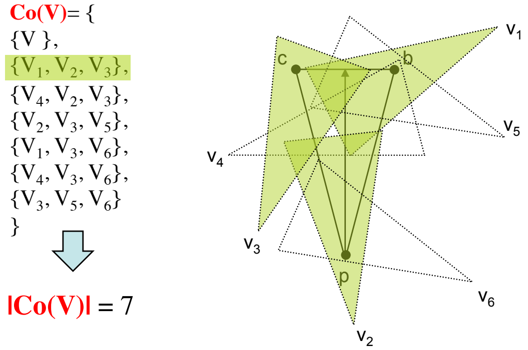

Fig. 2: Coverage model and cover set.

those whose sensing area are covered by others. In figure 2, the Field of View (FoV) of sensor V is represented by the triangle (pbc). If we consider nodes V, V_1, V_2 and V_3 the possible set of cover sets is $Co(V) = \Big\{\{V\}, \{V_1, V_2, V_3\}\Big\}$. A cover set for V is defined as a subset of image nodes which covers its FoV area. If we add nodes V_4, V_5 and V_6, $Co(V)$ has more elements as depicted in figure 2. However, in mission-critical applications where some sentry nodes are needed to increase responsiveness, nodes that possess a high redundancy level (their sensing area are covered many times by other nodes so that they have many cover sets) could rather be more active (awakening more often) than other nodes with less redundancy level. In [1] the idea we developed is that when a node has several covers, it can increase its frame capture rate because if it runs out of energy it can be replaced by one of its cover sets. Then, depending on the application's criticality, the frame capture rate of those nodes with large number of cover sets can vary: a low criticality level indicates that the application does not require a high image frame capture rate while a high criticality level does.

While we developed in [1], [2] the risk-based scheduling approach and in [13] we compared various methods to build cover sets, the contribution of this paper is at the cover set selection level. When a node detects an event such as an intrusion, it will *(a)* send one or several images to the Sink node depending on its frame capture rate, *(b)* alert its neighbor nodes and *(c)* activate one of its cover sets. On activation, cover set members will also send one or several images to the Sink to provide more information for disambiguation or situation-awareness purposes. Once again the number of images that will be sent depends on the frame capture rate of neighbor nodes. We can see that an event detection triggers the simultaneous transmission of a large volume of visual data from multiple sources to the Sink. With no control, this can produce significant data losses due to network congestion degrading the visual information quality at the Sink. Obviously, cover sets of a given node have different size, level of coverage/energy, and also different performance level for a transferring large amount of data to the Sink. In the context of mission-critical application, detecting events is important but receiving high quality images at the lowest latency is also very important. By taking into account the criticality level (frame capture rate), 2-hop neighborhood knowledge and routing information, our objective in this article is to significantly reduce congestion and increase image quality at the Sink when simultaneous images are sent towards the Sink.

In this paper, we first propose at the application level an optimized cover set selection approach based on 2-hop neighborhood information to determine the most relevant cover sets to be activated and to increase reliability for image transmission. Then, in order to be consistent with the proposed approach, a multi-path extension of Greedy Perimeter Stateless Routing (called T-GPSR) wherein routing decisions are also based on 2-hop neighborhood information is proposed. Recent studies on the performance in k-hop neighborhood-based geographic routing, where $k = 1, 2, 3, \ldots$, have established that the improvement from 1-hop searching to 2-hop searching is generally substantial [14]. As the improvement from k-hop searching ($k \geqslant 2$) to ($k+1$)-hop searching gets smaller due to the fact that the distance between nodes is now shorter, the authors in [15] showed that the 2-hop neighborhood knowledge is sufficient to get acceptable results in terms of accuracy in k-hop neighborhood-based distributed node localization for WSN. Hence, our motivation for 2-hop neighborhood knowledge in cover set selection.

The remainder of the paper is structured as follows. Section II outlines related 2-hop information-based algorithms. Section III describes the main guidelines of the proposed cover set selection approach for efficient image transmission. T-GPSR, our 2-hop information-based GPSR extension, is then presented in Section IV. Simulations and results are shown in Section V and we conclude in Section VI.

II. Related work

The usage of 2-hop neighborhood knowledge is not new: many broadcast/multicast algorithms have tried to reduce and eliminate redundant transmissions based on this information. Optimized Link State Routing (OLSR) protocol for Mobile Ad Hoc Networks (MANET) [16] is one of the many protocols that do so. In OLSR, multipoint relays (MPR) are selected to minimize the number of unnecessary retransmissions that would flood messages in the entire network. Each node selects its MPR set among one-hop neighbors in such a manner that the set covers all nodes that are 2-hop away. With the MPR method, OLSR can provide efficient routes in terms of number of hops.

2-hop neighborhood was also investigated in geographic routing protocols that are probably more related to our proposition. Some real-time algorithms for WSN [17], [18], [19] are based on 2-hop neighborhood knowledge. Some approaches propose to map a packet deadline to a velocity with the key idea of taking routing decisions based on the 2-hop velocity to meet the desired QoS. Another protocol [20] uses the 2-hop neighborhood information to find more paths of shorter lengths for duty-cycled systems.

Our work uses 2-hop neighborhood information at the application level in a cross-layer-like fashion to mainly determine which node or set of nodes will be more suitable to relay a large amount of image packets. Under the multi-path assumption, our approach defines metrics to probabilistically determine the likelihood of multi-path transmissions required by a given frame capture rate. Therefore, our approach is very targeted for mission-critical surveillance applications putting clearly the application's criticality in the control loop.

III. Cover set selection method

A. 2-hop neighborhood information and definition

As assumed in most geographic routing algorithms, each sensor node is aware of its location and of the Sink's location through either GPS capability or the ability to estimate their position through anchor nodes that have GPS capability [21]. Commonly found in many WSN algorithms and more generally in many distributed algorithms, an initialization phase usually exchange HELLO or a similar message to obtain information on one node's 1-hop neighborhood (this phase is usually referred to as the neighbor discovery phase). Extending to 2-hop neighbors can be done quite easy at a relatively low cost as each sensor node can broadcast its neighbor table at the end of the neighbor discovery phase.

Specifically for our surveillance application, each sensor during the neighbor discovery phase would collect from their neighbors their node id, GPS position, camera line of sight, angle of view and depth of field of the camera, initial level of criticality and residual energy. This list is non-exhaustive and other parameters can be sent at initialization.

Let us denote by $\mathbf{N}(v)$ node v's 1-hop neighbor set, see figure 3. $\mathbf{F}(v)$ is defined as the set of v's 1-hop potential forwarders, i.e. the closest 1-hop neighbors to the Sink:

$$\mathbf{F}(v) = \Big\{u | d(u, Sink) < d(v, Sink), u \in N(v)\Big\}$$

where $d(u, Sink)$ is the Euclidean distance to the Sink. The set of v's 2-hop potential forwarders is denoted $\mathbf{F_2}(v)$. Then, the subset of v's 2-hop potential forwarders with node u as intermediate node is defined as follows:

$$\mathbf{F_2}(v,u) = \Big\{k | d(k, Sink) < d(u, Sink), u \in F(v), k \in N(u)\Big\}$$

B. Cover Set Selection Approach

Mission-critical applications have QoS requirements such as reliability of received data at the sink with strict delay, especially for visual information. Congestion and contention on the radio medium are the main source of packet losses as the network load increases. Therefore the capture rate of image sensor nodes should guide the choice of cover sets as it will have a high impact on the data transmission performance, both at MAC and network level. Multi-path routing is often regarded as a solution to improve communication performance in WSN: data transmission reliability, bandwidth aggregation, load balanced transmission, congestion-free transmission, low latency transmission, …[22], [23], [24]. The establishment of multiple paths between a pair (source, destination) for data transmission can increase reliability and some approaches such as [25] even use the path redundancy to send multiple copies of the same packet on the various paths to the Sink. In our proposition this is not the technic we adopt. We use multiple paths for both load balanced and congestion-free transmissions when a large amount to visual information need to be sent on the network. Therefore, the idea we develop here is to link the image capture rate to the need of multiple paths: the higher the capture rate of a node, the higher is the need for multiple paths towards the Sink.

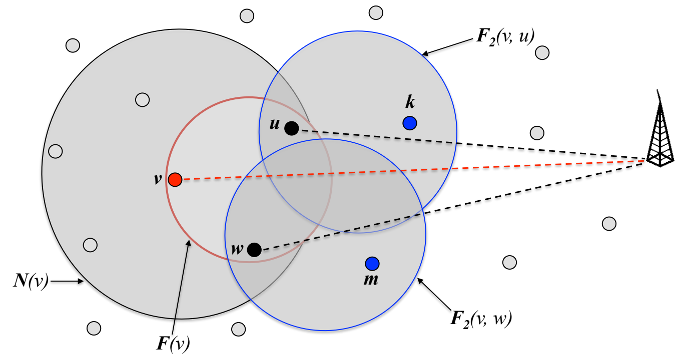

Fig. 3: Potential 1-hop & 2-hop forwarders for node v

Through the usage of the 2-hop neighborhood guided by the capture rate we define a first metric for cover sets selection: R_{2-hop} measures the likelihood of a given cover set to find as many needed 2-hop paths as required by the capture rate. R_{2-hop} for a given cover set $Co_i(v)$ of node v is given by the equation below:

$$R_{2-hop}(Co_i(v)) = \frac{1}{|Co_i(v)|} \sum_{w=1}^{|Co_i(v)|} \frac{|F_2(w)|}{NbOptimalPaths(w)}$$

where $|F_2(w)|$ is the number of w's 2-hop potential forwarders, $w \in Co_i(v)$), and $NbOptimalPaths(w)$ is the number of optimal paths of w. We define $NbOptimalPaths(w)$ to be proportional to w's image capture rate. Linking the capture rate to the number of required paths to correctly transfer images is an original feature of our approach because capture rates can be very different from an image sensor to another since some geographical areas could be at a higher criticality level than others [2]. As scheduling of sensors is very dynamic for these mission-critical applications, the best cover set is highly dependent on the required capture rate.

Alone, the R_{2-hop} metric does not necessarily guarantee improved performance for establishing disjointed paths. For a given cover set, having enough 2-hop potential forwarders, i.e. R_{2-hop} is high, is important but these 2-hop potential forwarders may have few relay nodes themselves, i.e. 1-hop potential forwarders, and may also share most of them making disjointed paths for decreasing inter-path interferences very difficult or impossible. A cover set with many unshared relay nodes per 2-hop forwarder has better efficiency to set up disjointed paths for load balancing purposes. Therefore a second criterion, noted R_{relay}, is combined with R_{2-hop} as follows:

$$R_{relay}(Co_i(v)) = \frac{1}{|Co_i(v)|} \sum_{w=1}^{|Co_i(v)|} \frac{|F(w)|}{|F_2(w)|}$$

where $|F(w)|$ and $|F_2(w)|$ are the number of w's 1-hop and 2-hop potential forwarders respectively, $w \in Co_i(v)$). The ratio $\frac{|F(w)|}{|F_2(w)|}$ expresses the likelihood that a 2-hop forwarder have several unshared relay nodes. For example, let w be a cover set member with 3 2-hop forwarders. If the number of unshared relay neighbors is also 3, this ratio is 1 and there is potentially for each 2-hop neighbor a different relay node. If this ratio exceeds 1, it is even better. However, there is no strict guarantees since a single 2-hop neighbor may well have all the relay nodes. Here we made a trade-off between the difficulty and to overhead to obtain and consider very accurate information and this is the reason why we propose a probabilistic approach that has the advantage of being very simple and requiring only a small additional cost in terms of message exchanged compared to traditional 1-hop information. The method we take here is an on-demand method: as all nodes know their 2-hop neighbors, a node v with cover sets would send a request to its cover set members to get their list of 2-hop neighbors.

Each cover set is then associated to a Transmission Quality (TQ) value which is used to score and classify cover sets at a sentry node. TQ is computed based on previous metrics with weights to indicate the importance degree of each metric according to equation below:

$$TQ(Co_i(v)) = \alpha \times R_{2-hop}(Co_i(v)) + \beta \times R_{relay}(Co_i(v))$$

where $\alpha + \beta = 1$. For a given sentry node, the cover set with the highest TQ value has better performance for transmitting image packets, i.e. with low latency and less packet losses. The selection algorithm can also consider the remaining energy of cover sets which can be defined as the minimum energy of the cover set members. Now, to be consistent with our proposed selection method, a multi-path extension of GPSR will be described in the next section to ensure that routing decisions are also based on the 2-hop neighborhood information that has been taken for image transmission at the application level.

IV. GPSR Extension

A. *Greedy Perimeter Stateless Routing (GPSR)*

GPRS is a geographic routing protocol originally designed for MANETS which has been rapidly adapted for WSN [26], [27]. Each node is aware of its location and of its 1-hop neighbors' locations. GPSR has two strategies for forwarding data packets to the destination: *Greedy Forwarding* and *Perimeter Forwarding*. In Greedy Forwarding, whenever a node needs to forward a data packet, it chooses the closest neighbor to the destination as the next hop. Figure 4 depicts a scenario where the source node at (x_s, y_s) wants to send a data packet destined for the destination node at (x_d, y_d). The packet will be transmitted and relayed hop-by-hop by choosing at each hop the next neighbor node which is the closest by Euclidian distance to the destination.

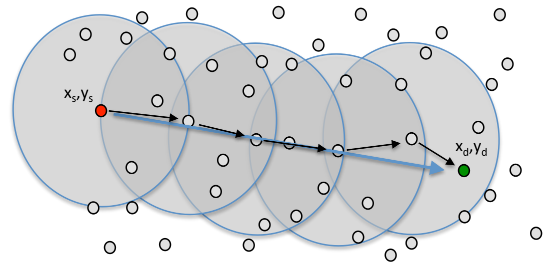

Fig. 4: Greedy Forwarding

Sometimes, the greedy forwarding strategy fails to find a neighbor closer to the destination than itself because of voids or holes due to random deployment, obstacles that obstruct radio signals or node failures. To overcome this problem, Perimeter Forwarding is used to route packets around voids using the right-hand rule: packets will move around the void until it reaches a node closer to the destination than the node which has initiated the Perimeter Forwarding process. To reach the final destination, a Greedy Forwarding phase is then started from this point.

B. *T-GPSR: a 2-hop-information-based GPSR Extension*

The T-GPSR extension is essentially based on collecting 1-hop & 2-hop neighborhood information during both the neighbor discovery process and the cover set selection process performed at the application level. This is similar to some so-called *cross-layer* approaches where information from lower levels are used by higher levels. These approaches are widely used in sensor networks [28], [29] but it is necessary to pay particular attention to what information should be considered and to avoid those that are difficult to get in a network with a large number of nodes. For example, network and/or link load is a difficult information to estimate, especially in a wireless network where the size of buffer queues is not simply correlated with the network load due to interference phenomena or contention on the radio support [30].

As an extension to GPSR, our proposed routing scheme incorporates an additional strategy, called *2-Hop-based Greedy Forwarding*, for taking account the 2-hop neighborhood information. In *2-Hop-based Greedy Forwarding*, whenever a source node v needs to forward a data packet, it chooses the closest 2-hop potential forwarder to the final destination (the Sink) in $F_2(v)$. Thus, packets are sent to this 2-hop potential forwarder as the temporary destination through one of v's 1-hop potential forwarder, in $F(v)$, acting as relay node. For instance, if we look back at figure 3, source node v selects the 2-hop potential forwarder m as temporary destination and 1-hop potential forwarder w as relay. When a relay node receives a data packet to forward, there is no additional next hop discovery to execute: it will just send the packet to the associated temporary destination, m in this case. Therefore forwarding decisions occur only every two hops which contributes to decrease latency especially when an important number of hops is required to reach the Sink. On the other hand, a temporary destination that receives a data packet to forward behaves as a source node. This process is repeatedly executed until the data packet reaches the Sink. This strategy is prone to failure if $|F_2(v)| = 0$, i.e. v has no 2-hop potential forwarder. In this case, T-GPSR will adopt the original GPSR *Greedy Forwarding* mode on $F(v)$. Finally, GPSR *Perimeter Forwarding* is used when the greedy forwarding fails.

Being multi-path T-GPSR has some advantages compared to GPSR. For instance, transmitting multimedia stream using the shortest path will drain the energy of the nodes along this path and shorten the network lifetime [31], this is the well-known funnelling effect. By exploiting multi-path capabilities of WSN to make load balancing T-GPSR limits this funnelling effect. In addition, T-GPSR algorithm can be executed repeatedly to look for multiple closer and shorter disjointed paths to the Sink. These paths are essentially based on 2-hop neighborhood information: whenever a node v, with several 2-hop potential forwarders, has to forward a data packet, T-GPSR will define a different path among these 2-hop neighbors according to certain criteria: image capture rate, path usage frequency, residual energy,... However multiple paths establishment may possibly be based on 1-hop neighborhood information when $|F_2(v)| = 0$. In this case, the above-mentioned process is performed on $F(v)$. T-GPSR also implements a load balancing mechanism on the 1-hop neighborhood. In fact, when a source v has already selected a 2-hop potential forwarder $w \in F_2(v)$ as a temporary destination and w has several relay nodes in $F(v)$, T-GPSR uses these relay nodes in a round-robin fashion. Another benefit of the proposed scheme is its ability to prevent voids in advance: when v adopts the Greedy Forwarding strategy, i.e. the 2-Hop-based Greedy Forwarding mode failed, an additional field can be used to indicate to the selected 1-hop potential forwarder in $F(v)$ to use Perimeter Forwarding when it will receive the packet.

V. Simulation results

We evaluate our proposal with the OMNET++/Castalia framework (http://castalia.research.nicta.com.au). We consider an homogenous WISN where 400 image sensor nodes are randomly deployed in a $400m*400m$ area, see figure 5. Sensor nodes have an 60^o angle of view, a depth of view of $25m$ and a communication range of $30m$. On this network topology, we perform a set of simulations to show the benefit of our cover set selection approach. In what follows, we consider three scenarios for transmitting images:

- Scenario 1: no selection algorithm is required. For instance, each sentry selects the first active cover set in its cover set table. The routing layer uses GPSR.
- Scenario 2: our selection mechanism is performed at the application level, and GPSR is also used for routing.
- Scenario 3: our selection mechanism is again performed at the application level but now T-GPSR is used at the routing layer.

In scenarios 2 and 3, the routing layer uses additional information from the selection algorithm such as shared relay nodes for example. In all scenarios, CSMA/CA is used at the MAC layer and the radio link throughput is 250kbps. We monitored the average packet loss rate, the average quality of received images at the Sink and the average image transmission delay to the Sink.

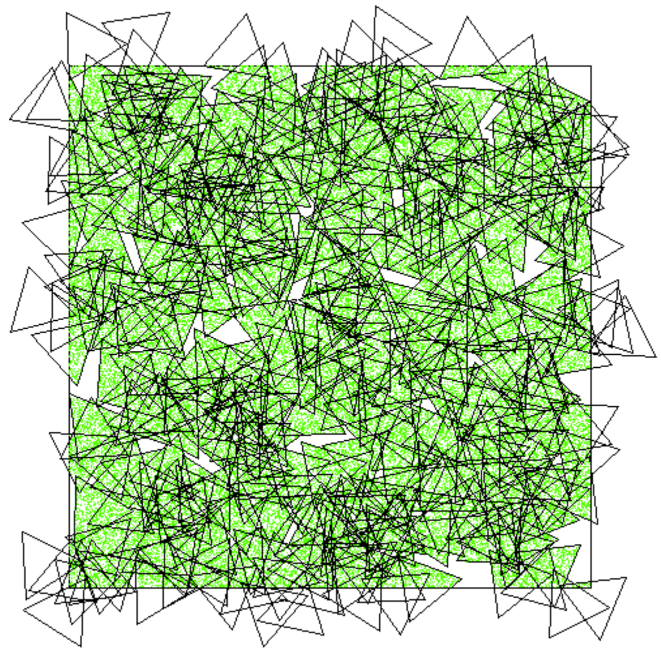

Fig. 5: A WISN with 400 nodes.

As described in Section I, when a node v detects an event such as an intrusion, it will *(a)* send one or several images to the Sink node depending on its frame capture rate, *(b)* alert its neighbor nodes and *(c)* activate one of its cover sets. On activation, cover set members will also send one or several images to the Sink to provide more information for disambiguation or situation-awareness purposes. The simulation model implements the transmission of real image files by taking into account all communication layers. We use an optimized image format for sensor networks that combines robustness with respect to packet losses, low power consumption in compression and small file size with a selectable quality factor [32], [33]. In addition, image packets can be received in any order at the Sink which is a desirable feature with multi-path routing. In our case, an image has $320 * 320$ pixels with 256 gray levels for a raw size of 102400B. We then use a quality factor of 50 that gives a final image size of 16621B. By setting the maximum payload size to 90B, the encoding scheme gives 205 packets.

A. Packet loss

As shown in figure 6, in scenarios 2 and 3 the average loss rate does not exceed 40% compared to Scenario 1. Scenario 3 shows a smaller loss rate than Scenario 2 thanks to the

2-hop neighborhood knowledge of T-GPSR which increases reliability. However, when the image capture rate gets higher, the numerous simultaneous transmissions of images create congestion and inter-path interferences to name a few issues.

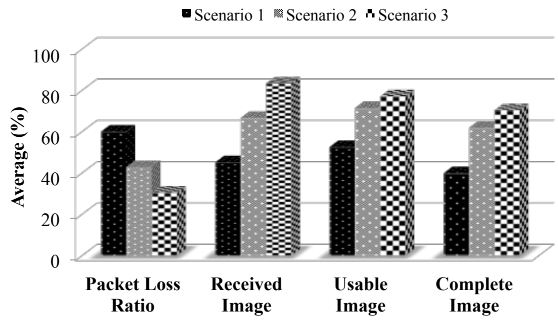

Fig. 6: Received mage statistics

In figure 6, we can see that the percentage of received images of scenarios 2 and 3 is much higher compared to Scenario 1. This result shows that the cover set selection mechanism succeeds in reducing contention in image transmission. In addition, the percentage of received images in Scenario 3 is larger by 20% than Scenario 2 clearly showing the additional benefit of T-GPSR 2-hop information usage.

B. Image quality

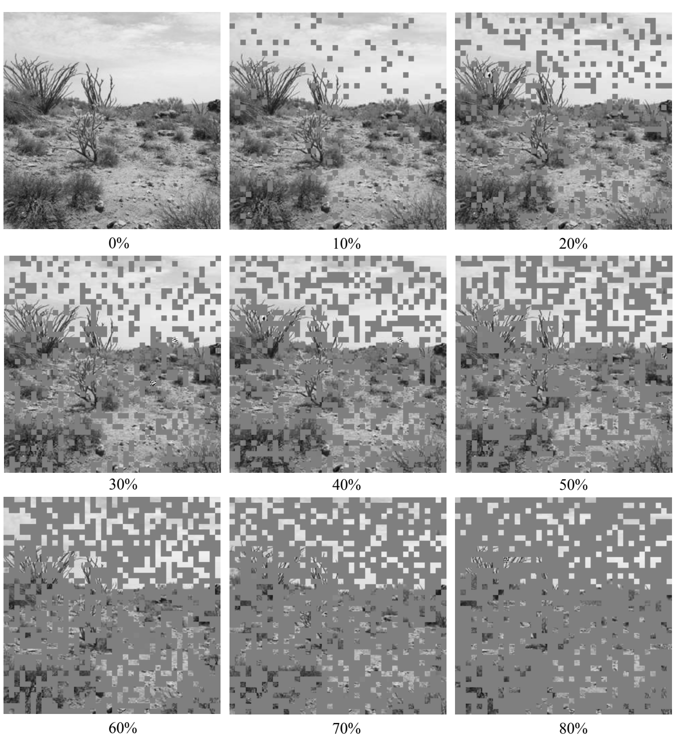

Fig. 7: Image quality at the Sink at various packet loss ratios

In the context of a mission-critical application, detecting events is important but receiving high quality images is also very important. Reception of a large number of images at the Sink does not necessarily mean that they are all exploitable. The packet loss ratio has a direct impact on the received image quality, and in all our simulations we observed that an image with more than 60% of packet losses is visually not exploitable (for identification purposes for instance). Also, a received image is either complete (no packet loss) or truncated. Figure 7 shows the $320 * 320$ original image and images with various packet loss ratios. Although image quality may be very application-dependent, we decide to set the threshold at 60% of packet losses and we will classify an image as unusable when the packet loss ratio is greater than 60%. By opposition, when the packet loss ratio is smaller than 60% the image will be classified as usable. With this convention, figure 6 shows that our selection approach (scenarios 2 and 3) increases the number of usable images at the Sink compared to Scenario 1. In addition, most of these usable images in these scenarios have complete (no packet loss). Once again, in Scenario 3, we can see that the usage of T-GPSR to reflect at the routing layer the 2-hop information collected at the application level further reduces packet losses, thus increasing the image quality at the Sink.

C. Image reception latency

As stated previously, achieving the lowest latency for image reception at the Sink is also very important. The packet loss rate can have a strong impact on the image reception latency. The implemented decoder can display an image regardless of the number of received packets and regardless of their reception order. However, we still need a timer that is set at the reception of the first image packet and that will trigger the display of the image regardless of the number of packet actually received. When the number of lost packets is high, the latency can be as high as the display timer which is set to 10s. With low loss probability, the latency is much lower and depends on the number of hops. Although neither the API various transmission limitations nor hardware limitations are accurately modeled, we can however compare the latency achieved by our approach with the case when there is no 2-hop neighborhood information used. In our current simulation model, a single image can be received in 0.94s in the very best case. Figure 8 compares the reception average delay of the three scenarios.

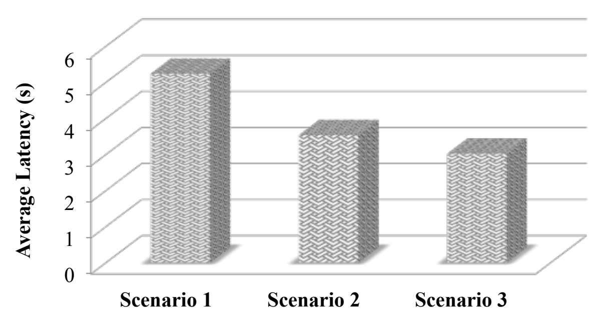

Fig. 8: Average image reception latency ratio

VI. Conclusion

In this paper, we first propose an optimized cover set selection approach based on 2-hop neighborhood information to determine the most relevant cover sets to be activated as the cover set member nodes will send a large amount of data towards the Sink. The motivation is to increase reliability for image transmission by reducing both funneling effect and contention on the medium. Then, in order to be consistent with the proposed selection approach, a multi-path extension of Greedy Perimeter Stateless Routing (called T-GPSR) where routing decisions are also based on 2-hop neighborhood information has been proposed. One key point of our proposition is to link and consider several important parameters that depend on the image capture rate and the network topology.

Simulations were carried out to show the benefits of our proposition. We simulated intrusion detection systems where images are sent for disambiguation or situation-awareness purposes. Performance evaluations have shown that our proposal reduces the packet loss ratio to provide better received image quality at the Sink. Our approach is particularly efficient when the amount of data is large, which is the case with increasing image capture rates. In our future work, we want to investigate cover set dependency issues and buffer queue management approaches to better control the multi-hop forwarding of time-constrained image data.

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