

DISTRIBUTED SENSOR PROCESSING OVER AN AD HOC WIRELESS NETWORK: SIMULATION FRAMEWORK AND PERFORMANCE CRITERIA

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Abstract—The evaluation of existing and future distributed sensor processing system concepts can be done well using simulation, provided that the simulation is faithful in representing both the medium in which the sensors interface with the phenomena that they measure or detect and the medium in which the sensors interface with each other to achieve a distributed mode of operation. In this paper, performance criteria for distributed sensor processing over ad hoc wireless networks are stated and an architecture for analysis and simulation of this kind of system is described.

Keywords—Ad hoc networks, MANET, sensor networks, self-organization.

I. INTRODUCTION

A. Network of Wireless Sensors

The two main goals of a wireless sensor network are to detect events of interest and estimate parameters that characterize these events. The resulting information needs to be transmitted to one or more locations outside the network. For example, a typical scenario may include a number of sensors spread over an outdoor area for the purpose of determining vehicle traffic. The first step is to determine if there is a vehicle present, and the second step is to classify the vehicle as a car, truck, jeep, *etc.* Parameters such as speed, direction, and cargo are of interest. Figure 1 shows a conceptual diagram of the three layers in the physical system. The cluster layer is where the collaborative signal processing occurs, while the wireless mobile ad hoc network (MANET) is responsible for routing and disseminating the information. Note that conceptually, the wireless network is larger than the sensor network, because it includes additional nodes such as soldiers and vehicles.

The issues in designing a sensor network include: (1) selection of the collaborative signal processing algorithms run at each sensor node, (2) selection of the multihop networking algorithms, and (3) optimal matching of sensor requirements with communications performance. For military networks, additional issues are:

⁰This work was supported by the Advanced Research and Development Activity (ARDA) under contract number 706400.

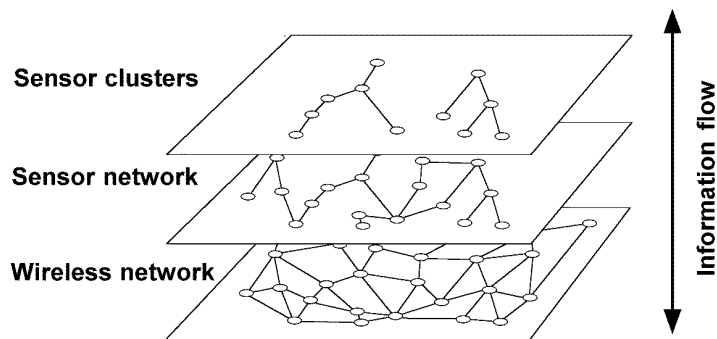


Fig. 1. Three conceptual layers in a wireless sensor network.

- Low probability of detection and exploitation.
- Resistance to jamming; reliability of data.
- Latency.
- Survivability of the system.

B. System Simulation

Given the interaction of the processing at the different layers of the protocol stack, analytical studies will most likely be insufficient for overall performance analysis. Therefore, an approach combining analysis and simulation is proposed. Even so, to make the design and optimization efforts tractable, the problem should be decomposed as much as possible. This is done by clearly defining interfaces between the different layers containing the various sensor, networking, and communication processes. Moreover, the simulation of the wireless sensor network must be coupled with the simulation of the environment and the target(s); there are two or more transmission media, one for the radio propagation and the other for the propagation of the sensor input (acoustic, seismic, *etc.*).

II. SENSOR CLUSTERS

To reduce the amount of power spent on long distance radio transmissions, we suggest aggregating the sensor nodes into clusters; this concept has been proposed by a number of authors [1] [2] [3] [4] [5] in various contexts, but it is especially useful here given that the ranges

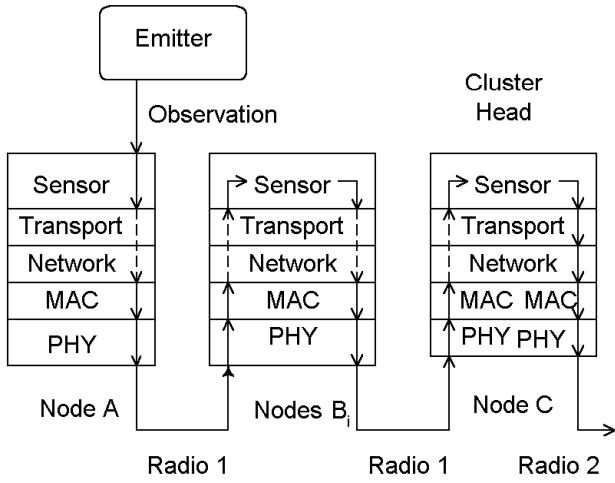


Fig. 2. The movement of data through the different protocol layers in a cluster-based wireless sensor network.

of the sensors are relatively short. During the process of distributed detection/estimation and data fusion, the radio transmissions are among nodes within a cluster, under the control of a “cluster head” or “master” node. While it is quite possible that all the nodes in a cluster are identical, it may be more desirable to provide the cluster head with more functionality. Location awareness using GPS and a longer-range radio are two useful additions.

Figure 2 shows the processing occurring at different layers in the protocol stack for such a cluster-based system. A short range radio (“Radio 1”) is used to communicate among the sensors in a cluster. The sensor layer is responsible for the collaborative signal processing; this processing can include beamforming, as well as the distributed detection/estimation and data fusion. Let us now consider how the system operates. An emitter generates observations at one or more sensors. In the figure, only node A receives a particular observation. The sensor layer processes the observation and make a tentative decision, thereby doing data reduction down to a few bits¹. This information is placed in a very short data packet that is to be sent to all other nodes in the cluster (Nodes B_i and Node C), assumed to be within one hop. Therefore, the packet can bypass the transport and network layers and go directly to the MAC layer for transmission at the appropriate time.

Upon reception of the packet, the other nodes update their tentative decisions. These decisions may then be re-broadcast to all nodes in the cluster. The number of iterations depends on the distributed algorithm, and eventually convergence is achieved. A number of parameters, such as the decision and a confidence measure, now need to be

¹For beamforming, either the raw data or a finely quantized version thereof is transmitted instead, required significantly more bandwidth.

P_D	Probability of Detection
P_F	Probability of False Alarm
$P(e)$	Probability of Error
i	Number of iterations
N_{ca}	Number of channel accesses
N_b	Number of bits transmitted
$R^*(d)$	Misclassification Probability
E_T	Total energy expended

TABLE I
SIGNAL PROCESSING-SPECIFIC METRICS.

transmitted from the cluster to a remote location using the larger mobile ad-hoc network.

So, a summary packet is generated and sent down to the network layer, as shown by the solid lines in the right side of node C. The network layer uses its routing protocol to select the next hop in the MANET. The network packet is encapsulated by the MAC and transmitted. The actual transmission may use the same radio system as was used for the cluster-based processing [1], albeit with increased power and changes in other radio parameters. For example, the virtual subnet approach [6] uses different channels for the intracuster and intercluster communications. However, it is also possible to use a completely different radio, as suggested in Figure 2.

III. DISTRIBUTED SENSOR PROCESSING

A. Performance Criteria

Firstly, let us consider distributed detection [7]. The basic idea is to have a number of independent sensors each make a local decision (often a binary one) and then to combine these decisions at a fusion center to generate a global decision. In the Neyman-Pearson formulation, one assumes a bound on the global probability of false alarm (P_F), and the goal is to determine the optimum decision rules at the sensors and the fusion center that maximize the global probability of detection (P_D). Alternatively, one can use the Bayesian formulation and compute the global probability of error, $P(e)$. Table I shows a number of metrics quantifying the signal processing performance. If the communication network is able to handle the increased load, performance can be improved through the use of decision feedback [8] [9].

Swaszek and Willet [9] propose an extensive feedback approach that they denote “parleying.” The basic idea is that each sensor makes an initial binary decision that is then distributed to all the other sensors. The goal is to achieve a consensus on the given hypothesis through

multiple iterations, i . Their n th-root algorithm constrains the consensus to be optimum in that it matches the performance of a centralized processor having access to all the data. The main algorithmic performance issue is the number of parleys (iterations) required to reach this consensus. Recently, we proposed an extension to the parley algorithm [10] that uses soft decisions in order to reduce both the number of channel accesses required (N_{ca}) and the total number of bits (N_b) transmitted. Finally, the parley algorithm leads to the same global decision being made at each node in the cluster.

When classifying a target, the true misclassification probability, $R^*(d)$, is the main metric of interest. For any parameters, the maximum likelihood (or maximum *a posteriori*, if possible) estimate of these parameters is desired, along with the variance of the estimate. Additionally, the total energy expended, E_T , in making the detection decision and doing any parameter estimation and classification is important.

B. Node Complexity Issues

While the use of decision feedback in a sensor cluster can certainly improve performance, there is an additional cost in the complexity of the sensor nodes and a possible increase in transmission energy requirements. Advances in integrated circuitry mitigate the first problem, and the use of short range transmissions helps with the second one. In general, the trend is to put more signal processing in the node in order to reduce the number of transmissions [3]. Cluster-based collaborative signal processing seems to provide a good tradeoff between improved performance and low energy use. Within a node, “multispectral” or “multimode” sets of collocated sensors, combined in a kind of local data fusion, may be used to improve the performance. This type of data fusion is generally different from the data fusion possibly occurring at a fusion center (cluster head).

C. Context Awareness

The overall utility of the sensor network may be improved if each sensor is “context-aware;” that is, it has some knowledge of its environment. Schmidt *et al.* [11] studied the use of context awareness for adapting the operating parameters of a GSM cell phone and a personal digital assistant. They proposed a four layer architecture. The lowest layer is the sensor layer, which consists of the actual hardware sensors. For each sensor, a number of cues are created. Cues are abstractions of a sensor, and they allow calibration and post-processing; when a sensor is replaced by one of a different type, only the cues must be modified.

Typical cues include

- The average of the sensor data over a given interval.
- The standard deviation over the same interval.
- Distance between the first and third quartiles.
- First derivative of the sensor data.

Multiple sets of contexts can be defined from the cues. For example, a single context is the terrain surrounding the sensor node, such as forest, urban area, open field, *etc.* Here, the choices are mutually exclusive, but this is not a requirement. Another context is the number of other sensor nodes with direct (single-hop) radio connectivity. A third context is the required level of transmission security or stealth. Determining the cue to context mapping is, in general, a difficult challenge. Once the sensor’s context is known, parameters such as transmit power, waveform, distributed detection algorithm, *etc.* can be set.

IV. PERFORMANCE CRITERIA FOR WIRELESS SENSOR NETWORKS

A. Critical Ad Hoc Networking Features

Regardless of the application, there are certain critical features that can determine the efficiency and effectiveness of an ad hoc network. These features can be categorized into quantitative features and qualitative features [12] [13]. Quantitative features include

- Network settling time: the time required for a collection of mobile wireless nodes to automatically organize itself and transmit the first message reliably.
- Network join time: the time required for an entering node or group of nodes to become integrated into the ad hoc network.
- Network depart time: the time required for the network to recognize the loss of one or more nodes, and reorganize itself to route around the departed nodes.
- Network recovery time: the time required for a collapsed portion of the network, due to traffic overload or node failures, to become functional again once the load is reduced or the nodes become operational.
- Frequency of updates (overhead): the number of control packets required in a given period to maintain proper network operation.
- Memory requirement: the storage space requirements in bytes, including routing tables and other management tables.
- Network scalability: the number of nodes that the ad hoc network can scale to and reliably preserve communication.

Qualitative critical features include

- Knowledge of nodal locations: Does the routing algorithm require local or global knowledge of the net-

work?

- Effect of topology changes: Does the routing algorithm need complete restructuring or only incremental updates?
- Adaptation to radio communication environment: Do nodes use estimated knowledge of fading, shadowing, or multiuser interference on links in their routing decisions?
- Power consciousness: Does the network employ routing mechanisms that consider the remaining battery life of a node?
- Single or multichannel: Does the routing algorithm utilize a separate control channel? In some applications, multichannel execution may make the network vulnerable to countermeasures.
- Bidirectional or unidirectional links: Does the routing algorithm perform efficiently on unidirectional links, *e.g.*, if bidirectional links become unidirectional?
- Preservation of network security: Do routing and MAC layer policies support the survivability of the network, in terms of low probability of detection, low probability of intercept, and security?
- QoS routing and handling of priority messages: Does the routing algorithm support priority messaging and reduction of latency for delay sensitive real-time traffic? Can the network send priority messages/voice even when it is overloaded with routine traffic levels?
- Real-time voice and video services: Can the network support simultaneous real-time multicast voice or video while supporting traffic loads associated with situation awareness, and other routine services?

B. Performance Metrics

Thread-task level metrics include average power expended in a given time period to complete a thread (task), including power expended in transmitting control messages and information packets, and task completion time. Diagnostic metrics, which characterize network behavior at the packet level, include end-to-end throughput (average successful transmission rate) and delay, average link utilization, and packet loss rate.

C. MANET Routing

As previously discussed, the performance of the sensor network depends on the routing of the underlying ad hoc network. MANET routing algorithms include the dynamic source routing protocol (DSR) [14] and the ad-hoc on-demand distance vector routing protocol (AODV) [15], either of which can be used as basis for the underlying wireless network. Perhaps of more relevance is the zone

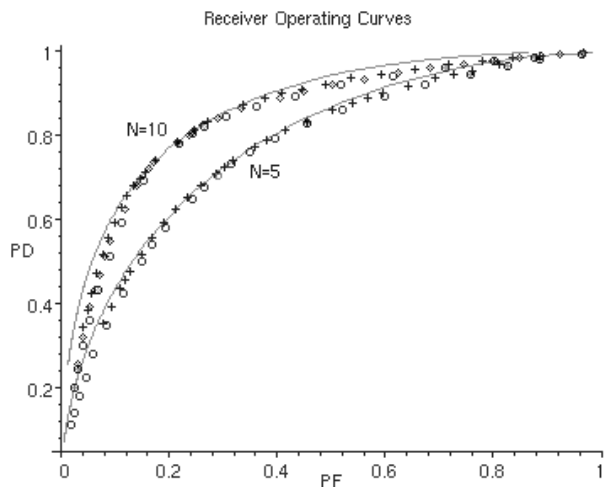


Fig. 3. Receiver operating curves for the two parley algorithms. The original algorithm [9] is indicated by crosses, while the improved one [10] is indicated by diamonds and circles. These curves are for a Gaussian shift in mean problem with means of zero and 0.5, and a standard deviation of one.

routing protocol (ZRP) [16], which it is a hybrid of proactive and reactive routing protocols. This means that the network is partitioned into zones, and the routes from a node to all other nodes in its zone are determined. Routes to nodes in other zones are found as needed. ZRP may allow the sensor network to implement decision feedback among all nodes in a zone in a straight-forward manner.

V. CURRENT WORK

Figure 3 shows receiver operating curves (ROCs) for clusters of 5 and 10 sensors using the parley algorithm with soft decisions [10]. The analytical curves are for the optimal central detector. Also plotted are the data for the original parley [9] algorithm. One sees that both algorithms achieve effectively optimal results. Now, the goal is to develop a self-organizing wireless sensor network so that the sensing performance at a given location is similar to that shown in the figure. At the same time, the network must form a routing backbone for data dissemination, while providing robustness to lost links and nodes.

As an example, consider the sensor network shown in Figure 4. The sensors have been placed along the roads, with the greatest concentration at the fork. The Linked Cluster algorithm (LCA) [1] was used to self-organize the network, leading to the creation of four clusters. Clusters 1 and 2 overlap, as do clusters 1 and 3, so only a single gateway node is used to connect each pair. Since clusters 0 and 1 do not overlap, a pair of gateways is created; the resulting backbone network that connects the clusterheads

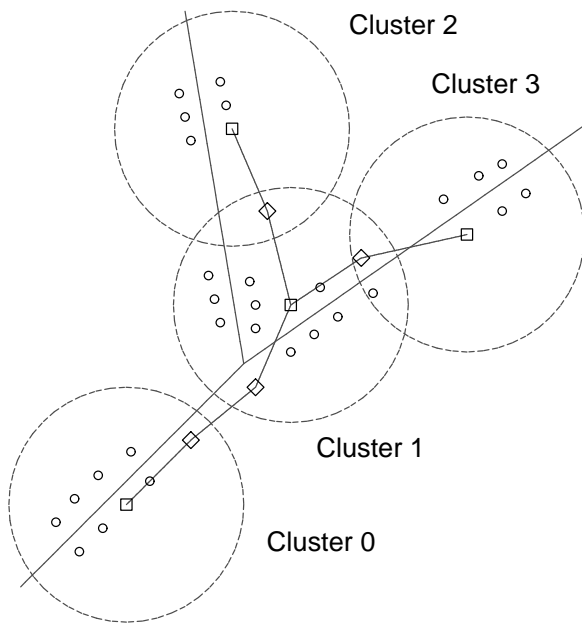


Fig. 4. Self-organized sensor network. The cluster heads are squares, the gateway nodes are diamonds, and the ordinary sensor nodes are circles. The transmission areas of the four clusterheads are indicated by the four large circles.

is shown in the figure.

A few points are worth mentioning. Firstly, the numbering of the nodes in the LCA determines which nodes become cluster heads and gateways. Since the initial topology was known, four specific nodes were assigned the highest node numbers, thereby ensuring that they would become cluster heads. By essentially choosing the cluster heads *a priori*, the clusters have shapes that are well-suited for the collaborative signal processing. Secondly, one may want to further decompose a cluster into subclusters. For example, cluster 1 could easily be divided into two or three sensor groups for the purpose of distributed detection. Once a decision is reached in a subcluster, it would be sent to the cluster head for dissemination.

Presently, we have developed OPNET simulation models for DSR and AODV, and we are engaged in developing algorithms for clustering the sensor nodes, based on the performance criteria given above. Since determining the optimal clusters is, in general, NP-complete [5], heuristics are required.

VI. CONCLUSIONS

To achieve optimal performance in a wireless sensor network, it is important to consider the interactions among the algorithms operating at the different layers of the protocol stack. While there has been much research on parti-

tioning a MANET into clusters, most of this work has focused on doing so for routing and resource allocation purposes. For sensor networks, a key addition is how the self-organization of the network into clusters affects the sensing performance. In this paper, we have discussed a number of metrics and proposed a cluster-based architecture for sensor networks. Ongoing work will develop simulations to compare the different self-organization algorithms in terms of both routing and sensing performance.

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