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A Review of the Use of Computational Intelligence in the Design of Military Surveillance Networks

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Abstract. This chapter is a review of how computational intelligence methods have been used to help design various types of sensor networks. We examine wireless sensor networks, fixed sensor networks, mobile ad-hoc networks and cellular networks. The goal of this review is to describe the state of the art in using computational intelligence methods for sensor network design, to identify current research challenges and suggest possible future research directions.

Keywords: sensor network; surveillance; wireless sensor network; MANET; cellular network; computational intelligence; evolutionary optimization; fuzzy logic; neural networks

1 Introduction

A key challenge in military operations is the ability to carry out intelligence, surveillance and reconnaissance (ISR). ISR can be achieved from fixed assets such as long range radars or surveillance cameras, or moving assets such as aircraft, satellites or unmanned aerial vehicles (UAVs), or a combination of both. There is a large variety of sensors enabling the creation of sophisticated systems of systems (where the lower-level system is each sensor) such as sensor networks (SNs). In general, an SN is a network of nodes which allows the monitoring of the environment via each node's one or more sensors. Sensors perceive their environment via a variety of sensors from video cameras to motion sensors to various radars.

SNs such as wireless sensors networks (WSNs) [1,2], Mobile Ad-hoc Networks (MANETs) [3,4] and cellular networks (CNs) [5] have been extensively studied in the open literature. Fixed sensor networks (FSNs) have not been studied to a great degree, given their primary military application domain. WSNs, MANETs and FSNs are critical for military ISR. Given some similarities between CNs and FSNs, we will also examine relevant CN research.

Enabling technologies are important in devising and managing sensor networks. A recurring theme in sensor network research is how to obtain the best overall situation awareness (SA) or picture from a variety of surveillance systems working cooperatively. SA may be improved by ensuring that sensor resolution is appropriate to the intended target type by scheduling different sensors to provide complimentary cover-

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age (notably by using data from one sensor to queue another) or by maximizing the size of the area covered by the sensor network.

For WSNs, given each sensor node's limited size, another important consideration is sensor power optimization. Computational intelligence (CI) methods are used in a variety of these sensor technologies, sensor coordinating technologies and systems of systems analyses [6]. Operations research and analysis has been used in the systems of systems analysis of sensor networks such as sensor placement, number of sensors, type of sensors, energy-aware protocols, power efficiency and optimization in sensor networks, network topology control, as well as sensor-embedded efficient clustering-based algorithms for data aggregation, and routing [7,8,9,10,11,12]. This chapter will summarize the state of the art in the use of computational intelligence to carry out operational analysis of SNs and will illustrate the importance of this work in the military and security domains. This survey will also summarize the types of problems studied and identify research gaps by suggesting new research directions.

This chapter is organized in the following manner. In Section 2, we will provide a general overview of the field and define most terms. In Section 3, we will discuss WSNs given that they distinguish themselves from other networks by their need to conserve battery power. Section 4 will summarize Large Sensor Networks (LSNs) which will group three similar groups of sensor networks: FSNs (e.g., the North Warning System in Canada and the United States), CNs (e.g., AT&T's cellular network in the United States) and MANETs (e.g., Survivable, Adaptive Networks known as SURAN initiated by the Defense Advanced Research Projects Agency - DARPA [13]). Section 5 will discuss linkages between SNs and common research challenges. Section 6 will conclude this chapter.

2 General Overview of Sensor Networks

In this section, we will discuss SN categorization, as well as define the common terms used in the paper.

2.1 Types of Networks

First, we will define and discuss several different sensor network types. The sensor networks we will examine include WSNs, FSNs, MANETs, and CNs.

Wireless Sensor Networks consist of a large number of miniaturized electronic devices equipped with wireless communication capabilities and processing power. These small devices, namely sensor nodes, can sense, actuate, process information, communicate among themselves thus providing significantly a higher sensing capability compared to each individual sensor node. Individual sensor nodes are generally equipped with non-rechargeable batteries and are considered expendable i.e., sensor nodes are typically not recovered when their batteries are depleted. A WSN usually needs one or more data sink nodes which are powerful transmission nodes with high computational power and energy resources, enabling them to reach a destination node or base station. These sink nodes could be mobile depending on the specific application. Taking into account the scarce energy resources of typical sensor nodes, a major WSN challenge is the requirement to extend the network lifetime by exploiting energy-aware design principles and power optimization schemes.

Fixed sensors are the surveillance and reconnaissance assets most common to military operations which operate over large distances (from kilometers to thousands of kilometers). These include any stationary sensor, such as primary radar installations. We also include satellite based sensors in this category. Even though these sensors are in motion, their trajectory cannot be altered as part of normal sensing operations. This results in repeated coverage pattern analogous to a very large, though slowly repeating, fixed sensor. When several of these sensor nodes are used together to provide improved SA, they become a Fixed Sensor Network.

Mobile Ad-hoc Networks are dynamic, self-configurable and highly adaptive multi-node networks equipped with mobile devices connected by wireless links. MANETs are rapidly deployable, autonomous networks, which do not require a fixed infrastructure. Mobile nodes are free to move independently in any direction over large areas. Thus, they can be deployed and used in remote areas (e.g., to help with disaster relief), and battlefields of various sizes. FSNs and MANETs can be considered large networks as compared to WSNs. Thus, LSNs will encompass FSNs and MANETs.

CNs can also be considered LSNs due to many similarities they share with FSNs. CNs are made up of linked cellular base stations. Cellular telephones connect wirelessly to cellular base stations, which are in turn connected to a larger telephone network (of wired and cellular telephones). Each base station has a range from one to ten kilometers depending on its location, and the network of base stations in aggregate provides coverage of an entire service area. While our focus is on surveillance rather than communications networks, the CN coverage problem is similar and, therefore, a review of the methods used to address this problem in the cellular industry will be carried out highlighting salient points relevant to LSNs.

The foremost metric by which sensors, sensor networks, or cellular networks are measured is network coverage. Three types of coverage will be studied [14]: blanket, barrier and sweep. Blanket coverage is the total surface area covered and is constant in time as long as all sensors remain functional. Ideally blanket coverage would encompass the entire area of interest (AOI). Barrier coverage is obtained by a line of sensors with some amount of overlap such that a target is not able to pass through the line undetected. The North Warning System (NWS) [15] is an example of an FSN which provides barrier coverage. Sweep coverage begins with barrier coverage but moves the barrier across an AOI over time, resulting in a total area covered that is akin to blanket coverage. An example could be a MANET helping in search and rescue; i.e., the search starts at the last known location of a missing plane and then expands in various directions in a sweeping action. Blanket coverage is the easiest form of coverage to measure as it is simply the total surface area within range of the SN.

Fig. 1 illustrates a few common examples of sensor network types useful in the military and security domain. **Fig. 1**a shows the barrier coverage provided by the NWS. The figure shows the area covered by the NWS radars based on publicly available radar locations [15] and ranges [16, 17].

Fig. 1b represents one example of a WSN: AOI covered by pan-tilt-zoom (PTZ) cameras that have a limited range. Cameras may detect activity in the AOI depending on the target size and type, given a rotatable restricted field of view for each camera [18]. In this figure, each camera has a "zoomed out" and "zoomed in" range represented by the inner and outer circles respectively. The zoomed out instantaneous field of view (FOV) is shown in blue and the zoomed in FOV in red. These sensors are attempting to provide blanket coverage, although some gaps in coverage are visible, and only a small portion of the AOI is covered at any given time. Sensors are often modelled as unchanging circular projections on a two dimensional map. This approximation does not necessarily hold (depending on the application) for sensors similar to a PTZ which have a FOV that is non-circular and moveable in three dimensions.

Fig. 1c illustrates another WSN example: small wireless magnetic sensors spread along a dirt road and used for vehicle detection [19]. This WSN essentially provides blanket coverage of the road; however, assuming the target is travelling on the road from one direction or the other, this WSN can also be seen as a series of barriers. In this case fairly large coverage gaps could be allowed while still being able to detect a truck passing through. In contrast, a set of PTZ cameras intended to detect a person on city streets (e.g., in London, United Kingdom) would have to be able to cover a very large portion of a potentially large AOI.

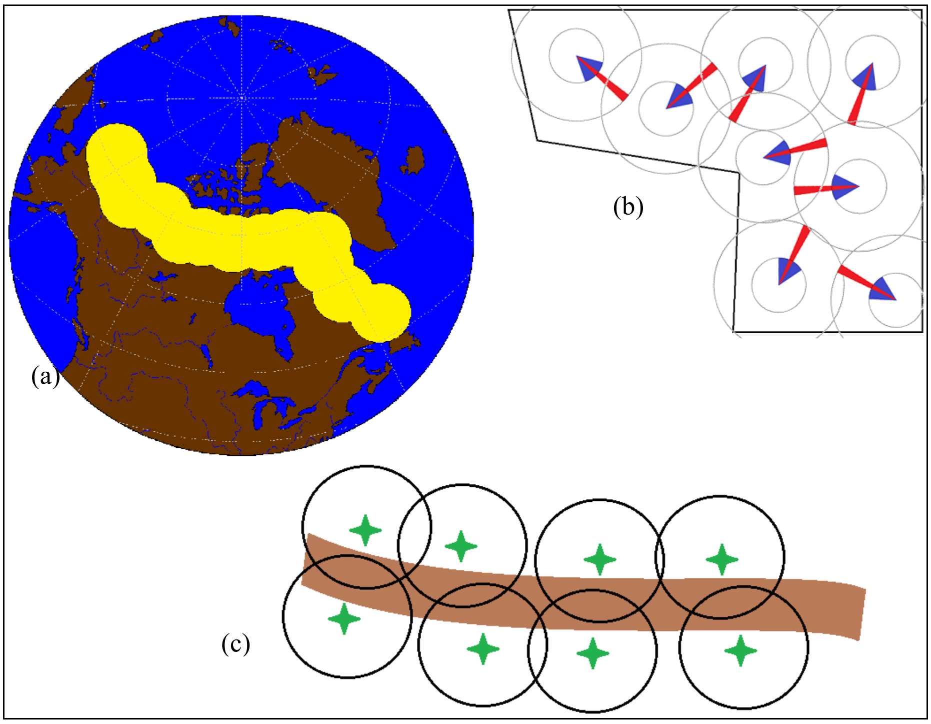


Fig. 1. A few examples of sensor networks with military and security applications

2.2 Network Characteristics

In this section, we will discuss SN characteristics and the importance of each in analysis. **Table 1** summarizes the characteristics of studied sensor networks by extending Table 1 from [2] and adopting most of their terminology. We subdivide sensor networks into WSNs, FSNs, CNs and MANETs.

Table 1. Network characteristics (modelled on Table 1 in [2])

		WSN	**Fixed Nets**	**Cell Nets**	**MANETs**
Sensors and base stations	**Size**	small	medium to large	medium	medium
	Spatial coverage	dense	sparse	sparse	sparse or dense
	Number	large	small	large	various
	Type	passive and active	passive and active	active	passive and active
	Mix	heterogeneous or homogeneous	heterogeneous or homogeneous	homogeneous	heterogeneous
	Deployment	random, ad-hoc or fixed / planned	fixed / planned	fixed / planned	ad-hoc
	Dynamics	stationary or mobile	stationary or mobile	stationary	mobile
Entities of interest	**Extent**	distributed or localized	distributed or localized	localized	distributed or localized
	Nature	cooperative or non-cooperative	cooperative or non-cooperative	cooperative	cooperative or non-cooperative
	Mobility	static or dynamic	mostly dynamic	dynamic	dynamic
Operating environment	**Threat level**	low to high	low to high	low	low to high
	Size of area	small	medium to large	large	large
Communication	**Networking**	wireless	wired	wired	wireless
	Bandwidth	low	high	high	high
Processing architecture		distributed or hybrid	centralized	hybrid	distributed or hybrid
Energy available		constrained	unconstrained	unconstrained	partially constrained

Table 1 first examines the sensor and base station characteristics. Miniaturization is a key technology enabling WSNs: sensor size is on the order of centimeters or smaller [2,20,21]. Cellular base stations are antennae or groups of antennae positioned on top of a cell tower or a building, while large sensors vary in size from a handheld camera to an antenna array the size of a large field [22]. WSNs compensate for their small size (and accordingly limited power) by being deployed in large numbers (typically hundreds or thousands [23]) over a relatively small area (up to a few city blocks). Fixed sensor networks are typically made up of sensors that were designed to be used individually to cover a large area (up to thousands of square kilometers). Cellular networks cover entire countries and the number of base stations required to do so is consequently large, even though the range of individual stations can be relatively large (on the order of tens of square kilometers). Passive sensors, such as cameras, only receive information while active sensors, such as radars, send out a pulse and wait for a return. Heterogeneous networks are made up of multiple types of sensors ideally providing complementary information. The ad-hoc nature of MANETs leads them to be heterogeneous and cellular base stations must be homogeneous to communicate with phones i.e., use the same communication protocols. The mix of sensors in WSNs and LSNs depends on the application type. Fixed sensor nodes and cellular base stations are always placed at predetermined locations, while MANET nodes may be located anywhere given that they are mobile [24,25]. WSN node locations may be predetermined but the nodes are typically deployed in a large group and often spread out randomly [1]. Once deployed, MANET nodes remain mobile, while cellular bases stations are fixed. WSN nodes are sometimes capable of autonomous movement, limited by their power supply. Other WSN nodes may be stationary or may be transported by the medium they are embedded in. Fixed sensor nodes are typically stationary but may be moved between uses [26], or in some cases, as part of their use (such as synthetic aperture radar [27]). Satellite or air-based sensors begin to blur the line between fixed sensor networks and MANETs as they are collecting data while in motion, though their movements are planned.

Sensor networks may be used to study entities that are distributed (weather) or localized (individuals), cooperative or not. Cellular nodes are the exception as they make contact with individual phones that want to be connected. Similarly sensor networks may be used in low or high threat environments i.e., from cities in countries at peace to battlefields. Cellular networks do exist in conflict zones where they may be attacked, but they are not designed to withstand an attack. Most targets of interest for each network are most likely mobile although WSNs may be embedded in an entity to monitor changes in that entity.

Communication refers to the link between the individual sensor and its network. For cellular networks the communication is between base stations and the communication backbone, which is wired, as opposed to the wireless communications it enables. WSNs and MANETs rely on wireless communications as part of their operations [24]. FSNs are typically wired, though wireless communication (e.g., via satellites) may be part of the chain.

Large fixed sensors typically send their data to some central repository for processing. Cellular base stations do some of the processing, but rely on the network switching subsystem to make a connection. In the case of WSNs and MANETs, at least some of the processing is expected to take place at the nodes though it may be distributed.

Fixed sensors and cellular base stations have either their own power sources or use power from an electric grid ensuring continuous operation. WSN nodes are usually powered by small batteries that have a limited lifetime. MANET sensors are powered by the platform that carries them, which typically needs to be refuelled periodically; therefore, energy-awareness is important although it is not a primary concern as it is in WSNs [21,28].

2.3 Discussion

While the focus of the remainder of this paper will be on the research carried out in each of the network categories, this section will provide the overall context by discussing linkages across the various network types. We will also provide a summary of numerous CI techniques that have been applied to each network type. The goal is to highlight similarities and differences between SN types.

Sensor networks are often treated as synonymous with WSNs. WSNs are an emerging technology that is receiving much attention in research and development. On the other hand, the concept of large-scale sensors, such as networks of radar stations is difficult to find in the literature despite being a well-known problem in defence and security domains.

For example, Kulkarni et al. [6] identifies four challenges faced by WSNs: (1) the wireless ad-hoc nature of the network, (2) mobility and changes in network topology, (3) energy limitations of nodes, and (4) physical node distribution. Of these, only the last is a common concern of fixed large-scale sensor networks. On the other hand, MANETs and WSNs share many challenges except that MANETs cover much larger areas. Consistent with the third WSN challenge, a common goal with MANETs is to minimize the energy consumed, often by minimizing the movement of mobile sensors or, in the case of small nodes, improving the data communications efficiency, in order to extend the lifetime of the network. This is not a significant concern for FSNs. Instead, FSNs generally look to maximize the coverage area while minimizing installation and operations costs [29,30]. These are the same objectives generally faced by cellular networks. In situations where all sensors (or cellular base stations) are identical, the number of stations is used as a proxy for cost [31,32,33,34]. The general relationships between these different types of networks are summarized in **Fig. 2**.

Table 2 summarizes how various optimization methods have been applied to different sensor network applications in the literature, while **Table 3** examines the optimization objectives that have been addressed with these methods. The numbers in these tables correspond to the references at the end of this chapter. Optimization methods include CI methods such as genetic algorithms (GA), multi-objective GAs, Swarm Intelligence (including Ant Colony Optimization and Particle Swarm Optimization), other heuristics such as tabu search as well as non-CI methods such as greedy algorithms or linear programming. In all cases where coverage is being used as an objective, it is blanket coverage (as defined in [14]) that is being measured.

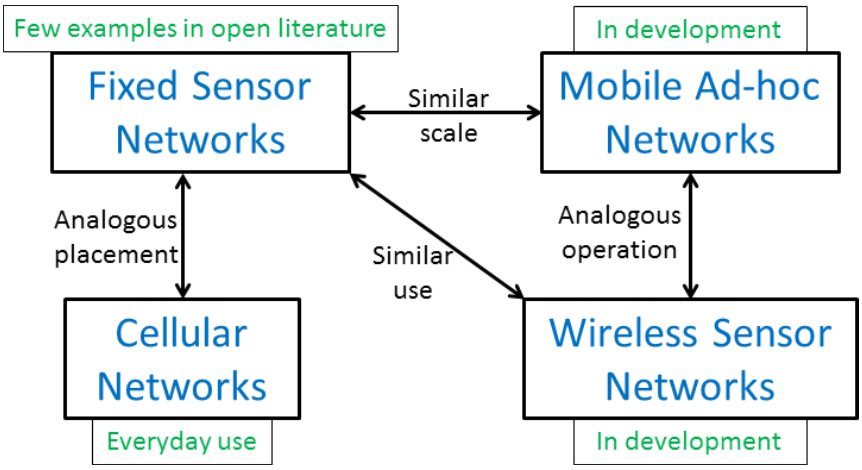


Fig. 2. Network relationships

There are several ways in which the competing objectives of maximum coverage and minimum cost are reconciled. Some studies use multiobjective optimization, resulting in a Pareto front of solutions [5,30,31,35]. Others assign weights to create a combined objective function [34,36,37]. Several studies also treat one or the other as a constraint, either fixing the number of sensors (and thus the cost) and determining the maximum area coverage [30,38,39,40,41,42], or fixing a minimum allowed coverage and determining the required number of sensors [29,33].

Sensor locations are generally dealt with in one of three ways. The most restrictive is to allow sensors to be placed at predetermined locations, which may be appropriate when the sensors require some pre-existing infrastructure or specific terrain (e.g., FSNs and CNs). The most general is to allow sensors to appear at any location within the area of interest. When location is treated as a continuous variable, we refer to this case as a high-resolution grid. For the intermediate case, a low-resolution grid, sensors could be placed at the vertices of a grid with a finite number of points.

Various CI and data modelling methods are grouped in **Fig. 3** based on the type of network they were used for. This diagram also identifies in red how sensor and base station locations were handled. In addition, many studies use methods to deal with conflicting objectives like multiobjective optimization (to create Pareto fronts of non-dominated solutions) and single-objective optimization with a weighted sum of several objectives. These two options are shown in green.

Table 2. Methods and applications

		Method							
		Genetic algorithm	Greedy algorithm	Fuzzy logic	Potential field / virtual forces	Linear Programming	Neural Network	Swarm Intelligence	Other
Application	Intrusion detection						72		19,57, 104
	Open Area (Volume) Surveillance	5,30, 31,36	32	38,86, 96	42	29		86	55,86, 97,98
	Confined Area Surveillance		40		41				18
	Target of Interest Surveillance / Tracking			71			99		18,42, 55,57, 85,103, 104
	Data Analysis	84							98,101, 102
	Data Aggregation								11,12
	Cell Base Station Placement	34,35	33						37
	Other		39,100	82					54,76

3 Wireless Sensor Networks

3.1 Background

The emergence of WSNs is a result of the development of small-size embedded microcomputer-based systems, which support a wide range of sensors. WSNs use a large number of small, inexpensive sensors instead of a smaller number of powerful sensors. As shown in **Fig. 4**, the main components of a wireless sensor node are: the sensor, embedded controller, memory unit, communication device and power supply. Sensing, actuating, communicating and processing capabilities of sensor nodes enable their capabilities to self-organize and communicate in the deployed areas. The low cost, miniaturized size and easy deployment, makes sensor nodes attractive for use in military applications with versatile requirements. Different sensor node architectures can be chosen based on the application requirements. Several comprehensive overviews of the research in the field have been written [1,20,21,43,44].

Table 3. Methods and objectives

		Method							
		Genetic algorithm	Greedy algorithm	Fuzzy logic	Potential field / virtual forces	Linear Programming	Neural Network	Swarm Intelligence	Other
Objective	Coverage / People Served	5,30, 31,34, 35,36	32,33, 39,40	38,82, 86,96	41,42	29,39		86	37,81, 86,97
	Cost / Number of Nodes	30,31, 34,35	32,33		41,42	29			37,56
	Transmission Energy	5		86				81,86	8,9,12, 28,51,52
	Movement Energy	36		38					
	Sensor Energy ("on" time)								19,47, 51,97
	Other	31	40,100	71,82, 96			72	81	11,19, 54,85

Some key points are that each sensor node, in addition to its sensing capability, has limited processing and data transmission capabilities. However, they are mainly deployed in large numbers, thus their computational load can be shared across all or a subset of nodes to save energy resources and extend the lifetime of the WSN. An example of effective use and conservation of the nodes’ energy is to organize neighbouring sensor nodes into local clusters using a technique such as the Low-Energy Adaptive Clustering Hierarchy (LEACH) proposed by Heinzelman et al. [9], where each cluster is assigned to a cluster head. The cluster head gathers the sensed data from its cluster members and performs data processing and aggregation prior to transmission of the data to the sink node. Moreover, the cluster head role can be rotated between cluster nodes thus ensuring that the energy load is distributed evenly.

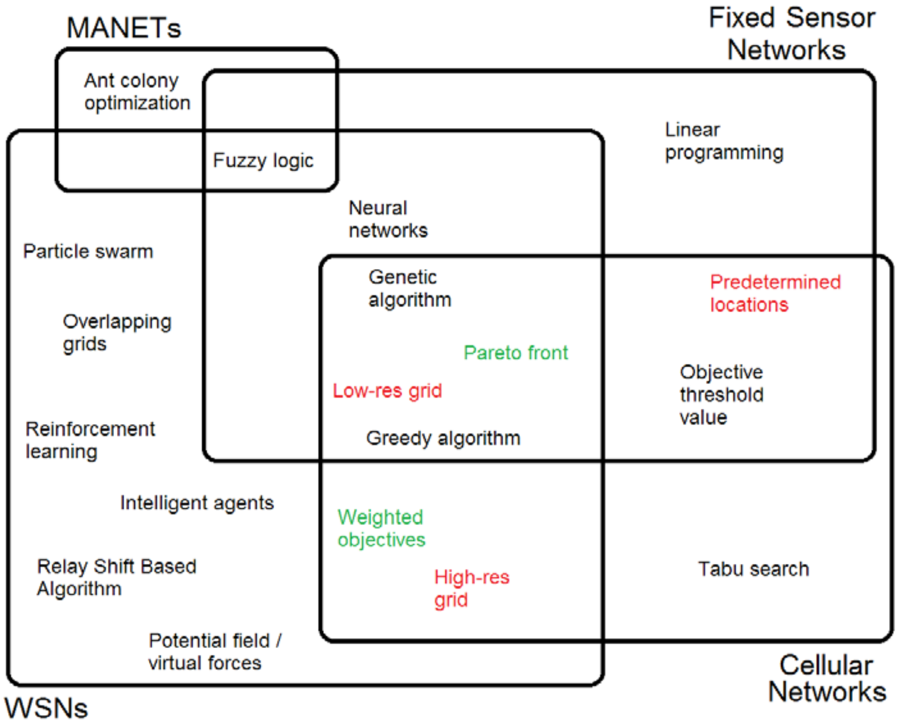


Fig. 3. Recurring themes across network types

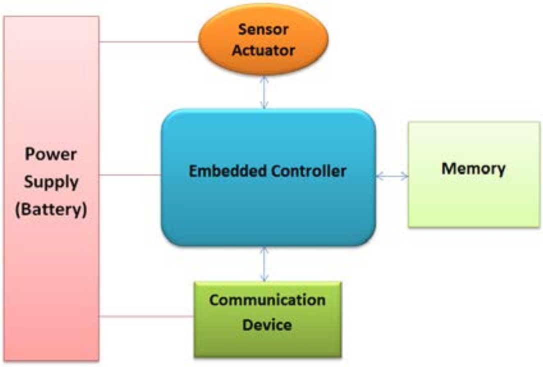


Fig. 4. Sensor Node Architecture

Individual sensor nodes can be considered expendable: the nature of wireless nodes requires them to be battery powered and when the battery dies, nodes are typically assumed to be irrecoverable [45]. The energy efficiency, which is closely related to the lifetime of the WSN, is one of the main constraints in the design of sensor nodes [46]. Thus, conserving battery life by minimizing the amount of work done by each node becomes a priority. Military applications may be data intensive and/or require WSNs to be deployed over large timeframes, thus making energy efficiency an important design characteristic. Energy-efficient topology control algorithms, data aggregation, routing, schedule-based protocols, sensor modes of operation (e.g., active, idle, sleep) can be all used to extend sensor network operation [47]. Furthermore, a WSN also has to be tolerant to the loss of individual sensors by exploiting redundant deployment of nodes, and/or use of a handoff mechanism, which enables the transfer of services to healthy neighbourhood sensor nodes to restore and maintain the connectivity of a failed link to a sink or destination node [48]. The Quality of Service (QoS) attributes of WSNs such as event detection, delay (latency of a sensor response), bandwidth (limited number of channels and data rate transmission capabilities typically in ranges of 250 kbit/sec or less), etc. differ based on the choice of hardware/software platform for specific WSN applications [20,49,50]; however, they are important factors to be considered during the WSN design and deployment stages.

The scalability of WSN architectures and protocols based on the number of sensors deployed is another important aspect to be considered, especially for military applications given the necessity to deploy WSNs in settings from small villages to large battlefields. Based on WSN application requirements, the densities of sensors in specific deployed areas might be non-homogeneous, and the network should be able to adapt to such changes in configuration. Moreover, as WSN dynamics change due to the depletion of energy resources of individual sensor nodes or different assigned tasks, the network must still be able to self-configure, adapt and remain operational [51,52].

3.2 Defence and security applications

Arampatzis et al. [23] provide a survey of WSN applications including a section on military applications where the areas of interest are not limited to information collection only, but also include enemy tracking, battlefield surveillance and target classification via networks consisting of sensor nodes equipped with seismic and acoustic sensing capabilities. He et al. [19] tackle an important aspect of WSN use in surveillance missions, where the sensors are deployed in large numbers with the ability to detect and track vehicles in a region of interest (1) in an energy-efficient manner, where only a subset of sensors nodes are active and monitoring at any one time, while the rest are in low power mode, and (2) in a stealthy manner, where the sensor network has a low probability of being detected given that sensors use minimal communications in the absence of events. Thus, by considering a trade-off between energy consumption and surveillance performance as a system design parameter, the sensor network is highly functional and long lasting while being adaptable to changes.

Đurišić et al. [53] examines some WSN military applications ranging in scale from sensors deployed across a large area such as a battlefield to detect infrared, chemical, or acoustic signatures, to multi-sensor systems used for perimeter protection to sensor networks worn by soldiers to monitor their vital functions. Liu et al. [54] test their Simulator for Wireless Ad-hoc Networks against a scenario depicting chemical agent dispersal in an urban area. Although their chemical plume dispersion model has been simplified, it still illustrates the importance of networked chemical detection sensors.

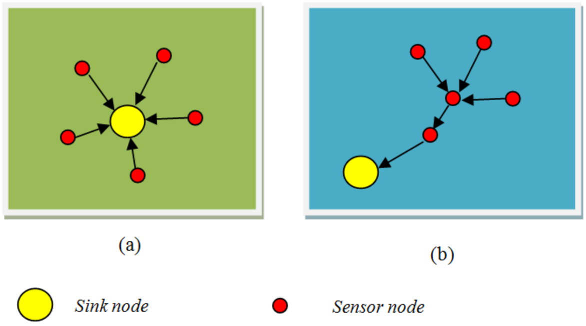
Afolabi et al. [55] discuss viable options in combining different advanced technologies, such as UAVs and wireless sensing devices to enhance surveillance capabilities. The cooperation and integration of UAVs in a WSN improves the performance of surveillance missions by using an efficient deployment of sensor nodes; where the maximum coverage is attempted with the least possible number of nodes via equilateral triangulation (this type of grid has the smallest overlapping area as compared to grids based on squares or hexagons) [56]. Thus, the addition of UAVs may provide a relatively inexpensive surveillance solution when linked with deployed sensor nodes to cover a specific region of interest.

Song et al. [57] analyze the performance of Passive Infrared (PIR) sensors and their use as WSNs for surveillance systems. For example, these systems can be used for tracking intruders by detecting the movement of the temperature gradient between the warm person and their cooler surroundings. Processing data from PIR sensors is efficient with an output as simple as “nothing detected” or “movement detected” compared to a vision-based device, which would require a larger onboard memory and computational power due to more complex data processing required for image processing.

Finally, sensor networks can be used in conjunction with UAVs in applications such as collaborative surveillance missions (e.g., to aid military troops during combat operations) including the detection and tracking of enemy forces or the detection of hazardous biological, chemical, and/or explosive vapor [58]. Naturally, this merging of UAVs and WSNs leads to the necessity of studying how WSNs and MANETs (discussed in Section 4.3) could interact and the research challenges this would bring. This topic will be discussed in more detail in Section 5.

3.3 Review of Methods and Applications

A common goal for WSNs is to maximize the lifetime of the network, while meeting the application requirements. In particular, energy-aware design to ensure the prolonged life of surveillance missions should be of interest in WSN design [19]. While efficient network topology control [9] exploits the redundant deployment of sensor nodes, it restricts the set of nodes which are considered neighbors of a given node to overcome the energy limitations; hence, minimizing the number of retransmissions required to deliver data to the receiver (by only a few selected nodes). Similarly, sensor nodes communicate with a sink node (or base station) via multi-hop paths, thus in-network processing is also used to reduce the amount of data sent (thus reducing overhead) throughout the network [1,51].


(a)

(b)

Fig. 5. Data aggregation: (a) radial configuration, (b) feasible configuration

The reduced overhead is achieved by lowering the number of messages forwarded throughout the network by applying data aggregation principles within sensor nodes. Benefits of data aggregation depend on the sensor nodes' configuration. If the sensors are configured in a radial configuration as shown in **Fig. 5**a where all the sensor nodes are one hop away from the sink, data aggregation is not beneficial. However, in the case shown in **Fig. 5**b, where the sensor nodes are more than one hop away from the sink, data aggregation at intermediate nodes leads to lower message overhead.

For WSNs, the choice of sensor node configuration, i.e. flat versus hierarchical, depends on the application and the size of the deployed network. In flat networks all nodes are considered equal and the main emphasis of network topology is power usage control. However, the scalability of a network due to non-homogeneity remains a concern. In hierarchical networks, the emphasis is on the backbone or cluster connected topology, which takes advantage of heterogeneity and aids in constructing a self-organizing network. A large-scale WSN deployment, in the case of battlefield and/or long-term missions would need to take into account the energy-awareness of a network, thus most likely utilizing hierarchical network topology.

The overall network coverage and energy efficiency depends on many factors including the existence of powerful mobile or fixed nodes (with lasting energy resources, a powerful processing core and transmission range) acting as intermediate nodes within a deployed sensor network. As an example, if energy constrained nodes transmit at longer distances frequently, the sensors' energy resources will be quickly depleted leading to node failures and sensor network lifetime reduction. However, if the role of transmission is taken by powerful nodes with considerable (or rechargeable) energy resources, prolonged operation of a network is possible. This is one of the reasons why node-based local clustering, data aggregation and in-network processing would be important for a viable and long lasting WSN [9,59].

Jourdan and de Weck [5] aim to maximize the total sensor coverage, as well as the lifetime of the network. This was done by randomly deploying the available sensors to create individuals in a Multi-objective Genetic Algorithm (MOGA). This is one of the rare cases of truly optimizing across multiple objectives; in fact addressing this gap is stated as part of their motivation. To measure network lifetime, they assumed that each sensor sends its data to a primary receiver once for each "sensing cycle." However due to multi-hoping, sensors may need to relay data other than their own. Each of these transmissions depletes some of the sensor's energy. The lifetime of the network is determined by the number of sensing cycles before any one sensor's energy is completely depleted. They concluded that a network of sensors whose communications range is more than double their sensing range is most efficient in a cluster configuration. A cluster allows multiple paths from any sensor in the cluster to the sink node. Otherwise, a hub and spoke configuration is more efficient.

Other studies [36,38] aim to maximize sensor coverage while minimizing the movement of sensors (and thus the energy expenditure) after an initial random deployment. A weighting factor is used by Jiang et al. [36] to treat both objectives as one, while fuzzy logic [38] allows a move if the coverage state is improved, and sometimes allows a move if the coverage state is to remain the same. GA calculations are done at the nodes based on information exchanged with neighbours [36]. As processing consumes less energy than communications, this method is more energy efficient than having all nodes report their locations to a central processor which would then determine the new locations and send them back to the nodes.

Osmani et al. [38] also measure the resulting "message complexity," which is the number of messages exchanged; however, they don't treat it as an objective to be optimized by the algorithm. Minimizing the movement of wireless sensors is an important military objective given that battery power is at a premium. Deployed WSNs should thus try to adjust their position only when there is a higher likelihood of obtaining more information by moving than by staying in the current position (e.g., based on analysis of previously sensed data).

Liu et al. [54] provide a scalable framework for the simulation of sensor networks, and its use for studying the performance of routing algorithms. In this case, the authors were not attempting to optimize the network, but rather to demonstrate that their simulator for wireless ad-hoc networks (SWAN) could be used to measure network capacity and performance of routing algorithms in sensor networks. Calculating the coverage of the network is outside of their scope; however, it should be a concern in the initial network layout. Their simulation environment allows proposed network configurations to be tested before being deployed. This way when a WSN is later implemented, it can use the most efficient configuration to route data to the sink.

Howard et al. [41] and Zou and Chakrabarty [42] simulate virtual forces (or potential fields) acting on the sensors, pushing them to spread out. Howard et al. [41] use a friction force to prevent the nodes from spreading out indefinitely, while Zou and Chakrabarty [42] apply a repelling force between nodes within some threshold distance and an attraction force between nodes outside some larger threshold distance.

The incremental development algorithm [40] addresses the issue of WSN coverage area; however, it assumes that the sensor nodes are deployed one at a time, which might not be a feasible solution in case of military applications (e.g., for large-scale deployment of thousands of nodes).

3.4 Research challenges

WSNs place a premium on energy efficiency with transceiver and processor being the main energy consuming blocks. Energy scavenging utilizing solar cells, vibration and/or other alternative means to recharge sensor's battery needs to be considered since it may change network design. In certain applications, the number of nodes could be reduced given that fewer nodes might be assumed to have their batteries depleted. Minimizing the unnecessary transmission (and reception) of data and processing performed by sensor nodes is essential due to the limited energy resources.

Secure messaging is required due to the threat of cyber-attacks on military surveillance systems. This issue is not discussed often in the WSN literature. However, it needs to be addressed in particular where the security breach in the network might cause casualties of friendly military troops on the battlefield. Butun et al. [60] elaborates on Intrusion Detection Systems (IDS) initiatives in addressing future WSN security concerns such as jamming, flooding attacks, eavesdropping, etc. which might degrade and incapacitate WSNs. However, due to the limited energy resources and computational capabilities of WSN nodes, access control techniques used for traditional wired and/or wireless network security do not apply [61]. The use of existing or new CI techniques to detect security threats to WSNs would pose a challenge especially when considered in conjunction with scarce energy resources of sensor nodes. Thus, there should be more research in secure communications of devices with limited energy capacity and into techniques to help WSNs thwart cyber-attacks.

The design and deployment of WSNs has many challenges with respect to network fault tolerance, lifetime, self-organization, scalability, node hardware/software considerations, feasible network architectures and between-node communication protocols to be adopted under different scenarios [62]. All of these characteristics are difficult to accommodate into a single optimal WSN solution. Thus, application-specific purpose-built WSNs should be studied. Furthermore, based on the overall trade-offs, selecting adequate design parameters of choice, which could provide an optimal solution with respect to cost and performance, poses another complex and interesting WSN design challenge, due to the dynamics and diverse requirements of military applications [2,55,58,63].

The WSN design requirements could be different when considering the deployment of WSN for non-critical or peacetime missions, where the security of the network and its lifetime are not of prime importance. WSN challenges related to energy efficiency, sensor node battery life (energy scavenging), control topology, in-network processing and self-organization in order to prolong a lifetime of network, while at the same time conforming to the (required) guaranteed network connectivity and security aspect of networks might differ considerably. Consequently, comparing network architectures of nodes built for high threat environments versus low threat environments (i.e., commercial off-the-shelf sensor nodes) would provide interesting insights into military WSN design (e.g., would commercial off-the-shelf sensor nodes be good enough for a given peacetime application?).

Moreover, over-the-air firmware upgrade of sensor nodes under different circumstances (e.g., tactical military sensor network in remote large-scale areas) to accommodate different functionality of versatile sensor nodes, could be considered in future research.

WSNs may also be combined in various ways with LSNs in order to create more comprehensive SA. Currently, there is increasingly more research being done into the use of WSNs in conjunction with one or more UAVs or other assets. The UAVs in those cases might be the WSN information recipients and further relay the sensed data to base stations. How WSNs might increase the effectiveness of single or multiple UAVs (and even MANETs) could be of considerable interest. Furthermore, how WSNs would improve the SA of LSNs should also be studied since depending on the application, LSNs might not be able to gather all relevant data (e.g., from a battlefield).

4 Large Sensor Networks

4.1 Background

Large Sensor Networks include networks of sensors typically associated with defence and security, such as MANETs made up of airborne sensors or FSNs of large early warning radar systems. These are used for homeland security, rogue aircraft detection, drug smuggling detection, etc. LSNs also include many civilian sensors such as air traffic control, Automatic Identification System (AIS) [64], and satellite-based sensors [65,66]. While the sensors are sophisticated, the networking aspect is not well studied. The fusion of data gathered from multiple sources should be a topic of interest ensuring that they may complement each other in the most efficient way possible. Like WSNs, these networks aim to provide the maximum coverage possible. Unlike WSNs, the replacement cost of a single sensor is a significant concern, while the energy expenditure is not.

While some of these large sensors are often used alone, the military should be interested in the ability of multiple sensors to provide a combined SA that is greater than the sum of its parts. Combining sensors with different sensing regimes, such as radar and optical sensors, allows the confirmation of detected objects between sensors and the detection of objects that might be visible in one medium but not others. Accordingly, if the coverage areas of multiple sensors overlap, then one sensor might be able to provide information that was missed by another. However, this overlap also represents a reduction in the total coverage area that could have been achieved by the same sensors if they were separated. Another approach to multi-sensor surveillance could be the use of a wide-area coarse resolution sensor to provide initial detections that are then followed up by a smaller area, higher resolution sensor.

A very large scale sensor network, the Distant Early Warning (DEW) Line created a radar barrier by placing sites along the “most northerly practicable part of North America” [67]. The NWS used many of the same sites [15]. **Fig. 6** shows how the main line of sites was not significantly altered during the transition from the DEW Line to the NWS.[1]

As part of LSNs, we also study methods used to optimize CN coverage. Although CNs are used for communication rather than surveillance, the base stations in each CN must be able to detect a cellular phone within their coverage area and, therefore, the placement of these base stations is analogous to the placement of sensors as both represent some type of coverage within a given radius of an installation. The goal of both CNs and FSNs is typically to maximize the amount of coverage provided by a network of installations (whether cell towers or radars) while minimizing the number of installations required.

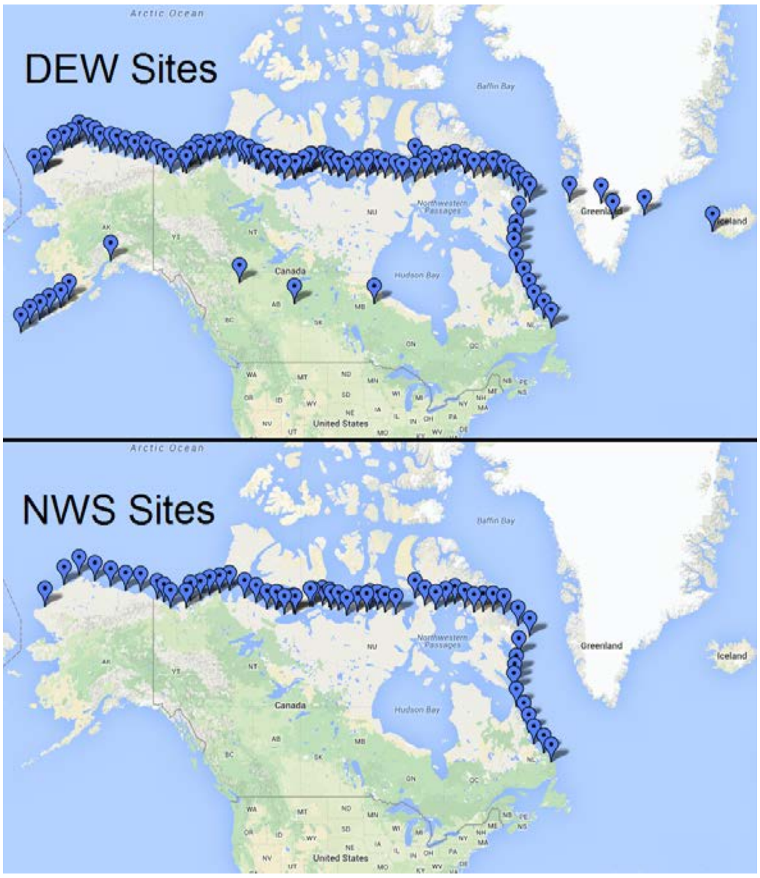


Fig. 6. DEW and NWS Sites

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[1] This figure was created in Google Maps [68,69] using data from [15] and [70].

4.2 Fixed sensor networks.

Sakr and Wesolkowski adapt their MOGA to optimize across three objectives, while also accounting for multiple types of sensors [30]. In their implementation, each sensor type was characterized by a unique coverage radius and cost. Their objectives were to maximize the total coverage, minimize the total cost, and minimize the amount of coverage overlap. They assumed a fixed number of sensors, which had the effect of reducing the search space. Although this work was framed in the context of a WSN, the methodology has more in common with FSNs. Specifically, it is limited to ten total sensors, and neither energy constraints nor the ability of sensors to move are accounted for. While the sensors modelled could indeed be wireless, this does not affect the methodology or results in this case. This research further shows the usefulness of creating different network architectures based on the emphasized objectives. The work could be extended more specifically for WSNs by including an objective to examine energy consumption. Another aspect of interest to FSNs would be to look at particular types of overlap coverage (e.g., overlap by two or three sensors). From a defence perspective, it is significant that this work accounts for a network of dissimilar sensors, although in this case the sensors are assumed to be redundant rather than complementary – hence the objective of minimizing, rather than maximizing, overlap. This work could be extended to seek to maximize the overlap of dissimilar sensors, while maintaining maximum coverage. In this case, increasing the limit on the total number of sensors would likely be required.

Oh et al. [31] examine the coverage by several sensors of different types. Each type of sensor is defined by a size and shape of its coverage area and each sensor can be placed anywhere on a grid; however, their algorithm does not allow the possibility of rotation of the coverage area about the sensor location. Their objectives are to maximize the coverage, to minimize the number of sensors used, to maximize a weight function based on a user-assigned sensor preference, and to minimize the distance of a randomly located target to the sensors. The objective of minimizing the number of sensors may be intended as a proxy for minimizing the total cost; however, another interpretation may be that a smaller number of sensors would be more manageable for the analyst receiving the data. The sensor preference function is unique. This could also be a proxy for cost although it is intended to be more situation dependant. Matching the right sensor to the intended target is an important consideration for defence surveillance, and this metric allows sensors to be ranked based on their appropriateness to the mission, while not exclusively considering the best sensor.

Church and ReVelle [39] set their objective as maximizing the number of people within a given service radius of any facility. They suggest solving this problem separately for a different number of facilities, essentially creating a Pareto front through a brute force approach. While this work was not presented in the context of surveillance, the number of people within a service radius could be substituted with the number of targets within a sensor range. This is a different perspective from which to look at the surveillance problem, and maximizing the number of targets in sensor range would be a preferable goal to maximizing the area coverage; however, it is also only measurable if target locations are known within some degree of certainty.

Miranda et al. [71] are not concerned with the implementation of an SN, but instead they address the problem of prioritising tasks assigned to available sensors using information provided by other sensors in the network. Their goal was to adjust priorities of radar tasks in such a way as to allow more effective scheduling; however, they have no metric for the effectiveness of the schedule. They specifically chose an example where their fuzzy logic algorithm performs differently from a hard logic version. The key point of this research is that sensors in a network can be used to inform the way in which other sensors belonging to the network can be used most efficiently. The priority of a sensing task was updated based on the current track quality on a target, the estimated hostility level of the target, the degree of threat, the appropriateness of the sensing platform's weapons systems, and the relative position of the target. All of this information is updated as awareness of the target improves.

Much of the work we have reviewed focuses on determining the ideal placement of sensors; however, CI methods can also be used in the data analysis that is required of a network of cooperating sensors. For example, Amato et al. [72] use neural networks to distinguish the movement of objects within a video from apparent movement due to the motion of the sensor itself. The United States Navy Cooperative Engagement Capability (CEC) does address the networking of multiple sensors but the network is not planned ahead of time, rather it combines the information provided by any available sensor in the same area [73]. The Brazilian system for vigilance of the Amazon region (SIVAM) similarly fuses data for environmental monitoring, air traffic control, and law enforcement [74]. These are large scale networks that combine elements of fixed and mobile sensors.

4.3 Mobile ad-hoc networks

MANETs are flexible, dynamic, self-configuring (connected) mobile wireless multi-hop systems, which have become increasingly common for use in the areas where the deployment of a fixed wireless infrastructure is challenging. The applicability of MANETs is indispensable for use in network-centric warfare (NCW), which requires mission-critical systems to be highly robust and reliable. Hence, network design and analytical techniques are applied to design MANETs for use in NCW [75].

As a result of their wireless mobility, self-configuration and flexibility to be deployed in remote (or difficult to access) areas, MANETs are appropriate for numerous commercial and military applications such as natural disaster assistance, battlefield ISR, and surveillance and reconnaissance missions [24,76]. A fixed wireless infrastructure is usually neither practical nor feasible in battlefield scenarios; as a result mobile wireless networks such as MANETs are essential for the rapid deployment and establishment of networks, consisting of adaptable, self-configurable mobile wireless nodes with real-time data, voice and video communications capabilities. The MANET system concept is instrumental in the development of vehicular ad-hoc networks (VANET) and flying ad-hoc networks (FANET), which are specialized MANETs. While in MANETs and VANETs, the focus is on moving nodes such as land vehicles, a FANET is a special form of MANET which addresses the concept of flying mobile nodes, i.e., multi-UAV systems [77].

The advantage of FANETs is in providing a more resilient and cost-effective solution compared to single UAV. Additionally, a FANET may extend the coverage area, survivability of a network, and speed of operation depending on the number of UAV systems included [78]. Nevertheless, due to high mobility of flying nodes and network dynamics (e.g., constantly changing node location), challenges exist with respect to multi-hop routing protocols. As an example, in airborne tactile networks, as speed increases, the successful delivery of the transmitted information (from all nodes to all nodes) drops [79]. Thus, the need for better interoperability of network layers is paramount such as for example leveraging link layer information for better cross-layer multi-hop routing decisions [80].

Sethi and Udagata [81] propose an efficient routing algorithm inspired by Ant Colony Optimization (ACO) techniques. The so called Ant-Efficient (Ant-E) algorithm improves the reliability of packet delivery by controlling the overhead and local transmission. The packets are divided into data and control packets, where data packets use information stored in the routing tables to reach the destination node. On the other hand, control packets, such as forward ant (FANT) and backward ant (BANT) are agents which are used to update the routing table and traffic information throughout the network. Lekova et al. [82] propose a delay tolerant event notification service utilizing fuzzy logic-based reasoning for sparse MANET networks in case of emergency or rescue situations, capable of capturing uncertainties in modeled data.

There are many similarities between MANETs and WSNs. For example, both network types do not need a fixed infrastructure and are self-configurable (adaptable to changes in network topology). They also rely on multi-hop routing for dissemination of data among network nodes. Power consumption is an important consideration in both MANETs and WSNs although of much more critical importance in WSNs. In comparison to WSNs, nodes in MANETs are typically equipped with more powerful and refuelable power systems.

On the other hand, some of the differences between MANETs and WSNs concern the number of nodes and their deployed densities. WSNs usually have many more nodes than MANETs; thus, scalability, while not a big concern in MANETs, can be an issue in WSNs. Moreover, while only a few nodes could be mobile in WSNs, usually all nodes are mobile in a MANET. Redundant deployment of nodes makes the use of data aggregation and in-network processing essential in WSNs, while it is mostly irrelevant in MANETs.

4.4 Cellular networks

The objective in CN base station placement is to maximize the coverage area or the amount of cellular traffic served [5]. Studies also define a QoS level that must be achieved [35]. The trade-off is to minimize the required number of base stations while maximizing coverage. The CN coverage area is a similar objective to that used in surveillance networks, while traffic served is analogous to the number of targets detected. In contrast, the QoS calculation is not directly applicable to LSNs because in an LSN the communications infrastructure is separate from the sensors.

Meunier et al. [35] use three different types of base stations, distinguished by their antenna types: omnidirectional, small directive, and large directive. This is analogous to a sensor network that has access to omnidirectional, narrow FOV and wide FOV sensors. In addition, sites with directive base stations are allowed to have between one and three base stations. In addition to three objectives (minimize the number of sites, maximize the amount of traffic served, and minimize the interference from overlapping cells), they also consider two constraints: covering the entire area, and having a handover area between cells. The handover area is an area of cell coverage overlap which enables a moving cell phone user to be switched between the cell they are leaving and the cell they are entering. While the objectives would have to be adapted for use with sensor networks, the ability to account for multiple sensor types is important in defence applications.

Amaldi et al. [37] define an installation cost associated with each potential base station site, rather than with the base station itself. This accounts for a range of considerations such as pre-existing infrastructure or remote, difficult to access, locations. This same concept is important for sensor networks, where an ideal location from a coverage perspective may not be as important as taking advantage of an infrastructure left behind by an older network.

4.5 Current research challenges

CEC [73] and SIVAM [74] incorporate inputs from multiple sensors but there is no indication that SIVAM sensor locations were optimized for most efficient coverage, and CEC focusses on fusing data from onboard sensors from all ships in a group, whose locations will also not be based on optimum coverage.

The logic that is used to move sensors after an initial random deployment could be modified to determine optimal placement of sensors before deployment, simply not accounting for movement from initial positions. However this may be overcomplicating the determination of ideal sensor locations.

It is difficult to measure how different systems should cooperate to provide the best overall SA. Using maritime surveillance as an example, suppose that satellites provide extensive coverage but no identification of vessels that aren’t broadcasting legitimate AIS signals [64], while aircraft equipped with a visual sensor may be able to provide identification [83] if they know where to search. Some mix of both systems (or alternatives) is almost certainly the best approach, but while area coverage is easy to measure, the value added by covering the same area with more than one sensor depends on the targets being sought.

Just as the NWS replaced the DEW Line, the NWS will eventually need to be updated, replaced, or abandoned. If a replacement is considered, it may be useful to consider new locations for the radars. While global warming and technological advancement may make it possible to move the radar line farther north, advances in the radar technology may allow the radars to achieve the same capability while being positioned farther south. Well-defined objective functions should be used to capture the specific requirements of the mission. CI methods that were not available during the previous planning iterations could then be used to determine the best locations for the radars.

The convergence of MANETs and WSNs could be a unique dynamic system solution with “high resolution” sensing capabilities and mobility. The integration of such a system could pose a great challenge in itself. Taking into consideration that VANETs and FANETs (UAVs) are also part of MANETs, the amount of available information, data dissemination and processing could prove to be very challenging. Finding effective CI techniques to be used and applied in the separation of “noisy data” from essential data for mission-critical scenarios should be of interest.

5 Future directions

We have examined large fixed sensors, as well as mobile sensors with limited movement capability relative to their sensing range (WSNs) or large possible movements (MANETs). In a defence and security system of systems approach, both LSNs and WSNs should work together with patrolling sensors (e.g., foot patrols or aircraft-mounted sensors), all the way to polar-orbiting satellites. The fact that that these mobile sensors may move significantly compared to their sensing range introduces significant challenges in making a comparison to stationary sensors and thus finding a proper mix. Very few studies [30,31,35] allow different types of sensors or base stations to work together, and in these cases it is only the shapes and sizes of the coverage areas that are considered. Approaches from similar resource-based fields such as fleet mix computation [84] could also be adopted.

Optimal use of sensor networks continues to be a challenge. Handoff between sensors for the purposes of maintaining a track is discussed in [85]. The authors assume that all sensors are omnidirectional and the motivation behind handing off the tracking duty is that non-necessary sensors can sleep and conserve energy. How would this translate to large networks where sensors may be of different types, may be directional, and may have gaps in coverage where a target might temporarily disappear, but where energy conservation is not a driving concern?

Much of the work on WSNs focuses on the movement of sensors into position after an initial deployment, but to conserve energy sensors are rarely moved once they are in position [86]. LSNs also have varying levels of mobility; however, their movement tends to be an aspect of their use, rather than deployment. These range from movement while in use (such as satellite-based radar [65,66] and Airborne Warning and Control Systems – AWACS [87,88]), to movement between uses (moveable radars such as Russia’s P-18 [26,89] or Belarus’ Vostok-D [90]), to no movement (permanent radar installations [16,17]). Sensors that move after initial deployment introduce the complication that instantaneous coverage is not enough to measure their utility. It would also be advantageous for these various systems to be used together and so finding the correct sensor mix is another important challenge.

When coverage has been used as an objective, it usually refers to blanket coverage (as opposed to barrier or sweep [14]). Barrier coverage may be trivial as the required length is either covered, or not. Sweep coverage allows more area to be covered over time than would be possible if the sensors were stationary; however, measuring the effectiveness of this type of coverage remains a challenge. This is related to the difficulty of evaluating the performance of multiple types of sensors working together. Moving sensors such as satellites and AWACS provide sweep coverage while stationary sensors provide blanket coverage, adding an extra layer of complexity to their evaluation as parts of a system of systems.

Multiple conflicting objectives are dealt in one of three ways: the first method is to assign weights to each objective [34,36,37]; the second is to treat one or more objectives as constraints [29,32,33,40,86]; and the third is to perform a multi-objective optimization resulting in a Pareto front [5,30,31,35]. The first two methods are related, as a constraint is equivalent to an objective with an arbitrarily large weight. No single method is ideal: weights attempt to rate the importance of each objective based on subjective individual preferences, and a Pareto front represents a large number of potential solutions from which to choose. A suggested course of action for future work is to first create the Pareto front and then examine the solutions using a multi-criteria decision tool [91].

Albeit currently at an infancy level, the convergence of MANETs and WSNs are instrumental in further development of new opportunities within Internet of Things (IoT) applications [92] where both technologies can be integrated for monitoring, public safety, surveillance and security applications. Ubiquitous sensing and the fast collection of data (supported by MANET and WSN) combined with computational intelligence could improve sensor network design.

Furthermore, as MANETs and WSNs merge with FSNs and IoT, many new challenges will arise including managing and processing this large amount of data. There will be big data analytics challenges where existing data processing methods do not apply. The shift towards big data in military ISR will require finding new methodologies capable of removing redundant information while extracting and processing essential data. The application of sophisticated new CI algorithms will be required.

Therefore, the synergy of IoT and big data technologies could offer an unparalleled opportunity towards using data driven discovery for military SA. The amount of data available from multiple sources of information could be used to predict and prevent natural disasters, potential dangers and threats, contributing to a safer future [93]. Therefore, leveraging CI methods within IoT and big data initiatives should be a focus for future military ISR applications [94,95].

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