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Collaborative Signal and Information Processing in Wireless Sensor Networks: a Review

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***Abstract*— Wireless Sensor Networks (WSN) have become a significant research challenge, attracting many researchers. This paper provides an overview of collaborative WSN, reviewing the algorithms, techniques and state-of-the-art developed so far. We discuss the research challenges and opportunities in this area. The major focus is given to cooperative signal and information processing in collaborative WSN in order to expose important constraints in wireless applications which require distributed computing, such as node localization, target detection and tracking. In this paper, we also present and discuss the applications of multi-agent systems into WSN as a core technology of cooperative information processing.**

***Keywords*— wireless sensor networks, collaborative information processing, cooperation, signal processing, localization algorithms.**

I. INTRODUCTION

In the last few years, technological progress has been taking the spread of embedded control steps further. Communication has been recognized as a crucial aspect in addition to computation and control in order to realize the vision of ubiquitous computing [1], where many different devices will gather and process information from many different sources to both control physical processes and to interact with human users.

Wireless Sensor Networks (WSN) is a technology, based on communication, digital circuitry and Micro Electro Mechanical Systems (MEMS) which promises considerable potential to satisfy the growing computing requirements [2].

The WSN consist of individual nodes that are tiny, battery-powered devices which can process, compute and communicate various signals/information in order to interact with their environment. They also contain sensors and actuators to control the physical characteristics of the world.

On the basis of nodes that have sensing and actuation capabilities, many different application scenarios have been constructed. Several current and potential applications of WSN include: security for military or personnel, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environmental monitoring, wildfire detection [3], building and structures monitoring [4], tracking people and assets, monitoring leaking chemicals in chemical plants; preventive maintenance of machines, medicine and health care [5].

Wireless sensor nodes are severely resource-constrained due to various constraints, such as their miniature size, low-complexity, limited battery power, and limited communication and computation capacities. Although each node has the capability to sense the environment, make computations, and communicate with other nodes, the wireless nodes have to cooperate and use collaborative signal and information processing techniques in order to fulfill their tasks as, usually, a single node is not always capable of sensing the whole environment.

In addition, the major constraint to individual node performance is energy, which is consumed primarily by sensing and communications operations. Thus, efficient collaboration among sensor nodes is needed to perform complex monitoring and processing tasks using low-complexity sensor nodes. Hence, reducing the utility of a remote sensor's data throughout the WSN cooperation is essential in the applicability of WSN to applications with physical constraints, reducing computation and communication loads and thus, conserving power.

Collaborative WSN architectures and algorithms are needed to create levels of cooperation in WSN operations for wireless signal and information processing in order to employ the cooperative WSN technology efficiently and cost-effectively into many useful application scenarios.

A typical example application using cooperative information processing in WSN can be easily considered as collaborative localization and tracking, which is one of the core areas of application in this field. The geospatially deployed remote sensor nodes collect signals from a moving object or another entity within their coverage area and they communicate information about this object with other sensor nodes to localize the objects. Depending on the area of application, the objects being tracked can be wild animals, vehicles, people or materials.

There are many challenging research issues that exist in the field of collaborative localization, which has attracted researchers to develop various localization algorithms and techniques for WSN.

This paper provides a research literature review on cooperative signal and information processing in WSN, and discusses challenging issues and future research opportunities

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in this area. The major focus is on collaborative localization and tracking, using WSN.

The rest of this is organized as follows: Section 2 presents a background in collaborative wireless sensor networks, Section 3 discusses challenging research issues of cooperative signal and information processing for WSN and corresponding state-of-the-art, Section 4 identifies future research opportunities and Section 5 provides brief concluding remarks.

II. COLLABORATIVE WIRELESS SENSOR NETWORKS

WSN evolved as a consequence of the advancements in several areas of research. These are mainly: sensing, wireless communication and computing (including hardware, software, and algorithms).

Examples of early WSN include the radar networks used in air traffic control. The national power grid, with its many sensors, can be viewed as one large sensor network [6]. These systems were developed with specialized computers and communication capabilities, and before the term “wireless sensor networks” came into vogue.

The rapid progress of wireless communication and embedded micro sensing MEMS technologies has made the development of WSN possible through the tiny, battery-powered nodes that have computational capabilities. The wireless nodes can communicate with each other and interact with their environment in order to gather, process and convey the information.

WSN are commonly referred to as ad-hoc or decentralized wireless networks, due to their capability of forwarding data to other nodes, and so the determination of which nodes forward data is made dynamically, based on the network connectivity [7].

The nodes in an ad-hoc wireless sensor network collaborate to collect and process data to generate useful information.

Collaborative signal and information processing over a network is a relatively new area of research and is related to distributed information fusion. Important technical issues include the degree of information sharing between nodes and how nodes fuse the information from other nodes. Processing data from more sensors generally results in better performance but also requires more communication resources (and, thus, energy).

Less information is lost when communicating information at a lower level (e.g., raw signals), but requires more bandwidth. Therefore, one needs to consider the multiple tradeoffs between performance and resource utilization in collaborative signal and information processing using wireless sensors.

Other processing issues include how to meet mission latency and reliability requirements, and how to maximize sensor network operational life. A dense network of cheap sensors may allow spatial sampling without the need for expensive algorithms. These algorithms must be asynchronous, as the processor speeds and communication capabilities may vary or even disappear and reappear. Research and experience have shown that optimal collaboration among sensor nodes can significantly improve the efficiency of sensing and processing in sensor networks.

There are instances when collections of nodes need to cooperate with each other in detection of signals or events [8]. In such instances, when a cooperative function is required to extract information about a specific target, a local network is built to facilitate the necessary signaling and data transfer tasks. Typically, cooperative functions involve a small set of nodes near the target location and operate for relatively short time spans. They are required to adapt quickly and efficiently to the appearance of the target and the nature of the signal processing techniques required.

III. RESEARCH ISSUES AND STATE-OF-THE-ART

The distributed nature of WSN introduces various challenges and opportunities for collaborative networked signal processing techniques that can potentially lead to significant performance gains.

In some applications, a single sensor node is not able to decide whether an event has happened but several sensors have to collaborate to detect an event and only the joint data of many sensors provides enough information. Information is processed in the network itself in various forms to achieve this collaboration, as opposed to having every node transmit all data to an external network and process it “at the edge” of the network.

By integrating sensing, signal processing, and communications functions, a WSN allows information to be processed on different levels of abstraction, ranging from detailed microscopic examination of specific targets to a macroscopic view of the aggregate behavior of targets. According to the concept of the hierarchical information processing in the sensor networks, the WSN can been considered as composed of three distinct levels; namely; node, local neighborhood and global [9]. Any events in the environment can be processed on these three levels. On the node level, data collection and processing occurs in each individual node, requiring no communication except for transmission of the results to some distant information sink. On the local and global levels, inter-nodal communication is required for gathering raw or preprocessed data from multiple nodes to a single location for cooperative signal processing, such as data fusion or beam forming.

When a sensor node receives information from another node, this information has to be combined and fused with local information. Fusion approaches range from simple rules of picking the best result to model-based techniques that consider how the information is generated. There is a tradeoff between performance and robustness. Simple fusion rules are robust but suboptimal while more sophisticated and higher performance fusion rules may be sensitive to the underlying models. In a networked environment, information may arrive at a node after traveling over multiple paths. The fusion algorithm should recognize the dependency in the information to be fused and avoid double counting. Keeping track of data pedigree is an approach used in networks with large and powerful sensor nodes, but this approach may not be practical for ad hoc networks with limited processing and communication resources.

WSN are frequently used in the detection, tracking, and classification of targets [11]. Data association is an important problem when multiple targets are present in a small region. Each node must associate its measurements of the environment with individual targets. In addition, targets detected by one node have to be associated with targets detected by other nodes to avoid duplication and enable fusion. Optimal data association is computationally expensive and requires significant bandwidth for communication. Thus, distributed data association is also a tradeoff between performance and resource utilization, requiring distributed data association algorithms tailored to sensor nets.

The wireless sensor nodes function much like individual ants that, when formed into a network cooperatively accomplish complex tasks and provide capabilities greater than the sum of the individual parts [10]. Several authors have studied various aspects of their collaboration.

Agre and Clare [12] have studied the architectural aspects of cooperative signal processing. They have emphasized the autonomy of the sensor nodes at the low level and have proposed a layered architecture for the distributed sensor networks, which integrates the cooperation into autonomy. The collective behavior of the complex sensor networks increases by moving to higher layers and the autonomy of the individual sensor nodes increases when moving to the lower layers.

Pradhan *et al.* [13] have proposed a method that allows minimizing the amount of inter-nodal communication while preserving the resolution of the data gathered. The goal is to compress sensor data from individual nodes while requiring minimal inter-sensor communication.

Sohrabi *et al.* [10] have developed a number of algorithms for establishing and maintaining connectivity in WSN. Their algorithms aim at the self-organization of the wireless sensor networks, exploiting the low mobility and abundant bandwidth, while coping with the severe energy constraint and the requirement for network scalability.

Chu *et al.* [14] have presented data-querying and routing approaches in WSN with the objective of energy efficiency. Their approach relies on two key ideas: information driven sensor querying to optimize sensor selection and constrained anisotropic diffusion routing to direct data routing and incrementally combine sensor measurements so as to minimize an overall cost function.

A. Collaborative Localization

The localization in WSN is a significant, key enabling technology. With the constrained resources of network sensors, as well as their high failure rate, many challenges exist in the automatic determination of the sensor's location. Various application requirements, such as: scalability, energy efficiency, cost, accuracy, responsiveness and privacy, influence the research and development of sensor localization systems [15].

In many circumstances, such as in objects tracking, the automatic detection of sensors' location, namely localization, is essential. It is necessary for a sensor node in a WSN to be aware of its location in the physical world in which it resides. In other words, the node's location must be known in order to collect meaningful data from a physical phenomenon. The sensor node's position is an essential input to many location-aware sensor network communication protocols, such as packet routing and sensing coverage [16].

Due to the fact that the sensor nodes are usually deployed in high quantities and their position is often subject to changes, each node has to be equipped with an onboard positioning system, such as GPS that tells the location. However, the GPS is often impractical to use in WSN due to cost and deployment limitations [17]. WSN are often facilitated with localization systems that use various special techniques for automatically detecting the position of nodes.

Sensor network localization techniques, developed so far, generally consist of the algorithms that estimate the locations of sensors with initially unknown location information by using knowledge of the absolute positions of a few sensors and inter-sensor measurements. Sensors with known location information are called 'beacons' or 'anchors'. The anchors define the local coordinate system to which all other sensors are referred. The coordinates of the sensors with unknown location information, also called blind or non-anchor nodes, will be estimated by various sensor network localization techniques.

In terms of computation, the WSN localization algorithms can be classified into centralized and distributed schemes. In the centralized scheme, sensor nodes send control messages to a central node whose location is known. The central node then computes the location of every sensor node and informs the nodes of their locations. In the distributed scheme, each sensor node determines its own location independently.

Collaborative localization techniques are a class of techniques which utilize distance measurements between pairs of location-unaware sensor nodes. Unlike traditional centralized localization techniques, collaborative localization techniques exploit the ad-hoc networking capabilities of all the sensor nodes instead of just the anchor nodes for location estimation. Collaborative location estimation algorithms allow location-unaware sensor nodes that are not in the range of any anchor nodes to be located, provided they have at least one neighboring sensor node. Such algorithms do not demand overlapping coverage of anchor nodes and work well in sparse reference node configurations.

The collaborative approach works much better for topologies in which the shortest path distance between two nodes does not correspond well to their Euclidean distance [18]. Generally, the collaborative approach yields more accurate results due to the availability of greater resolution of data to estimate a sensor node location.

Recently, several researchers have focused on developing algorithms based on multidimensional scaling (MDS), which is a technique from mathematical psychology, to derive node locations for those estimated distances and normalize the resulting coordinates to take into account any nodes whose positions are known.

Savvides *et al.* [19] proposed AHLoS (ad hoc localization system), which uses beacon nodes for a location discovery process called iterative multilateration. In this method, all the nodes collaboratively discover their positions by repeating the process of finding positions using the beacons that continuously broadcast their location information to the sensor network.

Shang and Ruml [20] have developed the MDS-MAP algorithm, which uses connectivity information to obtain location information of the nodes in a sensor network. The MDS technique is used to convert data proximity information to geometric embedding. MDS-MAP builds local maps and stitches them together to form a global map. It operates by setting the number of hops as the range for local maps and applies MDS-MAP within this range to generate its local map. These maps are stitched together by choosing local maps which share the maximum number of neighbor nodes with the current map.

Kwon and Song [21] have introduced a map stitching localization algorithm based on a technique for map-to-map stitching that exploits every available distance between two maps.

Costa *et al.* proposed distributed multidimensional scaling with an adaptive weighting algorithm [22], where each sensor node chooses a neighborhood of sensors and computes its position estimate by minimizing a cost function and then passes this position update to its neighbors. Further, the inhomogeneous character of range measurements is taken care of by applying weights to measurements which are believed to be more accurate.

B. *Source Localization and Tracking*

A typical application of WSN is to estimate the location of the moving targets, using the wireless nodes deployed around the field. One of the greatest challenges for developing WSN for target tracking is the battery power conservation. The batteries of each sensor node in the field might be very difficult to replace. Hence, several collaborative techniques and algorithms have been developed for this purpose.

The basic assumption is that each sensor in the network can exploit the information content of the data already received to optimize future sensing actions, and so efficiently manage the scarce communication and processing resources.

Zhao *et al.* [23] introduced the information driven approach in Ad-Hoc sensor networks through determining participants in "sensor collaboration" by dynamically optimizing the information utility of data for a given cost of communication and computation. Li et al. [24] presented a technique for tracking multiple targets using the probabilistic classification algorithms based on the spectral target signatures.

Brooks *et al.* [25] proposed a collaborative signal processing technique for target classification and tracking in distributed sensor networks based-on location-aware data routing that limits the scope of collaborative signal processing to a subset of nodes conserving network resources, such as energy and bandwidth.

Rabbat and Nowak [26] have presented collaborative source localization and tracking algorithm based on a received signal strength measurement. The small amounts of data communication scheme used by this algorithm aims to improve the energy efficiency.

Sheng and Hu [27] have proposed an acoustic energy based localization using a multi-modality energy detection and multi-modality region detection. The sensors collaborate to detect and localize the targets using the acoustic level in the region.

Arora *et al.* [28] have applied these source localization techniques into the application named 'line in the sand' for target detection, classification, and tracking in military operations. In this application, a network of binary wireless sensors has been used, which is not assumed to be reliable.

Lin *et al.* [29] have done an optimization study over the tracking techniques by analyzing the update and query operations by taking the physical topology of the sensor network into consideration.

Wang and Yang [30] have studied the acoustic source localization in WSN and have reformulated the centralized energy ratios using the NIG algorithm. During localization, the localization message cycles through the network from neighbor node to neighbor node, until the location estimation converges to a limit point or the itinerancy exceeds a predefined cycle number.

C. *Software Frameworks*

The software plays an essential role for defining the common gateway for the communication and collaboration of various wireless sensors to perform cooperative tasks. Software frameworks are generally determining factor of the performance of WSN systems based on tiny integrated sensor nodes with limited processing capability, low sensing quality, and scarce energy resources. The main reason is that, they provide various functions for collaborative processing such as; organization, clustering and information management. In addition, they provide various solutions for vertical and horizontal integration of WSN into other networks such as; existing telecommunication networks, other wireless networks and service infrastructures. There are a number of software solutions proposed in the literature for collaborative information and signal processing in WSN.

Lombriser *et al.* [39] presented a middleware architecture e-SENSE for distributed information processing in WSN. The system provides organization of the sensor nodes in the form of clusters based on shared context at the lower layer. These clusters form the basis for the service-oriented processing layer, where the functionality of the sensor network is expressed using service task graphs supporting distributed execution of applications. The higher layer is responsible for complex context inference and recognition. Each sensor node in the network contributes with its perception of activities by issuing events, which are subsequently fused by a distributed fuzzy inference system in order to derive a reliable aggregate decision of the actual activity performed.

Gravina *et al*. [40] have proposed the SPINE software framework for the design of WSN applications. The framework enables implementations of signal processing algorithms with the coordination level of the network of sensors and enhances development of WSN applications using a set of library routines for interoperability among different WSN applications through the components of typical WSN systems.

D. Agent Technology in WSN

Due to its distributed and collaborative nature, WSN has many similarities with multi-agent systems technology. Characteristics of agents (including mobile agents and multi-agents), such as autonomy, reactivity, and social ability, perfectly match the autonomous, reactive and collaborative features of WSN [31]. Collaborative processing is primarily accomplished by multi-agent cooperation and mobile agents can be used in cases of bulk data exchanges.

Hussain *et al.* [32] have introduced a multi-agent architecture in order to facilitate the design, implementation, and maintenance of applications for sensor networks that consist of wireless sensor nodes. The architecture contains four types of agents: interface, regional, cluster, and query agents. The agents are deployed in sensor motes to reduce the overall message communication and the energy consumption through collaborative processing.

Tseng *et al.* [33] proposed a protocol based on the *mobile agent* paradigm to solve the problem of *location-tracking*, the goal of which is to trace the roaming paths of moving objects in the network area. The mobile agent chooses the sensor closest to the object to stay and it will follow the object by hopping from sensor to sensor. The agent may invite some nearby slave sensors to cooperatively position the object and inhibit other irrelevant sensors from tracking the object in order to reduce sensing, computing, and communication overheads.

Wang *et al.* [34] introduced similar mobile agent architecture for WSN for energy-based localization and tracking applications.

The agent-based techniques have been preferred by some researchers for efficient data dissemination in WSN. Several authors, such as Sin *et al.* [35], Boonma, and Suzuki in [36] and [37] have proposed agent-oriented frameworks for the WSN, which are based on biologically-inspired approaches. The agent operates automatically with their behavior policies as a gene and aggregates other agents to reduce communication and gives high priority to nodes that have enough energy to communicate.

A Biologically-Inspired Architecture for Wireless Sensor Networks (BiSNET) [36] is a developed framework that allows agents to autonomously adapt to dynamic network conditions.

A Co-evolutionary Multi objective Adaptation Framework for Dynamic Wireless Sensor Networks (MONSOON) [37] is designed to support data-collective applications, event-detection applications and hybrid applications. Each application is implemented as a decentralized group of software agents, analogous to a bee colony (application) consisting of bees (agents). The architecture of MONSOON consists of two types of software components: agents and middleware platforms. Agents collect sensing data and/or detect an event on individual nodes, and carry sensing data to the base station.

Ruairí and Keane [38] also presented a framework of agent-oriented WSN with the objective of energy conservation. The overall WSN operates by seeding itself with a multi-agent paradigm with a number of agents, where each agent is composed of roles distributed across multiple nodes namely: Seeper, Leader, Member and Router roles.

IV. Future Research Opportunities

Collaborative WSN is a vast area of research with multiple aspects of study. The main concentration in WSN collaboration is to distribute the computational load among the network of sensor nodes in a co-operative manner for conserving energy and reducing costs. Cooperative processing is an essential utility for distributed applications of WSN, such as tracking and localization. Despite significant research developments in this area, there are still many unsolved problems in collaborative wireless sensor networks for cooperative information and signal processing due to the application-specific characteristics and requirements.

For example, one of the most significant problems, which affect the accuracy and efficiency in signal processing, is the path loss and unpredictable multipath, due to the reflections of radio signals. Several wireless hardware platforms have been developed over the years for resolving these issues. However, more experimental work is necessary to make WSN applications more reliable and robust in the real world.

In addition, as described earlier, agent technology promises great potential for WSN in enhancing cooperative information technology. However, the multi-agent based approaches are not deeply studied for the real world applications of WSN. The wireless nodes can be smarter and more cooperative with the aid of intelligent agents, supporting intelligent routing and self-organization features, which many researchers have been working with over the years. Agent technology needs to be investigated more for potential WSN applications.

V. Concluding Remarks

The research interest on the WSN is likely to grow with the increase in wireless sensor network applications. This paper has provided a review of several techniques and the state-of-the-art for distributed, cooperative signal and information processing in WSN. The systems and research work in the area presented were classified according to the core areas of application and the base technology used.

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