A Novel Characterization of Distributed Sensor Networks within the DoD

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Abstract

Distributed sensor networks (DSN) within the DoD are motivated by a need for pervasive and persistent military surveillance, as addressed in Navy DoD guidance documents [1, 2, 3, 4, 5, 6, 7]. Previous studies [8, 9] have sought to characterize DSNs based on various attributes, taxonomies, and design spaces from more of a theoretical perspective. This paper differs from previous studies by focusing on the establishment and use of measurable, orthogonal, design-level, discriminating attributes (*discriminators*) for classifying DSNs. DoD and non-DoD applications are then characterized in light of these discriminators. Senior Navy/DoD leadership and other decision makers interested in understanding the characterization of DSNs within the DoD, will find this paper valuable.

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14. ABSTRACT

Distributed sensor networks (DSN) within the DoD are motivated by a need for pervasive and persistent military surveillance, as addressed in Navy DoD guidance documents. Previous studies have sought to characterize DSNs based on various attributes, taxonomies, and design spaces from more of a theoretical perspective. This paper differs from previous studies by focusing on the establishment and use of measurable, orthogonal, design-level, discriminating attributes (discriminators) for classifying DSNs. DoD and non-DoD applications are then characterized in light of these discriminators. Senior Navy/DoD leadership and other decision makers interested in understanding the characterization of DSNs within the DoD, will find this paper valuable.

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1   Introduction

Operational commanders face the challenge of maintaining battlespace awareness in hostile, remote locations while undergoing troop drawdown. Distributed sensor networks hold promise to deliver the capability necessary to mitigate or nullify the loss of surveillance traditionally performed by troops. The challenge for decision makers is to quickly and effectively acquire and deploy DSNs to optimize the needs of the war fighter. To fulfill this need, the decision maker is faced with myriad DSN design options from commercial off-the-shelf (COTS) vendors and government off-the-shelf (GOTS) choices.

For this study, multiple DoD guidance documents were reviewed for the purpose of extrapolating current and future DSN needs and capabilities. Next, related DSN characterization literature was reviewed and synthesized in the context of DoD guidance. For support of current and future DoD operations, existing DSN characterization papers include classification attributes that fail to identify key differentiating features at the operational level. A more practical classification and decision-making tool is proposed based on a simple set of orthogonal (independent) and measurable discriminating attributes. Both existing DoD DSN applications as well as relevant non-DoD DSN applications are analyzed with regard to this novel classification system.

This paper is organized into five sections. The first section provides background on related work regarding the characterization of DSNs as well as the impetus for this work. Next, a novel design space enabling succinct and effective characterization of DSNs is presented. Several DoD DSN applications as well as defense-related non-DoD DSNs are compared and contrasted using this new taxonomy. A conclusion summarizing the advantages of this new classification system is provided. Finally, future work areas are discussed with particular attention to new questions that warrant consideration.

1.1   Background

As sensor networks and their features continue to proliferate and gain in popularity, the need to distinguish important attributes becomes vital for appropriate categorization and application-based selection. Many studies center on academic or commercial use. In these particular settings, the sensor networks described are wireless, ad hoc, range in size from a brick to dust particles, located in the immediate vicinity to a certain geographical region, and are battery operated [10, 11, 12].

Tilak et al. [8] proposed a number of mutually exclusive models to aid in defining appropriate communication infrastructures for different sensor networks applications. The paper begins by describing sensor networks and the metrics used to evaluate them. Next, Tilak decomposes the sensor networks communication infrastructures into three models that possess several characterics.

Römer and Mattern [9] discuss the various dimensions of wireless sensor networks and demonstrate that specific existing applications occupy different points in this design space. The work defines classes for sensor network applications and characterizes various dimensions of each. Finally, specific DSN examples are presented in terms of the paper's design space.

Akyildiz et al. [13] provided a list of descriptors for sensor networks. In the listing, sensor networks were distinguished from ad hoc networks. More specifically, sensor networks were considered much greater in quantity, more densely deployed, more susceptible to failure, and topologically dynamic in comparison to ad hoc networks. These distinguishers went on to characterize sensor networks mainly as battery operated, multi-hop or broadcast communication systems. The study also provides factors that influence sensor network design. These factors include fault tolerance, scalability, production costs, operating environment, sensor network topology, hardware constraints, transmission media, and power consumption. Examples of these types of sensor networks are

provided in applications that center on military, environmental, and commercial domains.

However, not all of the taxonomies described in previous studies are applicable to the military support role. While Akyildiz et al. [13] provide examples of military applications, the characteristics of the sensors are not detailed for clear classification. Römer and Mattern [9] note that before moving to commercial applications they were focused on military applications. Thus, the resultant taxonomy is an amalgam of features from both the civilian and defense domains.

The goal of this study deviates from previous DSN characterization studies by focusing on the construction of a minimal set of *discriminating* DSN features rather than a list of observable features. Moreover, this study centers around DoD applications and non-DoD applications that may be easily adapted for military support. The proposed list of DSN attributes are designed to be orthogonal and measurable. In fact, many of the attributes are binary, which are easier to understand and measure and thus more practical in terms of categorizing. For the purpose of this study, the list of attributes are referred to as *discriminators*.

1.2   Motivation

Evasive techniques employed by a modern adversary have driven the need for pervasive and persistent military surveillance abroad [1, 2] and improved integration and fusion of sensor data for national security interests at home [3]. To that end, investments have been made to develop a wide spectrum of sensor assets capable of improving battlespace awareness [4] and a vision for smart, autonomous, and inexpensive sensors has been established to guide the development of future defense technology [5].

As Joint and international efforts are underway to integrate sensor and network capabilities [6], increasingly the US Navy is positioned to be a leader in unmanned technologies where future networked sensor capability can proliferate [7].

Despite a predominant academic focus on wireless microsensors [8, 9], recent work at a naval engineering laboratory, SSC Pacific, has demonstrated employment of relatively large autonomous underwater vehicles (AUVs) as sensor platforms without wireless connectivity [14]. This divergence between theory and practice presents a resistive force to the capability development necessary to achieve pervasive and persistent surveillance, and therefore motivates this analysis.

2   Design Space

This section continues the efforts established in previous studies to effectively categorize sensor networks. The aforementioned discriminators are used to characterize DoD applications and non-DoD applications that may be used for the DoD. These applications as well as their characterizations are described in Table 1, with the corresponding legend provided in Table 2.

Rather than examine published literature or applications, this section defines and promotes each discriminator. Next, an inclusion test for discriminators is proposed. Finally, two currently popular DSN attributes are shown to fail the authors' inclusion test.

2.1   Discriminators

Following are seven practical, orthogonal, discriminating, and measurable design-based attributes for characterizing DSNs within the DoD.

Table 1: **Discriminators**

Paper	Application	Synchrony	Sensing Modality	Mobile	Wireless	Communicate	Effector	Active
[15]	Observation	ND	I	N	N	Y	N	N
[16]	Observation	ND	I	N	N	Y	N	N
[14]	AUV	N	Ac	Y	N	N	N	N
[11]	Fusion	Y	T	Y	Y	Y	Y	Y
[17]	Self-Healing Mines	Y	RF/Ac	Y	Y	Y	Y	Y
[17]	Wireless Integrated Sensor Nodes	ND	I, Ir	N	Y	Y	N	N
[9]	Observation	ND	T, H, Pr, O	N	Y	Y (ad-hoc, sat)	N	N
[9]	Observation	ND	GP, O	Y	Y	Y (flooding)	N	N
[9]	Glacier monitoring	ND	Pr, T, Or	N	Y	Y (base sta)	N	N
[9]	Herding	ND	GP	Y	Y	Y	Y	N
[9]	Oceanic sensing	ND	Pr, T, Co, Cu, Tu	N	Y	N (sat at surf)	N	N
[9]	Oceanic sensing	ND	T, Cu, Sa	Y	Y	Y (report to sat)	N	N
[9]	Precision harvest	ND	T, H, O	N	Y	Y (two-tier)	N	N
[9]	Temperature Monitoring	ND	T	N	Y	Y (two-tier)	N	N
[9]	Rescue	ND	Ox, Or	Y	Y	N (one-way)	N	N
[9]	Vital sign monitoring	ND	V	Y	Y	N (one-way)	N	N
[9]	Power monitoring	ND	Power usage	N	Y	N (one-way)	N	N
[9]	Parts assembly	ND	Physical forces	Y	Y	Y	N	N
[18]	Tracking	Y	M	Y	Y	Y	N	N
[9]	Force Protection	Y	Ac	N	Y	Y	N	N
[12]	Health, Environment-risk monitoring	ND	V	N	Y	Y	N	N
[19]	Direction Finding	Y	RF	Y	Y	Y	N	Y

Table 2: **Legend**

Ac	Acoustic	O	Optic
Co	Conductivity	Or	Orientation
Cu	Current	Ox	Oxygen
GP	Global Position	Pr	Pressure
H	Humidity	RF	Radio frequency
I	Imagery	Sa	Salinity
Ir	Infrared	T	Temperature
M	Magnetic Field	Tu	Turbidity
N	No	V	Vital signs
ND	Not Discussed	Y	Yes

2.1.1   Synchrony

The *synchrony* discriminator is a binary attribute which is true if each sensor operates at the same time step within an accepted tolerance. This discriminator supports a number of DoD applications. Synchrony is used for geo-location, such as GPS, of both allies and targets for battlespace awareness. Direction finding through the use of unmanned systems uses synchrony as well. Synchrony must be established by a sensor network for precision strikes. An important non-kinetic application of synchrony is fault tolerance. As cyber warfare continues to grow and become a part of the modern day war effort electronic defensive (ED) measures against malicious attacks on DoD networks become vital. Fault tolerance is also important in todays war effort by providing more reliability in the sensor network and invariably trust even from benign failures. A value of false (no) for the synchrony discriminator implies the sensors in the network operate independently. An example of this would be post-battle damage assessment where gathering the data is more critical than ensuring sensors work in concert to gather the information [13].

2.1.2   Sensing Modality

The *sensing modality* discriminator is a multilevel attribute which describes what type of data the main sensors are observing. The applications in Table 1 provide a number of different types of sensing modalities utilized. For example, the sensing modality of the distributed embedded cameras application [16] is optics. The camera selection manager for the camera cluster alternates based on which camera has the best view of the target.

The ad hoc wireless sensor networks described in [19] rely on the radio frequency (RF) sensing modality for range measurements between pairs of nodes and anchor nodes with a priori coordinates for direction finding. This discriminator also describes applications with multiple sensing modalities.

The self-healing mine network in [17] relies on the acoustic sensing modality to determine if one of the mines has detonated. It also uses the RF modality through broadcast synchronization to obtain the range and angle between pairs of nodes in a local area.

2.1.3   Mobility

The *mobility* discriminator is a binary attribute which is true if a sensor network possesses the ability to physically relocate its position. The mobility discriminator is considered false if the sensor network is stationary. DoD intelligence, surveillance, and reconnaissance (ISR) missions rely heavily on the mobility of its sensors. Mobile satellites and unmanned systems conduct numerous missions to gather data for battlespace awareness [20]. This information is used to find and target red forces and hideouts, especially in urban terrains such as Iraq and Afghanistan [21]. Sensor mobility also aids in other battle-related considerations such as weather. Weather satellites are used to determine if potential battlegrounds will experience reduced visibility or inclement weather and can blue forces take advantage of the scenario. It is important to note that movement of sensors from severe weather or carriage, in the case of portable sensors, does not constitute mobility.

An example of a sensor network that is not mobile would be a perimeter camera defense system on a forward deployed base. Since the purpose of this application is to provide constant surveillance for the base, providing a stationary visual sensor is considered appropriate.

2.1.4   Wireless

The *wireless* discriminator is a binary attribute which is true if each sensor possesses a wireless radio and can upload data on this link; otherwise, the value of this attribute is false. This discriminator does not infer the form or complexity of wireless communication that the sensor exercises. For example, a sensor may store sensed data and only at specified times, upload these data to a roaming wireless collection station. A different wireless sensor network may have each sensor periodically upload data to a satellite link. Yet another wireless sensor network may engage in a complicated distributed consensus or election protocol. When this attribute is false, each sensor has no wireless capability, but may be connected to a non-peer station or a subset of other sensor nodes using physical wires (e.g. coax, twisted-pair, fiber).

2.1.5   Communicate

The *communicate* discriminator is a binary attribute which is true if each sensor engages in two-way communication with either a neighbor sensor node or with a non-peer station; otherwise the value is false. The purpose of this discriminator is to differentiate among those sensor networks where each sensor merely uploads data, with those sensors networks where each sensor has a dialog with other peers, or possibly with one or more non-peers. Approximately a quarter of the sensor networks in Table 1 do not communicate—they merely report.

   The communication attribute could be sub-divided into more attributes identifying the manner of communication. For instance, sensors could communicate directly with the base station in a *single point-to-multipoint* fashion [22]. This provides low data-transmission latency but requires that all sensors nodes be within the radio communication link of the base station. Or, sensor nodes could communicate among themselves by forming a *mesh network*. In this case all directly communicating nodes should be within the radio transmission link. If not, they use intermediate nodes in a *multi-hop* manner to send message to the desired nodes. In yet other cases, nodes may form clusters with local nodes and use *hierarchical multi-hop* to communicate with a base station [23].

   The manner of communication also has an affect on power usage. For instance, nodes that implement multi-hop consume more power compared to other nodes. Also, in a single point-to-multipoint direct communication case, nodes closer to the base station have longer battery life compared to the multi-hop communication nodes where nearer nodes die faster than distant nodes [24].

   One may argue that the manner in which sensors nodes communicate is an implementation detail resulting from constraints of the application space. At the characterization (classification) level, there may be little differentiating two different DSNs that communicate. For example, a DSN using multi-hop is "similar"to a DSN using hierarchical multi-hop, at the conceptual level. Thus, in this paper, only a single communicate discriminator is considered.

2.1.6   Effector

The *effector* discriminator is a binary attribute indicating whether the network as a whole or part, is capable *by design* of affecting the environment, including the physical properties of the sensor itself. A simple example is the "cattle herding" sensor network [9] listed in Table 1. Here, each sensor is capable of emitting a sound that is expected to alter the path of a stray cow away from an encompassing fence. Another example listed in Table 1 is the "self-healing mine field" [17] where a mine breach can be detected and another mine can autonomously move to fill the breach.

2.1.7   Active

The *active* discriminator is also a binary attribute and indicates whether the sensing modality of each sensor is passive or active. A passive form of sensing is undetectable, aside from the sensor's physical footprint and its communicating activities. An active form of sensing emits some form of electrical, magnetic, compressive, or mechanical action for the purpose of direct and focused probing of the phenomena being sensed. Active sensors are easier to detect and consequently subvert or circumvent. Moreover, active sensors are expected to consume more power.

2.2   How Discriminators Were Chosen

With the exception of the *sensing modality* discriminator, all discriminators have purposely been chosen to posses a binary state (e.g. true/false, yes/no). This facilitates classification of sensor networks. Furthermore, these binary discriminators were selected to be as orthogonal as possible and yet provide comprehensive coverage of interesting DoD present and future DSNs. Collectively, the design goals for choosing type and orthogonality of discriminators effectively partitions the DSN design space into simple, measurable classes.

Many DSN characterization or design papers include a list of attributes with one or more of the following undesirable properties:

- one or more attributes *strongly imply another attribute*

- one or more attributes *exhibit little variability* in the studied applications

- one or more attribute terms have *ambiguous definitions*

- one or more attributes pertain to *system specific engineering tradeoffs* rather than *core operational properties*

- one or more attributes have *too large a range* of allowable values

The undesirability of the first four bulleted items is clear: redundant attributes, non-discriminating attributes, attributes that have not been universally defined and implementation-level attributes are not useful. The fifth bullet alludes to the confusion and frustration that arises when one is confronted with the task of identifying a particular attribute but given too many choices. Taking the idea in the fifth bullet to the limit, one is presented with a continuum of values. And, faced with a continuous range of attribute values, one is compelled to "cut up the space" along arbitrarily-established discrete categories, again, foiling a useful, universal system of classification.

2.3   "Fusion" and "Smart" Discriminators Considered

There are other DSN attributes commonly listed in technical DSN characterization/design papers which are missing from our table [8, 9, 11]. For one or more of the five reasons mentioned above, those other attributes are excluded from the list of discriminators in Table 1. In particular, two such excluded attributes elicited much discussion among the authors: "fusion" and "smart sensor". In the following subsection, arguments are made for excluding both "fusion" and "smart sensor" as useful discriminators.

2.3.1   "Fusion"

Originally, both a binary "fusion" column and a binary "smart sensor" column were proposed. Certainly including these two discriminators would have made Table 1 appear more elaborate and current. However, upon closer examination, it becomes evident that both of these terms suffer from

an overly-broad or ambiguous definition, in effect making them undesirable from a classification perspective.

First, consider what it means to say that a DSN possess the attribute of fusion (i.e. it expresses some manifestation of the fusion quality). In [11], information fusion is classified based on the relationship among the sources, based on level of abstraction, and based on input-output. The relationships among the sources is further categorized as either *complementary*, *redundant*, or *cooperative* as shown in Figure 1.
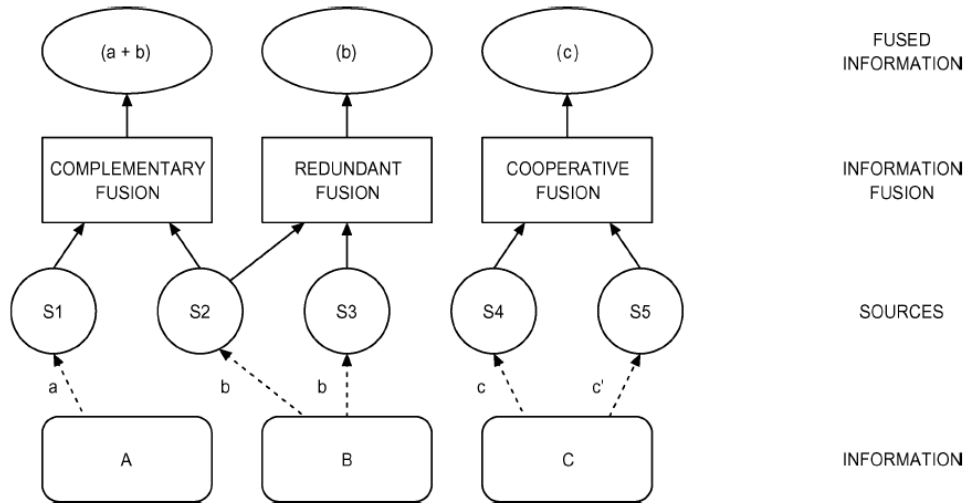

Figure 1: Types of information fusion based on sources[11]

In *complementary fusion*, sources S1 and S2 provide different pieces of information, a and b, respectively, that are fused to achieve broader information, denoted by $(a + b)$. *Redundant fusion* is used to increase the reliability, accuracy, and confidence of the information. Here two or more independent sources provide the same piece of information and these pieces are fused to increase the associated confidence. In *cooperative fusion*, two independent sources (S4 and S5) cooperate to provide new information (c) that better represents reality.

Another article [13] mentions the cooperative effort of sensor nodes as a unique feature of sensor networks. Each sensor node is equipped with an on-board processor capable of performing a certain extent of computation. Each sensor node performs some low-level processing before sending the raw data to the next level nodes responsible for fusion and transmit only the required and partially processed data.

Based on these differing views of fusion, one is stymied trying to develop a clear test for deciding whether a DSN is partaking in fusion. For example, two or more disparate sensing modality value streams could be "fused" into something else. Or, multiple sensed data from a common sensed event could be "fused" into a more accurate result. Yet another example includes a sensor that adjusts the interpretation of sensed values based on its awareness of time and position, for example. The possibilities are numerous. Listing fusion is a slippery slope.

One might propose as an alternative solution the listing of multiple discriminator columns for each of the categories of fusion mentioned above [11]. This would require the addition of three columns: source relationship-based fusion, level of abstraction-based fusion, and input-output based fusion. Unfortunately, these three discriminator columns would quickly become six if one includes the sub-categories of source relationship-based fusion: complementary, redundant and cooperative. Even more columns may be needed to also include definition elements of fusion mentioned in other

Table 3: **Correlative DSN Properties**

Correlative Property	Relevant Discriminators
Communication Requirements	synchrony, wireless, communicate
Power Requirements	*all discriminators*
Cooperation Potential	synchrony, communicate
Detectability	mobile, wireless, effector, active

articles (e.g. [13]).

2.3.2   "Smart"

Likewise, listing "smart sensor" as a salient discriminator is problematic. One might say that "smart" means the sensor posses a microprocessor. Does this include dedicated logic that exists as a part of the sensor that filters or transforms the input data in some way? Would a sensor with a field-programmable gate array (FPGA) be considered "smart"? Does software need to be present? Again, the possibilities are too numerous: the combinations and quantities of hardware, firmware, and software that could/should be considered "smart" is evasive. For this reason,"smart sensor" is excluded from the list of discriminators in Table 1.

3   Characterization

In Subsection 3.1, several DoD DSN systems are characterized using the discriminators listed in Table 1. These systems are further compared and contrasted in terms of additional correlative properties, demonstrating the usefulness of these seven "primary" discriminators as part of a virtual "color wheel" of DSN attributes. In Subsection 3.2, novel applications of non-DoD systems, within DoD settings, are discussed.

3.1   DoD Systems

A total of five DoD Distributed sensor networks are considered. Table 1 is employed to provide a practical characterization of each DoD DSN. This characterization is useful in that it provides quick understanding of the technical complexity of the DSN as well as insight into the DSN communication requirements, power requirements, cooperation potential, detectability and/or environmental impact.

With a relatively small set of simple, well-considered discriminators, one can deduce other interesting correlative properties of the DSN. Table 3 lists some of these other interesting DSN attributes along with the relevant discriminators. DoD DSNs are compared and contrasted in light of the discriminators and correlative properties.

3.1.1   DSSN

The Distributed Surveillance Sensor Network (DSSN) is an investigative network of "small" Autonomous Undersea Vehicles (AUVs) for the purpose of surveillance and enhancing submarine connectivity [14]. Using Table 1, this network is classified as an asynchronous, acoustic-sensing, mobile, non-wireless, non-communicating, non-affecting, and non-active DSN.

The acoustic capability of the AUV can be useful for both communication and active sensing. With sufficient signal processing capabilities on micro-processors, it is claimed that the AUV network can be configured into "a huge multi-static active sonar capable of detecting and localizing anomalies within the volume of seawater supporting the acoustic propagation paths". Due to limited storage capacity, sensor data must be uploaded on occasion. A fiber optic cable connected by means of a remote-controlled vehicle is used for this purpose.

Due to a lack of two-way communication, absence of a wireless radio, and asychrony, one can deduce that the (hardware and software) communication requirements are meager. The acoustic modality, mobility, and requisite signal processing are the main power consumers. Cooperation potential is limited. Detectability is primarily a function of size, mobility, and the acoustic modality.

3.1.2   Self-Healing Minefield

The Self-Healing Minefield (SHM) [17] represents a DSN with a significantly different characterization than the experimental DSSN. The SHM is classified as an acoustic-sensing and RF-sensing, mobile, wireless, communicating, affecting, and active DSN. The SHM is a more complex DSN than the DSSN and requires fairly precise timing (synchrony).

Communication, mobility, and active sensing all translate to increased power requirements. Cooperation is more easily achieved due to synchrony and two-way communication. Because the SHM is a mobile, wireless, communicating, active, environment-affecting DSN, it is more vulnerable to detection. In addition, maintaining synchrony, in the absence of special hardware [25], demands more sophisticated communication activity.

3.1.3   Tracking Military Vehicles

The 29 Palms Experiment [18] documents a DSN for Tracking Military Vehicles (TMV) using Unmanned Aerial Vehicles (UAVs). It is important to note that the role of these UAVs is as a data transfer intermediary. The UAVs merely transfer tracking information to an observer, rather than actively participate in the DSN. The sensing nodes are separate from the UAVs and occupy fixed locations on the ground.

Using Table 1, the TMV DSN is classified as a synchronous, magnetic-field-sensing, non-mobile, wireless, communicating, non-affecting, and non-active DSN. Synchrony is vital for tracking and is achieved through a simple broadcast mechanism. Continuous use of the magnetometer for sensing magnetic fields reduces the sensor lifetime to just one hour.

As depicted in Table 3, it is obvious that the sensing modality (magnetometer) along with wireless communication consumes much power. Power requirments are further compounded by the increased communication activity of the required synchronization protocol. Second, detectability, also in Table 3, is minimal, only reduced through smaller size and elimination of wireless communication. Third, synchrony and two-way communication both facilitate cooperation.

3.1.4   Sniper Localization

The Sniper Localization (SL) DSN seeks to locate snipers as well as predict the trajectory of bullets [9]. A distributed network of acoustic-sensing nodes measures muzzle blast and shock waves. By comparing time of arrival of characteristic shock waves at individual sensor nodes, a sniper can be localized.

The SL DSN is classified identical to TMV, with the exception of sensing modality: a synchronous, acoustic-sensing, non-mobile, wireless, communicating, non-affecting, and non-active

DSN. As with TMV, synchrony is critical to accomplishing tracking. Similar observations and conclusions made for TMV apply here.

3.1.5   Detecting and Tracking Multiple Persons

The Detecting and Tracking Multiple Persons (DTMP) DSN [16] is classified as an image-sensing, non-mobile, non-wireless, communicating, non-affecting, and non-active DSN. The maintenance of time synchrony is not discussed in the paper, but time scales and frequencies for feature aggregation are mentioned. Thus, synchrony is implied.

DTMP is another example of a non-wireless DSN, the other being DSSN. Furthermore, DTMPs absence of wireless connectivity distinguishes it from both TMV and SL in only its sensing-modality (video imagery). As indicated in Table 3, the wireless discriminator has an impact on detectability. DSNs deployed within environments requiring Emissions Control (EMCON) should consider this discriminator. Other environments imposing (RF) wireless constraints are oceans and large lakes requiring extended communication paths through water (see [9]).

3.2   DoD Applications of Non-DoD Systems

The advance of micro electro mechanical systems (MEMS) technology provides new opportunities for distributed sensor networks. MEMS sensors are small, consume little power, and are produced in large numbers. They offer several technical and operational advantages for distributed sensor networks [13]. MEMS are massively deployed as ad hoc wireless distributed sensor networks to monitor various environments.

DSNs are often deployed to perform tasks such as detection, classification, localization and tracking of one or more targets within the sensor field. DSNs can be used to monitor airport surveillance, traffic-control monitoring, environmental monitoring, surveillance against bio-terrorism, battle field damage assessment, etc.

DSNs can be used to classify vehicle type—an important signal processing task that has found widespread military and civilian applications such as intelligent transportation systems [26]. MEMS-based DSNs are used to measure sound and pressure activity to determine the location of a seismic or acoustical events [27]. Another exciting application of DSNs is the early detection of onset of insidious computer viruses by using a set of geo-sparse Internet nodes equipped that communicate amongst themselves through a channel other than the Internet [27].

A patients physiological data can be monitored remotely by a doctor using sensor networks. This allows the doctor to better understand the patients current condition and is convenient [13]. The continuous monitoring of the physiological condition of crew members, space flight equipment, and habitat during long space missions is also an important area application of DSN [12].

DSNs play a vital role in precision agriculture to collect effective soil data for maximizing the crop yield and minimizing the impact on the environment [28]. Water quality can be improved by the utilization of sensor networks in precise-control irrigation for crop water-demand information [29].

Among the other promising applications of DSNs are forest anti-fire [30], underwater [31], industry [32] and climate monitoring [33].

4   Conclusions

In terms of classifying DSNs within the DoD, previous design space and taxonomy papers have included classification properties that fail to identify key differentiating features at the operational

level. Such properties include aspects pertaining to "dust-sized" sensors and network sizes of thousands or more, illustrating a divergence between theory and practice. In addition, many previously espoused attributes exhibit pair-wise dependencies, little variability, ambiguity, or system specific qualities.

Based on comprehensive study of DoD guidance and the analysis of currently deployed DSNs within the DoD, a clear scope of salient DSN core operational capabilities was identified. This scope fostered the development of a novel DSN classification system based on seven discriminating attributes that possessed the desirable properties of orthogonality, variability, clarity, and practicality.

As troop drawdown increases, reliance on DSNs to maintain battlespace awareness will become critical. Decision makers should be provided with relevant tools and information in order to determine appropriate DSN requirements quickly and effectively. The characterization of DoD DSNs discussed in this paper as well as the proposed taxonomy can assist decision makers in choosing "best-fit" solutions for acquiring and deploying DSNs in the field.

5   Future Work

The work presented in this paper raises new questions which warrant investigation.

First, the divergence between theory and practice in DSNs identified in Römer and Mattern [9] and supported by evidence found in this study remains unexplained. A thorough literature review of the subject may discover the cause of the divergence.

Having prepared a collection of discriminators by which to classify DSNs, an organized means by which to explore the DSN application space has been created . It now remains to apply that organization scheme in the broadest of ways—to explore the corners of the DSN application space and identify those areas which are over or under represented. Over represented areas will correlate with common design and engineering trade-offs whereas under represented areas will serve as targets for novel academic study. A more thorough review of sensor applications within the DoD will offer opportunities for discriminator refinement and will lend confidence to the completeness of the discriminator set. It is the authors' expectation that new and orthogonal discriminators will be discovered, resulting in a more nuanced and valuable DSN analysis framework.

Finally, the authors believe fault tolerance will play a major role in the future adoption of DSNs within the DoD, and have found it useful to cast DSNs as complex component-based systems when discussing the challenges of sensor faults. Work is underway to explore the role that robust Byzantine Fault Tolerance (BFT) has to play in the design and operation of DSNs. The authors believe that BFT models will prove too constraining for defense-oriented DSN applications and that a more relaxed model—specifically one that facilitates operator-selected tradeoffs in precision, trust, and efficiency—will be necessary.

6   Acknowledgments

Notes

[1]Disclaimer: The authors affiliations with SSC Atlantic are provided for identification purposes only and are not intended to convey or imply the above organizations concurrence with or support for the positions, opinions, or viewpoints expressed by the authors.

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