A Simulation Study of the Effectiveness of the Self-healing Autonomous Sensor Network for Early Warning Detection

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Abstract

The Self-healing Autonomous Sensor Network (SASNet) Technology Demonstration project will demonstrate an ad-hoc wireless network of heterogenous, unattended ground sensors (UGS) that can be rapidly deployed to perform remote surveillance for the Canadian Army. In late 2008, the first of three annual SASNet trials will demonstrate the ability of the system to conduct early warning detection. This memorandum reports on a simulation study of the effectiveness and suitability of SASNet for this type of scenario. The key variables of the system that are investigated are (1) the probability of detecting targets crossing the instrumented barrier, (2) the rate of false alarms, (3) the delay between a target being detected and an alarm being received by an operator, (4) the time to deploy the system, and (5) the cost. These variables were optimized with a simulated annealing algorithm. The optimal values are investigated as a function of the length of the early warning barrier. Under the current assumptions of cost and performance for SASNet's components, it is shown that SASNet is suitable for early warning detection along barriers that are up to one kilometre in length. This is a significant improvement over the UGS that is currently used by the Canadian Army.

Résumé

Le projet de démonstration de technologie (PDT) du Réseau de capteurs autonomes à autorétablissement (SASNet) fera la démonstration d'un réseau sans fil ad hoc de détecteurs au sol autonomes (UGS) hétérogènes, pouvant être déployé rapidement pour effectuer de la surveillance à distance pour l'Armée canadienne. à la fin de 2008, le premier des trois essais annuels du SASNet mettra à l'épreuve la capacité de détection avancée du système. Le présent document porte sur une étude par simulation de l'efficacité et de la conformité aux besoins du SASNet dans ce type de scénario. On a étudié les variables clés du système suivantes : 1) la probabilité de détection des cibles qui traversent la barrière instrumentée, 2) le taux de fausses alarmes, 3) le délai entre la détection d'une cible et la réception par l'opérateur d'une alarme, 4) le temps nécessaire au déploiement du système, et 5) le coût. Ces variables ont été optimisées au moyen d'un algorithme de recuit simulé. Les valeurs optimales sont étudiées en fonction de la longueur de la barrière de détection avancée. Selon les hypothèses actuelles de coût et de rendement des éléments du SASNet, il est démontré que le SASNet convient pour la détection avancée le long de barrières dont la longueur va jusqu'à un kilomètre. Il s'agit d'une amélioration marquée par rapport au système de détection d'intrusion au sol qu'utilise actuellement l'Armée canadienne.

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Executive summary

A Simulation Study of the Effectiveness of the Self-healing Autonomous Sensor Network for Early Warning Detection

D. Waller; DRDC CORA TM 2009-019; Defence R&D Canada – CORA; July 2009.

Background: The Self-healing Autonomous Sensor Network (SASNet) is a Technology Demonstration project whose purpose is to demonstrate an ad-hoc wireless network of heterogeneous sensors that can be deployed rapidly and left unattended to perform surveillance tasks for the Canadian Army. In preparation for SASNet's first demonstration in October 2008, a simulation study was performed to investigate SASNet's effectiveness at early warning detection.

SASNet model: A model of SASNet was developed in MATLAB for the simulation study. The model calculates the values of a number of important performance sub-objectives:
- deployment time,
- alarm latency time,
- detection probability,
- false alarm rate, and
- cost of the system.

These values depend on a number of fixed parameters and several independent variables.

Optimization of SASNet design: A simulated annealing algorithm was used to optimize the SASNet design for a range of barrier lengths between 0.5 and 2.0 km. The optimization deals with multiple sub-objectives by formulating the problem as a minimax, goal-attainment problem. For each barrier length, the least attained sub-objective is maximized.

Optimization results: The performance and cost goals are attained for barrier lengths of 1.0 km or less. For longer barriers, at least one of the sub-objectives cannot be met under the current assumptions. The detection probability and false alarm constraints are satisfied if there are four complimentary sensors on each sensor node and at least three sensors are required to detect a target.

Recommendations: This study indicates that SASNet is suitable for early warning detection for barriers 1.0 km or less. SASNet's suitability for such long surveillance barriers is due its low cost per node, ease of deployment, and multiple, complimentary sensors per node. Complementary sensors are vital for achieving a high detection probability and low

false alarm rate. Longer barriers are possible with SASNet if the assumptions made for this study are conservative or if either the performance and cost goals, or constraints are relaxed. SASNet field trials will provide data that will test the accuracy of the assumptions. It is strongly recommended that all of the parameters that have been assumed for this study be measured during the trials.

Obtaining more data on the relationships between cost and performance variables will be useful for understanding the trade-offs in the design of SASNet. Acquiring the relevant data may require significant work.

Despite its paucity of data, the SASNet model developed for this study will be useful in future simulation studies. The model can easily be updated. Additional sub-objectives (performance goals), like power consumption, can also be added to the model and the simulated annealing optimization code. For these reasons, it is recommended that the MATLAB code developed for this study be re-used in future OR studies of SASNet.

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A Simulation Study of the Effectiveness of the Self-healing Autonomous Sensor Network for Early Warning Detection

D. Waller ; DRDC CORA TM 2009-019 ; R & D pour la défense Canada – CARO ; juillet 2009.

Introduction : Le projet de démonstration de technologie (PDT) du Réseau de capteurs autonomes à autorétablissement (SASNet) vise à faire la démonstration d'un réseau sans fil ad hoc de détecteurs hétérogènes, pouvant être déployé rapidement pour effectuer de la surveillance à distance pour l'Armée canadienne. En vue de la première démonstration du SASNet en octobre 2008, une étude par simulation portant sur l'efficacité du SASNet quant à la détection avancée a été effectuée.

Modèle du SASNet : Un modèle du SASNet a été développé dans MATLAB en vue de l'étude par simulation. Le modèle permet de calculer la valeur de plusieurs sous-objectifs de rendement importants :
- temps de déploiement,
- délai d'alarme,
- probabilité de détection,
- taux de fausses alarmes,
- coût du système.

Ces valeurs dépendent d'un certain nombre de paramètres fixes et de plusieurs variables indépendantes.

Optimisation de la conception du SASNet : Un algorithme de recuit simulé a été utilisé pour optimiser la conception du SASNet pour une gamme de longueurs de barrière allant de 0,5 à 2,0 km. L'optimisation tient compte de sous-objectifs multiples en réexprimant le problème sous la forme d'un problème d'atteinte d'objectif qui est résolu au moyen de la méthode minimax. Pour chaque longueur de barrière, le sous-objectif le moins bien atteint est maximisé.

Résultats de l'optimisation : Les objectifs de rendement et de coûts sont atteints pour des longueurs de barrière de 1,0 km ou moins. Pour les barrières plus longues, au moins un des sous-objectifs ne peut être atteint selon les hypothèses actuelles. Les contraintes de probabilité de détection et de taux de fausses alarmes sont respectées si chaque noeud de détection comporte quatre capteurs complémentaires, il faut au moins trois capteurs pour détecter une cible.

Recommandations : La présente étude indique que le SASNet peut servir à la détection avancée pour les barrières de 1,0 km ou moins. Le SASNet peut convenir à des barrières de surveillance aussi longues grâce à son faible coût par noeud, à sa facilité de déploiement et à l'utilisation de capteurs multiples complémentaires à chaque noeud. Les capteurs complémentaires sont essentiels pour atteindre une probabilité de détection élevée et un faible taux de fausses alarmes. Des barrières SASNet plus longues sont possibles si les hypothèses de la présente étude sont prudentes, si les objectifs de rendement ou de coûts sont réduits, ou encore si les contraintes sont assouplies. Les essais sur le terrain du SASNet fourniront des données qui permettront de mettre à l'épreuve la précision des hypothèses. Il est fortement recommandé que tous les paramètres pour lesquels des hypothèses ont été utilisées dans la présente étude soient mesurés au cours des essais.

L'acquisition de plus de données sur la relation entre les variables de coût et de rendement permettra de mieux comprendre les compromis qu'exige la conception du SASNet. L'obtention de ces données pourrait nécessiter beaucoup de travail.

Malgré le manque de données, le modèle SASNet développé pour la présente étude sera utile à de futures études par simulation. Le modèle peut facilement être mis à jour. Il est également possible d'ajouter des sous-objectifs (de rendement) supplémentaires, comme la consommation d'énergie, au modèle et au code d'optimisation de recuit simulé. C'est pourquoi il est recommandé de réutiliser le code MATLAB développé pour la présente étude dans les futures études de RO du SASNet.

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1 Introduction

The Self-healing Autonomous Sensor Network (SASNet) is a Technology Demonstration project with a purpose to demonstrate an ad-hoc wireless network of heterogeneous sensors that can be deployed rapidly and left unattended to perform surveillance tasks for the Canadian Army. SASNet is a collaboration between teams from the Communications Research Centre of Industry Canada, Defence R&D Canada Valcartier, and Newtrax Technologies of Montreal. If successful, SASNet will improve situational awareness, and contribute to mission planning and force protection [1]. SASNet can be used for a number of different applications. Three specific applications will be demonstrated during the project. In chronological order, they are (1) early warning detection at a barrier, (2) choke-point monitoring, and (3) road junction surveillance. In preparation for the first demonstration in late 2008, a simulation study was performed to investigate SASNet's effectiveness at early warning detection. This technical memorandum documents this simulation model and presents results from an optimization study.

2 Background

Unattended ground sensors (UGS) have been used for military surveillance since the Vietnam War. The United States Army used seismic and acoustic sensors to monitor the movement of enemy vehicles and personnel behind enemy lines in remote locations of the jungles of South East Asia [2]. Unfortunately, the performance of these first UGS was compromised by the enemy's ability to "spoof" the sensors by providing misleading information for the sensors to relay. Spoofing was possible due to the simplicity of the first generation of sensors and the fact that the enemy often knew where the sensors were located. Until recently, only modest improvements have been made to operational systems since this first generation of UGS [3]. The current systems are significantly more capable due to advances in electronics, data processing and wireless networks [3].

Further improvements are possible if the sensors are networked so that they can collaborate and share information. Two of the main problems that have plagued UGS have been their high false alarm rate [4, 5], and the inability to instrument large areas due to cost constraints. A typical off-the-shelf UGS (with one simple sensor) costs approximately $20,000 [6]. Since the range of sensors can be as short as a few metres, depending on the sensor type and target, it is not cost-effective to instrument large areas (e.g. the perimeter of a large camp). Instead a smaller number of large, line-of-sight optical or radar sensors are typically used for the surveillance of large areas [7]. The false alarm problem can be greatly diminished by having complementary sensors that cover the same area and communicate with each other or a common processing unit so that the data from the different sensors is analyzed together. Recent improvements in wireless communications and networking make communication and data sharing amongst sensors easier [8, 9]. Also, continued miniaturization and improvement of inexpensive computing hardware (processors and memory) make the automated, *in situ* processing of sensor data feasible.

Improved wireless communications between sensor nodes, and cheaper and smaller nodes should also solve the problem of instrumenting large areas. By taking advantage of these recent advances, SASNet should provide an effective network of low-cost sensor nodes that has a low false alarm rate and can be used over larger areas than were typically instrumented in the past.

The features of commercially available UGS, and non-military wireless sensor networks are summarized in Table 1. The final column shows the features specified as design goals for SASNet [10]. Definitions for the features listed in Table 1 are given below.

- Rapid deploy: the ability to deploy each sensor node in five minutes or less.
- Net self-config: after the sensors are deployed network connections are established between nodes and the network configures itself to allow efficient transmission of data.
- Ad hoc mesh net: the network which forms is ad hoc (nodes in the network can communicate directly with whichever nodes are within communications range) and has a mesh (as opposed to a hierarchical or structured) topology.

Table 1: *Summary of features of commercially available UGS, and non-military wireless sensor networks. Explanations of the features are given in the text.*

Features	Unattended Ground Sensors (UGS)				Wireless Sensor Network					SASNet
	Falcon Watch	Classic 2000	Terrain Comm 2	IDF Seraphim	Newtrax Nodes	Dust Smartmesh	Crossbow Mica2	MoteIV tmote	IWT AXON	
Rapid Deploy	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Net Self-config	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Ad Hoc Mesh Net	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Localization	GPS	No	No	No	No	No	No	No	No	Yes
Cross Cueing	No	No	No	No	No	No	No	No	No	Yes
Re-tasking	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Self-heal	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Anti-tamper	Yes	Yes	Yes	No	No	No	No	No	No	Yes
Classification	Yes	Yes	Yes	No	No	No	No	No	No	Yes

- Localization: nodes are able to determine and report their own locations. (The Falcon Watch UGS [see Table 1] uses the Global Positioning System [GPS] to determine the locations of its sensors.)
- Cross cueing: a detection by one sensor is used to cue (turn on and/or orient) another sensor.
- Re-tasking: sensors can have their tasks/instructions changed remotely.
- Self-heal: if a part of the network fails, the network can "heal" itself by re-arranging the connections between nodes in the network.
- Anti-tamper: if a sensor is physically tampered with, it will alert the user of the network and take counter-measures.
- Classification: the sensor nodes are able to differentiate different classes of targets (e.g. people, wheeled-vehicles, tracked-vehicles).

Combining the best features of these UGS and wireless sensor networks should make SASNet a highly effective surveillance asset for the Canadian Army.

2.1 SASNet Design

SASNet's design philosophy follows John von Neumann's idea that a "reliable" machine can be built from "unreliable components" (or "automata") [11]. Building the sensor network from "unreliable" components means that the cost per component (and hopefully per system) can be significantly less than current commercial UGS. The network, as a whole, is made reliable by having multiple, complementary and/or redundant sensors. For example, if part of a perimeter is monitored by seismic, acoustic, magnetic and imaging sensors simultaneously, it is very unlikely that all of the sensors will produce a false alarm at the same time (even if each is less reliable than the best available sensor of its type). By requiring two or more sensors to detect a target simultaneously, the rate of false alarms can be greatly reduced (see Section 4.2 for details). Also, building the sensor network from much cheaper components means a larger area can be instrumented without the cost becoming prohibitive.

SASNet is composed of four types of components. The hierarchy of these components is shown in Figure 1. At the lowest level are the automata of SASNet: numerous inexpensive, disposable sensor nodes. Each of these "level-one" nodes has an antenna for radio communications, a small computing platform and a variety of seismic, acoustic, magnetic, and passive infra-red sensors. The detection ranges of these sensors vary from a few metres (magnetic sensor detecting a dismounted soldier with rifle) to hundreds of metres (seismic sensor detecting large vehicles). The sensor nodes can communicate with each other and higher-level nodes via low-power radio links. The range of the radio links is terrain-dependent, but is typically between 10 and 100 metres and the transfer rate is approximately 10 to 100 kilobits per second.

The second level of the SASNet network consists of nodes that perform aggregation and analysis of the data collected by the level-one sensor nodes. These second level nodes are called fusion nodes. They have more computing power, higher power and higher bandwidth radio links (a few hundred kilobits per second). The range of the radio links is up to one kilometre.

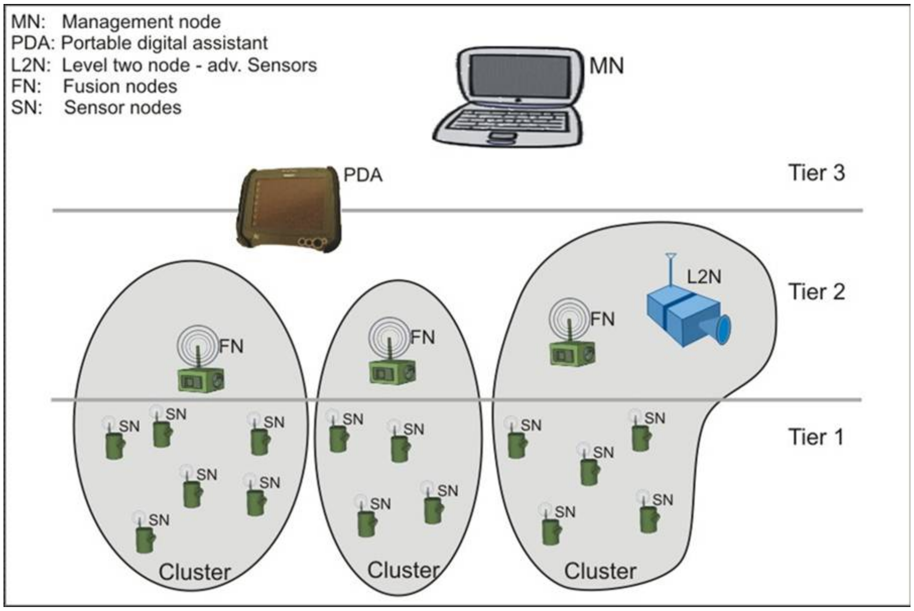

Figure 1: *Hierarchy of nodes in SASNet.*

More sophisticated “level-two” sensor nodes can be deployed. These nodes include electro-optical infra-red (EO-IR) cameras or acoustic arrays used for sniper detection [12]. Because of their much higher cost, these nodes will be deployed in much smaller numbers and will not be considered disposable. However, their long sensing range (hundreds of metres) means that fewer of these sensors are required to cover a fixed area. Because of the large amounts of data produced by these sensors, they will require high bandwidth links like those of the fusion nodes. The level-two sensor nodes use large amounts of energy. Consequently, they will only be activated when level-one nodes that have detected a target of interest.

Fused data and alarms from the fusion nodes are sent either to a personal digital assistant (PDA) carried by a soldier in the field, or to the third level of SASNet (the management node), which is likely a computer located in a static headquarters or a in vehicle. If necessary, relay nodes can be used to pass data between the fusion nodes and a PDA or management node. Both the PDA and management node require specific SASNet software to communicate with the SASNet components. Besides providing an interface for monitoring SASNet, the PDA and management node allow a user to control the nodes remotely.

SASNet will be a self-healing network as it will be able to reconfigure its network connections without operator intervention if some nodes stop working. Its ability to self-heal depends on the availability of redundant wireless communication links. If too many nodes stop working, the network will eventually lose its ability to reconfigure. When this happens SASNet users will not be able to communicate with part of the network. Self-healing is an important feature as (1) the large number of nodes would make manual repair of the system extremely onerous, and (2) the security environment might not permit soldiers to deploy more sensor nodes.

SASNet will be autonomous so that it requires minimal intervention or monitoring by a soldier. SASNet must not add extra tasks for the soldier. Instead, it should make their jobs (particularly surveillance tasks) easier by providing reports/alarms from areas that would otherwise require extra soldiers to patrol.

2.2 Concept of Operations for SASNet

A detailed description of the concept of operations (CONOPS) for SASNet can be found in Reference [13]. This section gives a brief review of how SASNet will be used in an early warning detection scenario. Figure 2 shows a range of example applications. There are three basic tasks that must be performed to conduct surveillance with SASNet: (1) deploy the system, (2) monitor for alarms, and (3) react to alarms.

SASNet nodes will be deployed as rapidly as possible to provide early warning for temporary outposts or bases. SASNet is most useful in areas where line-of-sight observation is not possible. After securing the area where SASNet will be deployed, an Army section or platoon will transport the nodes from the temporary base to the perimeter. The nodes will be deployed in a covert fashion one cluster at a time.

Nodes will usually be concealed except when there is a desire to deter encroachment on an area. Concealing a node is likely to be the most time consuming part of deployment of SASNet. If the emplacement time per node is less than five minutes, that would be considered “rapid” with respect to current UGS. After a node is emplaced, a quick check should verify that its RF communications and network link are functioning properly.

After all of the nodes are deployed, the system is activated so that it can provide early warning. Once activated, one soldier must monitor the system for alarms. This does not require the soldier to be looking at a computer or PDA screen constantly, but the soldier should be vigilant for alarms/messages that can be signalled by audible signals (or for a PDA which is worn, by vibration). The first-level sensor nodes will cue the nearest second-level sensor node to capture an image if a target passes through the sensor field. The alarms from the first-level sensor nodes and images from the second-level nodes will be sent immediately to the monitoring soldier.

Depending on the speed of the approaching target and the stand-off distance from the perimeter, the time before contact with the target may be as little as a few seconds. Therefore, when an alarm is received by the monitoring soldier, it is important that he react quickly.

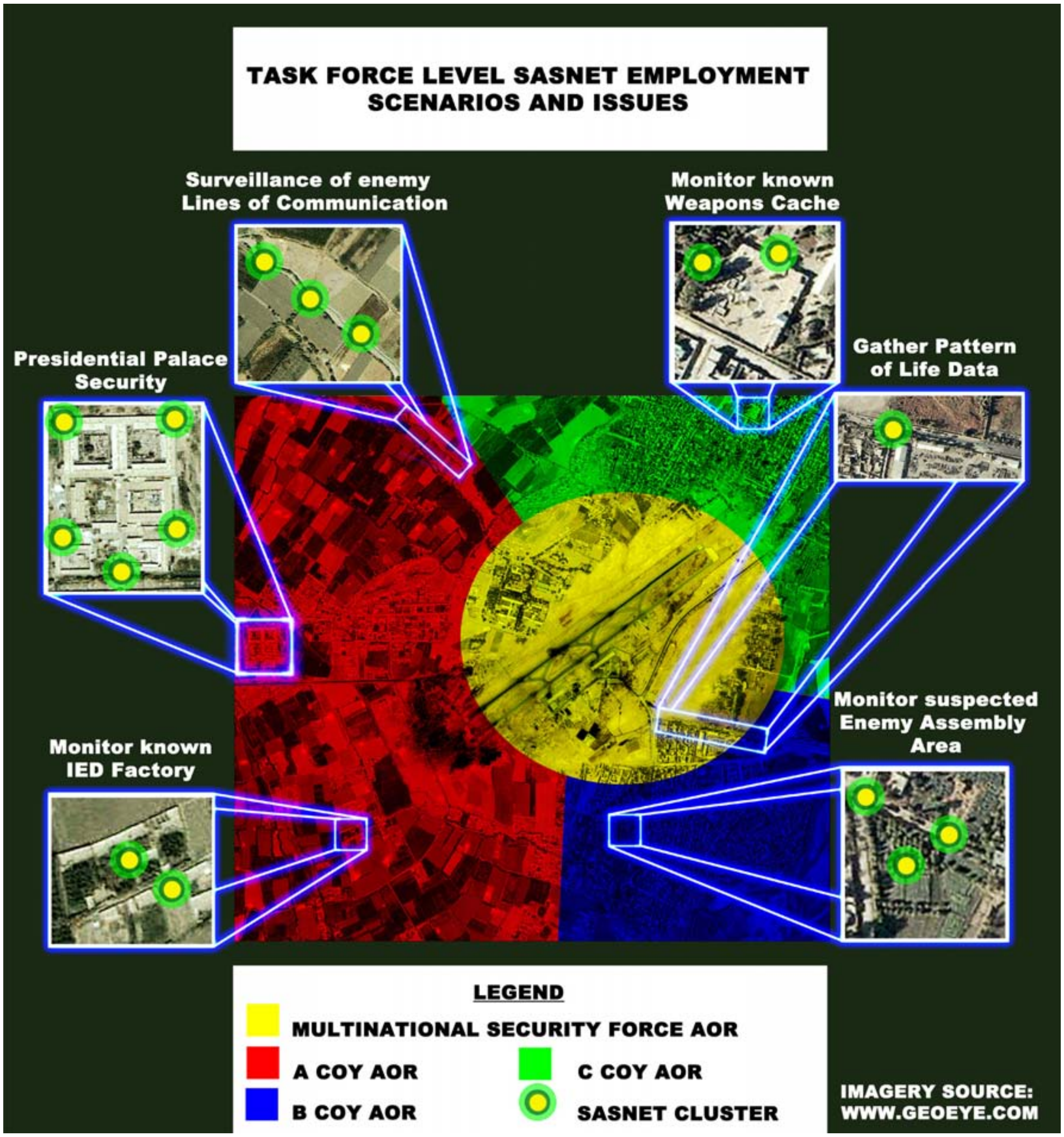

Figure 2: *Example of Task Force level SASNet employment scenarios [13]. Kandahar Air Field is used for illustrative purposes to show how and where SASNet might be used. The specific locations indicated on the map are arbitrary, and so do not represent tactically relevant information. The colour-coding indicates hypothetical Areas of Operation (AORs) of different army companies (COY).*

3 Early Warning Detection Scenario

The first scenario in which SASNet will be demonstrated is early warning detection with a barrier of sensor nodes. The barrier covers approximately 100 m by 50 m of the perimeter around a single soldier. Figure 3 shows the layout for the first live demonstration. Only part of the perimeter will be instrumented as a much larger number of sensor nodes would be required to instrument a full perimeter. Subsequent demonstrations of SASNet will involve larger numbers of sensor nodes. Despite this limitation for the first trial, the simulated scenario studied in this paper is for a full perimeter (or equivalently, a much longer barrier).

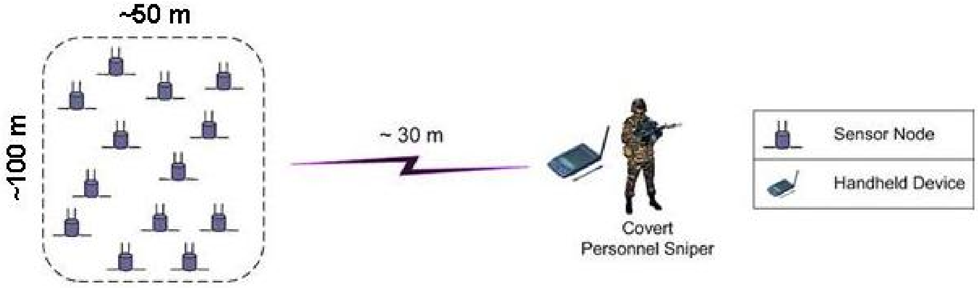

Figure 3: *Early warning detection scenario.*

It is unlikely that SASNet would actually be deployed for an entire perimeter, as line-of-sight observation will more likely be employed where possible [13]. SASNet is more likely to be used in areas where line-of-sight observation is not possible. Despite this, the simulation assumes a full perimeter as the total length of the surveillance barrier is of great interest (contiguous or not). The perimeter is assumed to be circular as this shape minimizes the number of sensor nodes required for a fixed detection stand-off distance. The barrier length is varied from 500 m to 2 km. This range includes the length of interest (1.5 km) for an ongoing Army UGS acquisition project [14].

The primary goal of SASNet in this scenario is to provide early warning detection of targets moving through a barrier of sensor nodes. In addition to detecting targets with a high probability, SASNet should have a low false alarm rate. Cost is an important factor as this has a significant impact on how and where SASNet can be used. SASNet must also be rapidly deployable as it is intended to protect temporary outposts and camps.

Finally, the warning provided by SASNet must be transmitted to a soldier in a timely fashion. Consequently, this study is focused on five variables:

1. probability to detect target;
2. false alarm rate;
3. cost;
4. time to deploy;
5. alarm latency.

4 SASNet Model

A model of SASNet was constructed in MATLAB [15] to calculate the values of the relevant variables. For a given set of input parameters, the model calculates a number of intermediate variables, then computes the values of the five variables listed in the previous section. Figure 4 indicates the main steps in the model's calculations.

In the model, the barrier of sensor nodes for early warning is deployed in three concentric circles with radii R, $R-2R_{sense}$, and $R-4R_{sense}$. Three circles are assumed so that there is enough information to track a target as it passes through the sensor field. If the sensors were perfect, each target would be detected three times. The nodes are spaced so that the sensing fields of the sensors just overlap for nodes in the same circle, and between circles. This minimizes the number of nodes that needs to be deployed. The sensing range can be varied in the model.

The wireless communications range of the sensor nodes is constrained to be at least twice the sensor range so that nodes can communicate with their neighbours. The communications range is also an independent variable in the model so that the trade-off between alarm latency (which increases with the number of communications hops to the fusion node) and cost (which increases with communications range) can be studied.

The model of SASNet includes a level-two sensor node that has an electro-optical infra-red (EO-IR) camera. The camera is directed to take images of candidate targets by the level-one sensors through the fusion node. The image is assumed to be sent to and interpreted by a soldier in order to classify the target. The operational parameters of the camera (range, field-of-view, size, and weight) are assumed to be the same as those for the AMIGO camera node, that was recently developed at DRDC Valcartier [16]. For a list of the camera parameters and all of the other parameters used in the SASNet model, see Appendix A.

4.1 Number of sensor nodes

The number of sensor nodes required depends on the detection range of the sensors. In order that there are no gaps in coverage for a perimeter, the adjacent sensors cannot be separated by a distance more than twice their sensing range, R_{sense}. For each of the three concentric circles of sensor nodes, if the radius of the circle satisfies $R \gg 2R_{sense}$ then the number of sensor nodes in the circle is given by

$$N_{ring} = \mathrm{int}(2\pi R/2R_{sense}) + 1. \tag{1}$$

For all practical applications with a circular perimeter, the radius of the perimeter is much larger than the sensing range of the sensors.

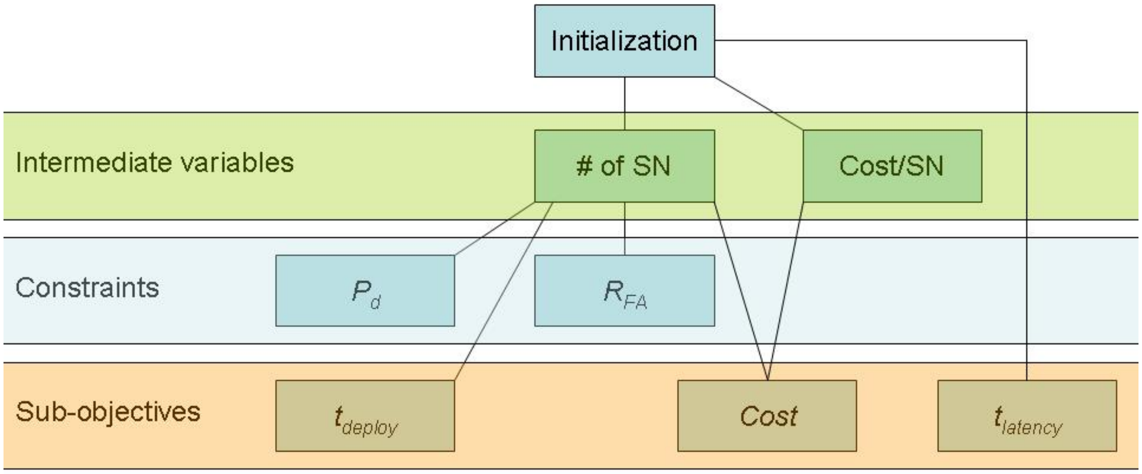

Figure 4: *MATLAB model of SASNet. After the SASNet model parameters are initialized, the intermediate variables for the number of sensor nodes (SN) and cost per SN are calculated. The probability to detect a target (P_d) and rate of false alarms (R_{FA}) are determined from the number of SN. P_d and R_{FA} are used as constraints for the optimization of SASNet's design. The time to deploy (t_{deploy}), cost and alarm latency time ($t_{latency}$) are calculated as sub-objectives for the SASNet optimization.*

4.2 False alarm rate

For surveillance systems, false alarms fall into two generic categories:

1. alarms triggered by external events that are not of interest (e.g. animals, wind, rain can trigger UGS alarms).
2. spurious alarms that are internal to the surveillance system (e.g. sensor noise, noisy electronics, electrical pick-up);

False alarms can be caused by a number of different external sources, depending on the type of sensor (see Table 2). False alarms caused by external events can be reduced by combining information from different sensors in such a way that false alarms can be discriminated from real targets.

Depending on the cause of the false alarms (e.g. civilians, non-military vehicles), this type of false alarm can be very difficult to avoid. However, in many cases, combining the information from many sensors should reduce the incidence of false alarms. For example, a change in ambient light can cause a passive infra-red motion detector to trigger an alarm, but it will not affect a seismic sensor.

Table 2: *External causes of false alarms for different types of UGS sensors [4, 5].*

Sensor type	Source of false alarm
magnetic	ferrous material other than weapons
seismic	thunder, distant explosions, animals
acoustic	wind, rain
passive infra-red	change in ambient light, moving vegetation

The false alarm rate due to external events is highly variable and depends on where SASNet is deployed. In heavily populated areas, the false alarm rate from civilians is likely to be high. In rural areas with large animal populations, the false alarm rate might also be high depending on the sensors, data fusion capability and terrain. Not surprisingly, SASNet (like all UGS) will be most effective where no civilians or animals are present.

False alarm rates that are due to phenomena internal to the sensor system are easier to reduce as long as they originate from a single sensor and are not correlated with false alarms in other sensors. If this type of false alarm involves only events that are independent from each other, then the false alarm rate of the system can be significantly reduced by requiring multiple detections in coincidence in time and space.

Individual sensors tend to have relatively low internal false alarm probabilities per unit time, P_{fa}; however, since a large number (L) of sensors is usually required to cover a perimeter, the probability for one of the sensors to have a false alarm, $P_{fa}(1/L)$, in a fixed time period is much larger than the probability for a single sensor:

$$P_{fa}(1/L) = 1 - (1 - P_{fa})^L. \tag{2}$$

By having N sensors cover the same portion of a perimeter, one can require coincident detections. If one requires M or more of the N sensors to have detections during the same detection cycle, the false alarm probability, $P_{fa}(M+/N)$, is given by

$$P_{fa}(M+/N) = \sum_{i=M}^{N} P_{fa}(i/N) = 1 - \sum_{i=1}^{M-1} P_{fa}(i/N), \tag{3}$$

where

$$P_{fa}(i/N) = \frac{N!}{(N-i)!(i)!} P_{fa}^{i} (1 - P_{fa})^{N-i}, \tag{4}$$

is the probability density function for independent Bernoulli trials [17].

Equations 2 to 4 assume that P_{fa} is the same for all the sensors. If sensors of different types cover the same area (heterogeneous system), then the probability of a false alarm for a sensor j, P_{fa_j} will be different for each sensor. In this mixed case,

$$P_{fa}(1/L)_{mix} = 1 - \prod_{j=1}^{L}(1 - P_{fa_j}), \tag{5}$$

and

$$P_{fa}(M+/N)_{mix} = \sum_{i=M}^{N} P_{fa}(i/N)_{mix} = 1 - \sum_{i=1}^{M-1} P_{fa}(i/N)_{mix}, \tag{6}$$

where

$$P_{fa}(i/N)_{mix} = \frac{N!}{(N-i)!(i)!} \prod_{k=1}^{i} P_{fa_k} \prod_{g=k+1}^{N-i} (1 - P_{fa_g}). \tag{7}$$

The SASNet model used for this study assumes that P_{fa} is equal for all sensors, so equation 3 is used. To calculate the false alarm rate (R_{FA}) for different time intervals (e.g. second, minute, hour, or day), P_{fa} (probability per unit time [second]) must be multiplied by an appropriate conversion factor. Having a low false alarm rate per sensor node is vital to achieving large scale deployments of SASNet, so it is imperative that SASNet combine information from multiple sensors whenever possible [18].

4.3 Detection probability

If L sensors with the same detection probability are used to cover the same area, the probability one sensor in the system will detect a real target in that area is

$$P'_d(1/L) = 1 - (1 - P'_d)^L, \tag{8}$$

where the modified probability of detection, P'_d, is given by

$$P'_d = 1 - (1 - P_d)(1 - P_{fa}). \tag{9}$$

P_d is the probability for detecting a real target, and P_{fa} is the probability for having a false (internal) alarm, which is the same whether or not a real target is present. The chance of having a false alarm when a real target is present is small but is included for completeness. Its inclusion results in a small increase in P'_d. Note that equation 8 is identical in form to equation 2.

If a target must be detected by more than one sensor (in order to reduce the false alarm rate), the expressions for the probability for detection are identical to the expressions that describe false alarm probabilities (equations 3 and 4), except P_{fa} is replaced by the modified detection probability, P'_d:

$$P'_d(M+/N) = \sum_{i=M}^{N} P'_d(i/N) = 1 - \sum_{i=1}^{M-1} P'_d(i/N), \tag{10}$$

where

$$P'_d(i/N) = \frac{N!}{(N-i)!(i)!} P'^i_d (1-P'_d)^{N-i}. \tag{11}$$

Although requiring multiple sensor detections reduces the false alarm rate, it also reduces the detection probability as multiple sensors must correctly detect a target at the same time.

4.4 Cost of deployed system

The cost of the deployed system is determined by the number of nodes of different types and the costs per node. In this model the cost per node for the EO-IR, relay and management nodes are fixed and are assumed to be \$15,000, \$300, and \$5000 respectively. The costs per node for the first-level sensor and fusion nodes depend on a number of decision variables. The cost assumptions for this study were based on estimates provided by members of the SASNet project team [19].

The cost per sensor node depends on its communications range, sensor range and volume. The greater the communications and sensing ranges, the more expensive the node. Also, the smaller its volume, the more expensive it is. In dollars, the cost per sensor node, $Cost_{SN}$, is given by

$$Cost_{SN} = (R_{sense} - 5)^2 + R_{comms} + \frac{5}{V_{SN}/(80 \times 40 \times 20)} + 35, \tag{12}$$

where the sensing range, R_{sense}, and the communications range, R_{comms}, are measured in metres, and the sensor node volume, V_{SN}, is measured in mm^3. The first term represents a quadratic increase in cost with sensing range (R_{sense} is constrained to be greater than 5 m). The second term shows a linear relationship between communications range and cost. The third term shows an inverse relationship with respect to sensor node volume; this term is normalized so that the "volume cost" is \$5 if the sensor node is the nominal size of $80 \times 40 \times 20$ mm^3. The last term in equation 12 is a fixed cost per sensor node due to various fixed design, manufacturing and overhead costs.

The cost per fusion node, $Cost_{FN}$, depends on the maximum number of sensor nodes that a fusion node can be associated with, SN/FN. The cost of a fusion node increases quadratically as SN/FN increases:

$$Cost_{FN} = (500)(\frac{SN/FN}{20})^2 + 1500. \tag{13}$$

The last term in Equation 13 is a fixed cost per fusion node.

4.5 Deployment time

The time to deploy SASNet, t_{deploy}, depends on the length of time spent traveling to the deployment area and the time spent on deploying the nodes once in the area. For all the scenarios considered for SASNet, the time spent deploying the nodes is dominated by the time spent emplacing each node. As the number of first-level sensor nodes is much greater than all of the other nodes, and the emplacement time for the other node types is assumed to be five minutes per node, the time to emplace each sensor node is the most important variable in the determination of the the total deployment time. The time per sensor node, t_{SN}, depends linearly on the volume of the sensor:

$$t_{SN} = 60 + \frac{240V_{SN}}{80 \times 40 \times 20}, \tag{14}$$

where the time is in seconds, and the volume is in mm^3. For the nominal volume of $80 \times 40 \times 20$ mm^3, it takes five minutes to emplace a sensor node. As the cost per sensor node decreases with V_{SN}, there is a trade-off between t_{deploy} and $Cost$.

4.6 Alarm latency

The alarm latency of SASNet, $t_{latency}$, depends on the time required for each hop (t_{hop}) in the network, and the number of hops. The maximum value of $t_{latency}$ occurs when the sensor node that is farthest from its associated fusion node sends an alarm to the fusion node. The number of hops that this alarm must take as it propagates through the network depends on the communication range of the sensor node. The longer the range, the fewer the number of hops. In this study, the time per hop is assumed to be constant and independent on the number of hops, but this is not always the case. Depending on the network topology and routing algorithms, the time per hop can increase as the number of hops increases. This results in $t_{latency}$ increasing in a non-linear manner. Since this study assumes a linear relationship between $t_{latency}$ and the number of hops, it represents the most optimistic scenario. SASNet's maximum value for $t_{latency}$ is calculated assuming that the barrier has three rows of sensor nodes with the fusion node in the middle of its associated sensor node. The alarm latency decreases as SN/FN decreases and R_{comms} increases. This results in a trade-off between $t_{latency}$ and $Cost$: fewer SN/FN means that a greater number of expensive fusion nodes are required, and longer R_{comms} increases the cost per sensor node.

5 Optimization of SASNet design

The objective of this study is to determine the effectiveness of SASNet for providing early warning. Of particular interest is the length of the surveillance barrier that SASNet can provide subject to operational and cost constraints. An optimization of SASNet's design is carried out for a range of lengths: 0.5 km to 2.0 km in 0.1 km steps.

5.1 Sub-objectives, constraints and decision variables

As mentioned in Section 3, the five key variables in the study are (a) the probability to detect a target (P_d), (b) the false alarm rate (R_{FA}), (c) the cost ($Cost$), (d) the time to deploy (t_{deploy}), and (e) the alarm latency ($t_{latency}$). For the remainder of this paper, we will use the probability to miss a target ($P_{miss} = 1 - P_d$) instead of P_d; this simplifies the presentation of data later in the paper. For the optimizations, P_{miss} and R_{FA} are used as constraints:

$$\begin{aligned} P_{miss} &\leq 0.01 && (15) \\ R_{FA} &\leq 1/\text{day}/\text{km}. && (16) \end{aligned}$$

These values were determined from consultations with the Army sponsors of the project.

The variables which are optimized are $Cost$, t_{deploy} and $t_{latency}$. In all three cases, the smaller the values of these variables, the better. These three sub-objectives are combined into a single objective function. Since the design goal is to ensure that each of these variables meets or exceeds the Army requirements, the optimization problem is formulated as a goal attainment problem [20] where the objective is to maximize the extent to which each sub-objective (x) exceeds its design goal ($goal(x)$). More precisely, the objective function, Obj, is equal to the maximum value of the attainment of the sub-objectives:

$$Obj = Max\{Attain(Cost), Attain(t_{deploy}), Attain(t_{latency})\}, \tag{17}$$

where $Attain(x)$, the attainment of each sub-objective, is

$$Attain(x) = \frac{x - goal(x)}{goal(x)}. \tag{18}$$

Since $Attain(x)$ is achieved for the variables if $x \leq goal(x)$, $Attain(x)$ takes a negative value when a sub-objective is met. Thus, the goal of the optimization is to minimize Obj. This type of optimization is referred to as a “minimax” problem [21]. The design goals for the sub-objectives are listed in Table 3.

Table 3: *SASNet design goals and constraints.*

Constraint/Sub-objective	Goal
P_{miss}	0.01
R_{FA}	1/day/km
$Cost$	\$250k
t_{deploy}	8 hours
$t_{latency}$	5 seconds

Table 4: *Dependence of the optimization constraints and sub-objective on the decision variables.*

Decision Variables	Constraints		Sub-objectives		
	P_{miss}	R_{FA}	t_{deploy}	$t_{latency}$	$Cost$
sensors per node	X	X			X
N_{hit}	X	X			
SN/FN			X	X	X
R_{comms}				X	X
R_{sense}			X		X
V_{SN}			X		X

In the optimization, six decision variables are allowed to float to minimize the objective function. These are the

1. sensors per node,
2. sensor hits required to trigger alarm (N_{hit}),
3. SN/FN,
4. R_{comms},
5. R_{sense}, and
6. V_{SN}.

The dependence of the constraints and sub-objectives on the decision variables is summarized in Table 4. An “X” indicates that the constraint or sub-objective depends on the corresponding decision variable.

It is clear from Table 4 that the constraints are almost completely decoupled from the sub-objectives. The only decision variable that affects both a constraint and a sub-objective is the number of sensors per node. This simplifies the optimization as the problem can be broken down into two sub-problems. First, the number of sensors per node and value of N_{hit} that satisfy the P_{miss} and R_{FA} constraints at the lowest cost can be determined. Next, the objective function is minimized with the number of sensors per node and N_{hit} fixed and the remaining four decision variables left free to float.

Table 5: *Values for P_{miss} and R_{FA} for three combinations of sensors per node and N_{hit}.*

Sensors per sensor node, N_{hit}	P_{miss}	R_{FA} (day^{-1}km^{-1})
4,3	2.3×10^{-3}	4.7×10^{-4}
3,2	1.2×10^{-3}	1.3
2,2	4.0×10^{-2}	4.2×10^{-1}

5.2 P_{miss} and R_{FA} constraints

At the very most, SASNet's sensor nodes will have five sensors each. This makes it very easy to determine the values for the sensors per node and N_{hit} that minimize $Cost$ while meeting the P_{miss} and R_{FA} constraints. All that is required is to calculate P_{miss} and R_{FA} for the 15 possible combinations of sensors per node and N_{hit} and determine which of the combinations that that meet the constraints is the cheapest. Figure 5 shows P_{miss} versus R_{FA}.

Only three combinations satisfy the constraints: (sensors per node, N_{hit}) = (5,4), (5,3), and (4,3). Since the cost per sensor node increases as the number of sensors per node increases, the option that minimizes $Cost$ is (4,3). If it is not feasible to use four different sensors on a sensor node, then either the sensors must perform better than assumed or at least one of the constraints must be relaxed. If the false alarm rate per sensor is lower than assumed, or the false alarm rate constraint is relaxed, then (3,2) is a viable option. Alternatively, if the probability to miss a target per sensor is lower than assumed, or the P_{miss} constraint is relaxed, then option (2,2) may be viable. Table 5 summarizes P_{miss} and R_{FA} for options (4,3), (3,2) and (2,2) under the current model assumptions.

5.3 Simulated annealing algorithm

After fixing the number of sensors per node and N_{hit} to 4 and 3, respectively, four decision variables remain free to float in the optimization problem. These variables are both integer (SN/FN) and real (R_{comms}, R_{sense} and V_{SN}). The objective function (equation 17) that is optimized is real, non-linear and discontinuous. As a result, a simulated annealing algorithm [22, 23] is suitable for performing the optimization. Simulated annealing algorithms can deal with decision variables of different types, and non-linear and/or discontinuous objective functions [24]. Also, simulated annealing performs a random search, so it is less likely than local search algorithms to be trapped in local minima. The simulated annealing algorithm used in this work is the default algorithm implemented in MATLAB's Genetic Algorithm and Direct Search Toolbox [15].

Simulated annealing algorithms follow a process analogous to the physical annealing process that occurs in metals as they are cooled. In "real" annealing the rate of cooling (or

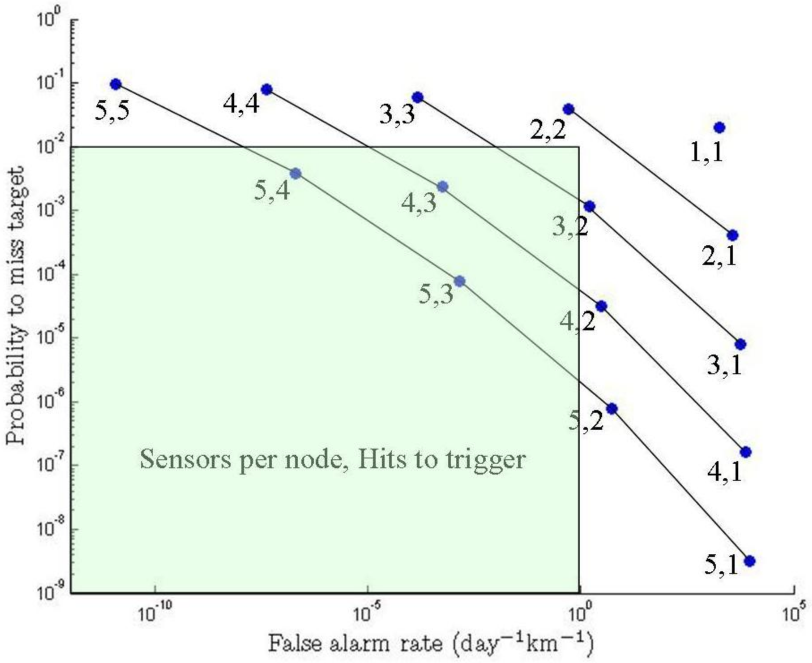

Figure 5: *P_{miss} versus R_{FA} for the 15 possible combinations of sensors per node and N_{hit}. Data points with the same number of sensors per node are joined by solid lines. The green (or grey) box indicates the region where the P_{miss} and R_{FA} constraints are satisfied.*

cooling schedule) of the metal determines the physical properties (e.g. crystalline structure) of the cooled material. In simulated annealing, the cooling schedule determines (a) the likelihood that the algorithm will stop at a local minimum, and (b) the rate at which a minimum is found.

Simulated annealing algorithms are characterized by three functions: the cooling schedule, the generating function, and the acceptance function. The algorithm used in this work uses a standard exponential cooling schedule:

$$T_i = T_0 a^i, \tag{19}$$

where T_i is the temperature at step i of the algorithm, and T_0 is the starting temperature. The value of a, here chosen to be 0.97, determines how fast the system cools (i.e. the algorithm's rate of convergence) [1]; a must be < 1, and values > 0.8 have been shown to be very effective for a wide range of problems [25].

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[1] The value of 0.97 was determined after many runs of the algorithm with different values of a from 0.90 to 0.99. The chosen value resulted in a good compromise between run time and consistent convergence near what appeared to be the global minimum.

The generating function determines the values of the decision variables for each iteration of the algorithm:

$$x_{i+1} = x_i + f(randn, T_i), \tag{20}$$

where x_{i+1}, the value of a decision variable at iteration $i+1$ is determined by its value at the previous step plus a function that depends on a random number that is drawn from a normal distribution of mean 0 and a standard deviation that is proportional to the system temperature. The smaller the standard deviation (i.e., the lower the temperature), the smaller the difference between the decision variables at successive iterations of the algorithm.

The acceptance function determines whether or not a new set of decision variables (determined by the generating function) is used by the algorithm. The acceptance function is

$$A = \frac{1}{1+\exp(\frac{Obj_{i+1}-Obj_i}{T_i})}, \tag{21}$$

where Obj_i is the value of the objective function at iteration i, and T_i is the temperature. The value of A is compared to a random number drawn from a uniform distribution between 0 to 1 to determine whether the new set of decision variables is accepted. The stochastic generating and acceptance functions of the algorithm allow it to explore the solution space in order to escape local minima.

Figure 6 shows the shape of Obj near its minimum value as a function of R_{sense} and SN/FN. It is clear from this figure that Obj is highly non-linear and discontinuous. There are numerous local minima over the range of parameter space that is shown. For these reasons, simulated annealing is a suitable algorithm for dealing with this complex solution space.

The step-like features on the right side of Figure 6 indicate a region of parameter space where Obj is determined by the attainment of $t_{latency}$ (whose steps are in increments of 0.2). In other words, $t_{latency}$ has the worst attainment of the three sub-objectives. These steps occur when SN/FN or R_{comms} cross thresholds that increase the number of hops that messages must take to go from a sensor node to a fusion node. The sawtooth-like pattern on the left of Figure 6 is due to discrete thresholds being crossed where the number of sensor nodes required for a deployment changes by integer values. This causes discrete steps in the $Cost$ of SASNet. In this region, Obj is limited by $Cost$.

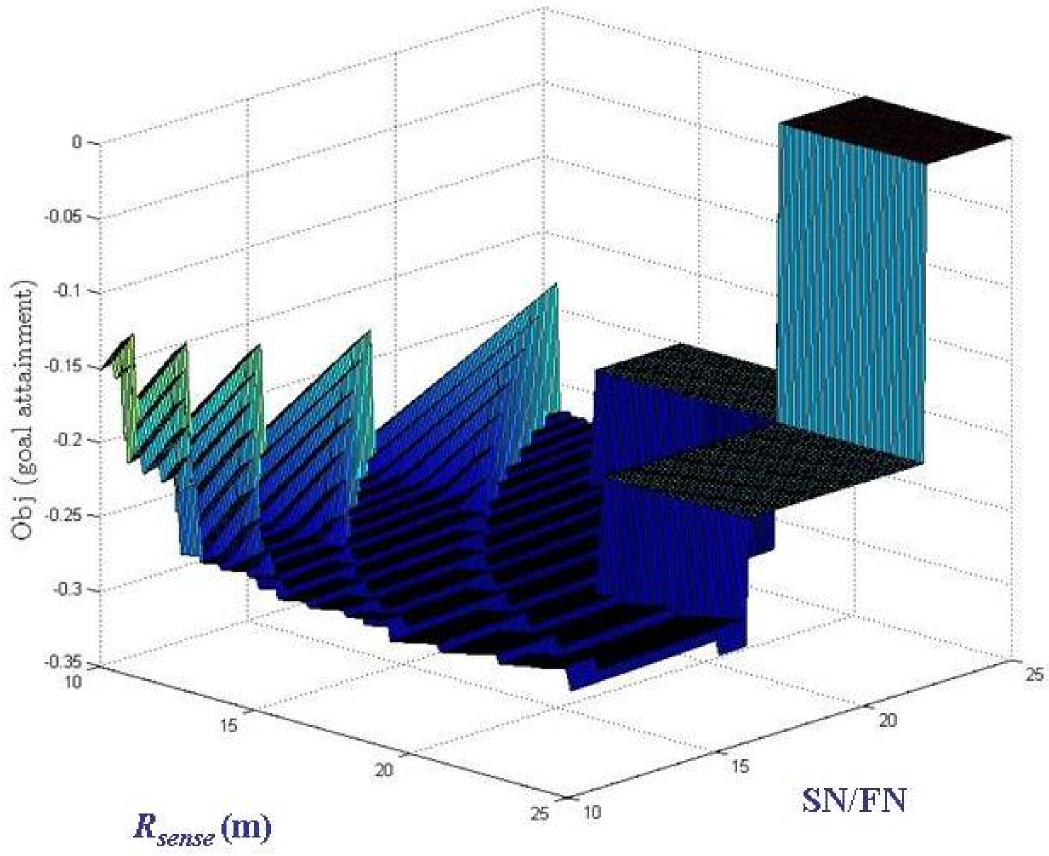

Figure 6: *Obj as a function of the sensor range and number of sensor nodes per fusion node.*

6 Optimization Results

For each length of the SASNet surveillance barrier, from 0.5 to 2.0 km, the minimization of the objective function determines the attainment of the sub-objectives and corresponding values of the four remaining decision variables. Figure 7 shows the minimum value of Obj as a function of the barrier length. A negative value for Obj indicates that all of the $Cost$, t_{deploy}, and $t_{latency}$ goals were attained. A positive value means that at least one of the goals was not attained. The figure also shows the attainment of the sub-objectives of Obj. For barrier lengths 0.8 km or less, $Cost$ is the sub-objective that limits Obj. For all longer barriers, except 1.1 km, the deployment time is the sub-objective with the maximum (i.e. worst) attainment value. All the sub-objective goals are met for barriers that are 1.0 km or shorter. For longer barriers, at least one of the sub-objective goals is not attained.

Figure 8 shows the optimal values of the decision variables as a function of barrier length. For barrier lengths of 0.7 km or more, the sensor range is close to the 25 m upper bound on this variable. This suggests that attainment of the sub-objectives (and objective function) might improve if the sensing range was relaxed, as long as the cost per sensor node, or the false alarm rate does not increase too much.

The communications range for the sensor nodes is also close to its upper bound for the barrier lengths that were investigated. Increasing the communications range would reduce $t_{latency}$ for SASNet at the expense of a greater cost per sensor node. Since Obj is not limited by $t_{latency}$(see Figure 7), an increase in communications range would not improve Obj unless t_{deploy} could also be reduced. Consequently, it is not worthwhile increasing the communications range of the sensor nodes beyond the assumed upper bound of 60 m.

The optimal value of SN/FN tends to increase as the barrier length increases. This is a result of the high cost per fusion node. As the barrier gets longer, more fusion nodes are required unless SN/FN increases. The maximum number of node hops increases as SN/FN increases, but, as already mentioned, $t_{latency}$ does not limit Obj, so the value of SN/FN does not significantly influence Obj (at least for barriers that are 1.0 km or longer; shorter barriers are limited by cost, so SN/FN does influence Obj here).

V_{SN} is very close to its lower bound for barriers that are longer than 1.0 km. This is a result of Obj being limited by the deployment time; the largest component of t_{deploy} is the time to emplace each sensor node. This time is significantly affected by the volume of the sensor nodes (see equation 14). This suggests that SASNet could be used for longer barriers if the time to deploy each sensor node could be reduced (by reducing V_{SN} or other means).

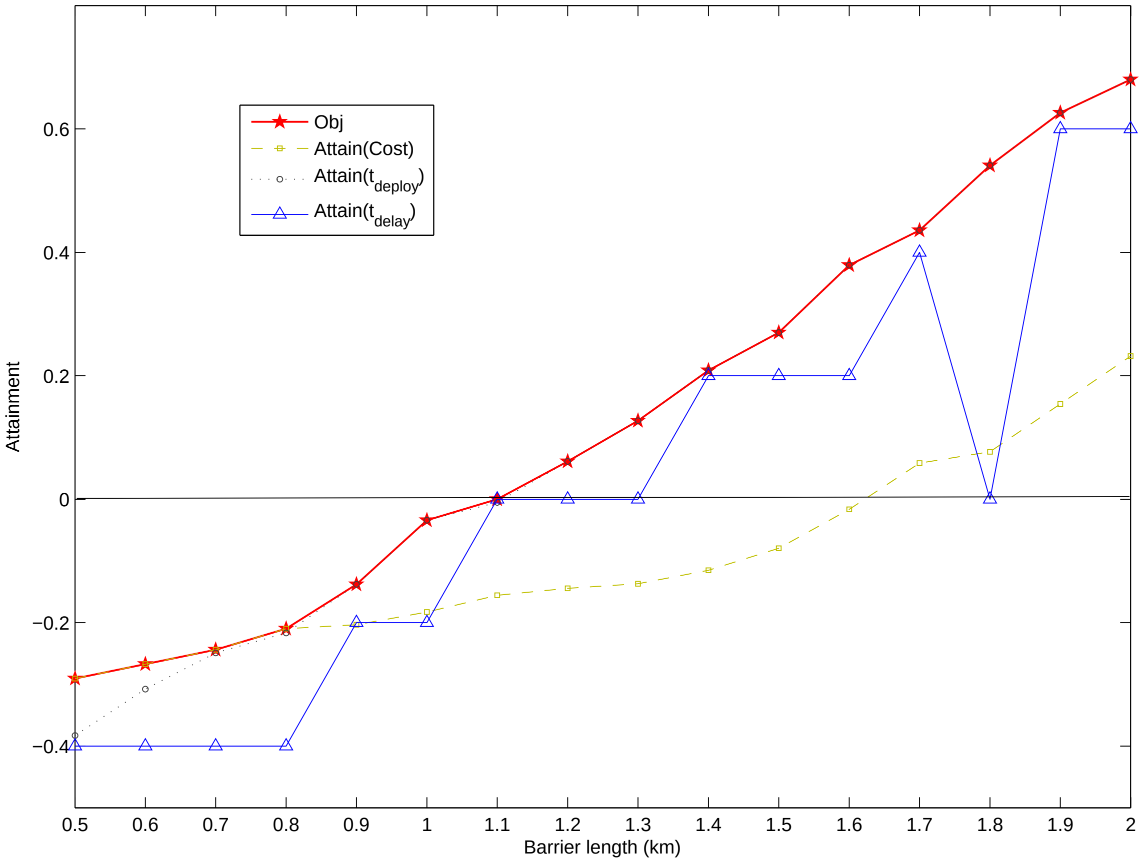

Figure 7: *Value of the objective function, Obj, and the attainment of the sub-objectives as a function of barrier length. Negative and 0.0 attainment values indicate that the sub-objectives were achieved. The Obj and Attain(Cost)lines overlap for 0.8 km and below. The Obj and Attain(t_{deploy}) lines overlap for longer lengths.*

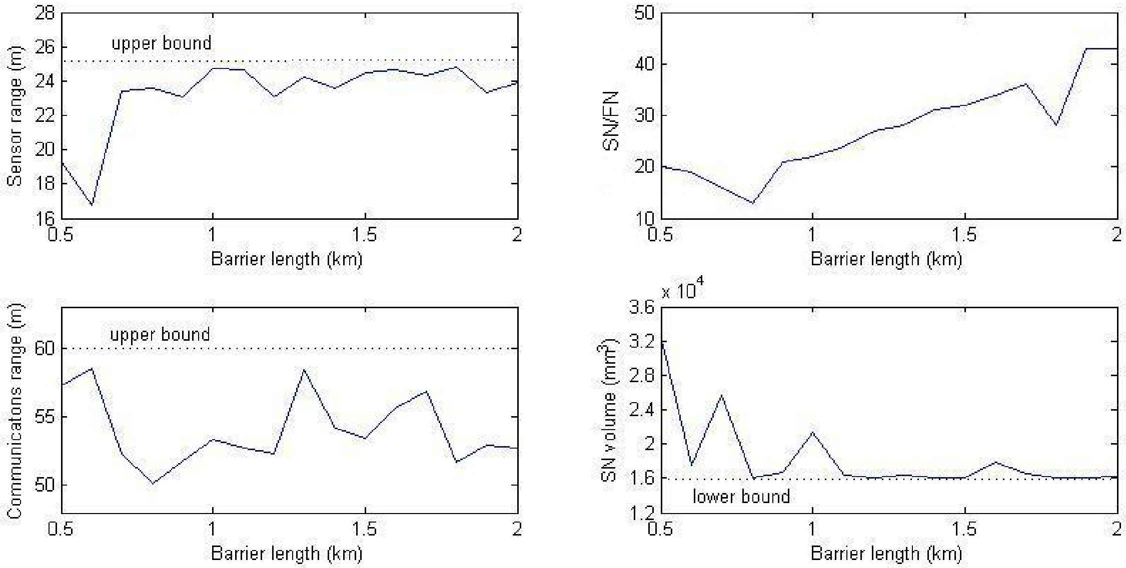

Figure 8: *Optimal values of the decision variables as a function of barrier length. The upper and lower bounds of the decision variables are indicated on the plots for the cases where the optimal values are close to the variable bounds. The bounds are estimates of the feasible ranges of variables.*

7 Recommended Future Work

The results presented in the previous section help to show how the design of SASNet can be optimized. However, many improvements to this work are possible. The main limitation of this study is that almost all of the data are notional. The relationships between the different variables in the model should be validated or improved. Once field trials with the real system have been conducted, more realistic performance numbers can be input into the MATLAB model of SASNet. This simulation study has been useful to identify key system parameters (e.g. P_d, R_{FA}, t_{hop}, t_{deploy}) that should be measured at the first trials near the end of 2008.

This study has assumed that the sensor nodes are deployed exactly where they are desired so that there are no sensing gaps between nodes. In reality, the spacing from node to node will vary. As a result, nodes will have to be spaced closer together to reduce the probability of gaps in the barrier. Future studies should include a random element to the placement of nodes; typical values for this random element can be determined from field trials of node deployment. Under more realistic conditions, it is valuable to know the probability that there are gaps in the barrier. Calculations like those presented in References [26] and [27] can be used to determine this probability. The localization of nodes will also be imperfect, so this additional uncertainty should be included in these calculations.

As mentioned in Section 4.4, the current models for cost are somewhat speculative. In order to improve these models, time must be spent gathering data on the relationship between cost and performance for the main components of SASNet. Once sufficient data are available for the cost models, the data can either (a) be fit with continuous functions that describe the relationship between cost and performance, or (b) be used as is to provide points in a discrete cost-performance model.

Although several sub-objectives were considered in this optimization, more can be added to the objective function. Power consumption is a very important consideration for wireless sensor networks, especially as they must function for long periods of time. The SASNet concept of operations calls for the network nodes to last at least two months in non-urban areas [13]. The probability of classifying a target correctly could also be added as a sub-objective. This study has assumed that classification is provided by images from the EO-IR camera and is always correct. Classification can also be performed by combining information from multiple sensor nodes. The probability to classify targets correctly depends on the quality of information obtained from the sensors and the manner in which the information from multiple sensors is analyzed. Time permitting, these and additional sub-objectives can be added to the SASNet model for more refined studies.

Additional decision variables can also be included in the SASNet model. While this study included decision variables related to the number and performance of the first-level sensor nodes, the performance of the fusion and second-level sensor nodes was not varied in the optimization. Variables that could be considered for these nodes include their performance (e.g. communications range, camera range, field-of-view), volume, weight and cost. If power consumption is included as an extra sub-objective for the optimization, then the duty cycle of the different sensors (fraction of time that a sensor is active) should also be included as a decision variable: the greater the duty cycle, the greater the power consumption, but the lower the probability of missing a target. The performance of the wireless network was also assumed to be perfect. In reality, packets can be lost due to bursts of traffic or unreliable wireless links [28, 29].

A greater number of inter-dependencies between system variables could also be included in the SASNet model. For example, there is currently no dependency between sensor range and false alarm rates. In reality, when the range of a sensor is increased, there is usually a correlated increase in the false alarm rate [18]. Adding this relationship to the model would increase its fidelity.

The optimization problem was set-up as a minimax, goal-attainment problem. This was very useful for optimizing SASNet's design for each barrier length; however, it provided only one "best" solution per length. An alternate approach would have been not to combine the multiple sub-objectives into a single objective function, but rather determine the Pareto frontier for the multiple objectives. This can be done with a variant of the simulated annealing algorithm [30]. This approach could be taken in future SASNet optimization work to provide the system designers with more information on the trade-offs between different variables.

Finally, this work considers only one scenario: early warning detection for a single type of target. SASNet can be used in a much larger number of scenarios with a variety of different targets; see Reference [13] for examples. The optimization could be done across many scenarios and targets so that the system design is optimized for a wider range of applications. To do this, the relative importance of different scenarios and targets will have to be determined by Army subject matter experts.

8 Conclusions and Recommendations

This study indicates that SASNet is suitable for early warning detection for barriers 1.0 km or less. SASNet's suitability for such long surveillance barriers is due to its low cost per node, ease of deployment, and multiple, complimentary sensors per node. Complimentary sensors are vital for achieving a high detection probability and low false alarm rate simultaneously. The maximum length of 1.0 km is shorter than the 1.5 km length requirement for an ongoing Army UGS acquisition project [14]; however, that project does not specify any cost or deployment time requirements. SASNet can meet the 1.5 km length requirement if its other sub-objectives for this study were relaxed.

Longer barriers are possible with SASNet if the assumptions made in this study are too conservative or if either the performance and cost goals, or constraints are relaxed. SASNet field trials will provide data that will test the accuracy of these assumptions. It is strongly recommended that *all* of the parameters that have been assumed for this study are measured.

Obtaining more data on the relationships between cost and various performance variables will improve the understanding of the trade-offs in the design of SASNet. Obtaining the relevant data may require significant work but it should prove valuable in the optimization of SASNet's design.

The simulated annealing algorithm used for the optimization portion of this study performed well. Once the temperature and cooling schedule parameters were appropriately tuned, the algorithm appeared to converge to the parameter space around the global minimum. The time to perform each optimization was also acceptable (less than one minute), so it is recommended that the same algorithm be used in future optimization work with SASNet.

Despite the paucity of real data, the SASNet model developed for this study should be useful in future simulation studies. The model can be updated with new data. Additional sub-objectives/performance goals (e.g. power consumption) can also be added to the model and simulated annealing optimization codes. For these reasons, we recommend that the MATLAB code developed for this study be re-used in future OR studies of SASNet. For example, this code could be expanded to simulate scenarios besides early warning detection: choke-point surveillance, monitoring a road-junction, and others.

The results of SASNet simulation and optimization studies should guide the development of the system over the course of the project. Doing so will ensure that the system is as effective as possible. Ultimately this should lead to a sensor network that achieves its objective of providing Canadian soldiers with effective remote surveillance.

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Annex A: SASNet model parameters

Table A.1: *SASNet model parameters.*

horizontal field of view for EO-IR camera	40^o
false alarm probability per sensor	1.0/hour
P_d per sensor	0.98
latency per hop	1.0 second
cost per relay node	\$ 300
cost per EO-IR camera	\$ 15000
cost per management node	\$ 5000
classification range of EO-IR camera	220
R_{comms} for fusion node	500
R_{comms} for relay node	1000
redundancy of fusion nodes	2
redundancy of relays	1
redundancy of EO-IR cameras	1
time to deploy fusion node	5 minutes
time to deploy e/o camera	5 minutes
time to deploy relay	5 minutes
mass of sensor	0.090 kg
mass of fusion node	0.200 kg
mass of EO-IR camera	0.800 kg
mass of relay	0.250 kg
volume of EO-IR camera	$156 \times 85 \times 75$ mm^3
volume of relay node	$160 \times 80 \times 40$ mm^3

List of Abbreviations

AOR	Area of Operation
CF	Canadian Forces
CONOPS	Concept of Operations
CORA	Centre for Operational Research and Analysis
COY	Company
CRC	Communications Research Centre
DND	Department of National Defence
DRDC	Defence Research and Development Canada
EO-IR	Electo-optical infra-red
FN	Fusion Node
GPS	Global Positioning System
N_{hit}	Number of sensors hits required for alarm
Obj	Objective Function
P_{fa}	Probability of false alarm for a sensor
PDA	Personal Digital Assistant
P_d	Probability of detection
P'_d	Modified probability of detection
P_{miss}	Probability of missed detection
R_{comms}	Sensor Node Communications Range
R_{sense}	Sensor Node Sensing Range
R_{FA}	False Alarm Rate
SASNet	Self-healing Autonomous Sensor Network
SN	Sensor Node
SN/FN	Sensor Nodes Per Fusion Node
t_{deploy}	Deployment Time
$t_{latency}$	Alarm Latency Time
UGS	Unattended Ground Sensors
V_{FN}	Fusion Node Volume
V_{SN}	Sensor Node Volume

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The Self-healing Autonomous Sensor Network (SASNet) Technology Demonstration project will demonstrate an ad-hoc wireless network of heterogenous, unattended ground sensors (UGS) that can be rapidly deployed to perform remote surveillance for the Canadian Army. In late 2008, the first of three annual SASNet trials will demonstrate the ability of the system to conduct early warning detection. This memorandum reports on a simulation study of the effectiveness and suitability of SASNet for this type of scenario. The key variables of the system that are investigated are (1) the probability of detecting targets crossing the instrumented barrier, (2) the rate of false alarms, (3) the delay between a target being detected and an alarm being received by an operator, (4) the time to deploy the system, and (5) the cost. These variables were optimized with a simulated annealing algorithm. The optimal values are investigated as a function of the length of the early warning barrier. Under the current assumptions of cost and performance for SASNet's components, it is shown that SASNet is suitable for early warning detection along barriers that are up to one kilometre in length. This is a significant improvement over the UGS that is currently used by the Canadian Army.

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ad-hoc network
sensors
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