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SEMANTIC NEIGHBORHOOD SENSOR NETWORK FOR SMART SURVEILLANCE APPLICATIONS

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Abstract. *Smart situation detection is a key feature of today’s surveillance systems. The human operator has to be relieved from overseeing all activities of a monitored area simultaneously. By using smart sensors the operator can be notified about uncommon situations and evaluate only these situations. A key feature of such a system is the flexibility of smart node interaction and the ease of setup. This paper introduces a new method to establish communication paths in large-scale multi-modal sensor networks. Nodes use wireless communication allowing high-range, medium-bandwidth, and secure communication. Some of the nodes also possess wired Ethernet connections to allow the transport of video streams to the supervisor and to make the network truly scalable in terms of number of nodes without scarifying bandwidth. In a stepwise procedure the nodes first discover neighbor nodes by means of wireless connection strength and then try to find overlaps on the semantic level by utilization of the loopy belief propagation algorithm. This procedure is executed various times with increased wireless transmission power what ensures scalability. Finally, all nodes know about their neighbor nodes with overlapping sensor fields and can establish direct communication between them.*

1 INTRODUCTION

Security relevant application of sensor networks have to solve different issues to be successful. In a large network with a some tens or hundreds of nodes it is not feasible to collect all information centrally, especially if video and audio modalities are used. Furthermore there is a need for nodes to communicate between each other, but this again has to be limited to keep the network operable; otherwise the network would be flooded with irrelevant information and valuable memory and processing time would be wasted. Both issues can be solved by processing information locally in each sensor node and transmitting only relevant information to a central or to other nodes. In the system design that is described here, the nodes are able to do video and audio processing as well as semantic processing of the preprocessed sensor information. Based on locally gathered information, the nodes communicate with their physical neighbors to find a global view of the environment that they observe. For example, a person that is visible in one camera view may also be visible in another camera and shall therefore be communicated in the network. Having the same person visible by multiple sensors improves reliability and allows person tracking over multiple sensor nodes. Such information is important for surveillance applications. An application that employs the above mentioned sensors is the airport security system that is built in the SENSE [7], [8] project[1].

While communication between neighboring nodes is important, it is at the same time necessary to reduce communication between nodes that are not neighbors in the logical sense. It is not always the case that nodes which are located close to each other are also semantically connected. Nodes that are mounted on different sides

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of the same wall may observe areas that are not related at all and should therefore not have to exchange information and waste resources. Thus it is important to differentiate between neighborhoods in terms of network connectivity and neighborhoods in the semantic sense.

The system that is described here relies on wireless communication between nodes, but also supports mixed wired and wireless communication. This allows to use network cables where available and establish wireless links otherwise. The wireless communication has another important role when it comes to detecting semantic neighbors. Based on the assumption that nodes, which are spatially far away are also semantically not connected the wireless communication is used to make a first preselection of potential neighbors. Certainly this method runs the risk of missing semantic neighbors that are not colocated, but the possibility of this rare case is sacrificed for improved scalability of the system. Especially in the surveillance context, if the areas monitored by two nodes that are physically distributed, there is likely to be no simple causal link between events identified by those nodes.

Neighbourhood relationships are not predefined, but are inferred by the nodes during operation. This is done by statistical analysis of the shared environment. If two nodes share parts of their sensing areas, some of the events are temporally correlated. If a person is visible in one sensor in a given direction, then the person may also be visible in a neighbouring sensor a briefly afterwards; the direction is influenced by the relative position of the nodes (or the node's sensors, respectively). Frequent repetition of this pattern results in a correlation that is detected by the nodes.

This can be used to increase the dependability of a node's observations, and to establish common views. A common view improves learning about commonly taken paths (i.e. many persons walking in the same direction), even over sensor boundaries. If nodes don't detect significant correlations to neighboring nodes, no information is shared. Over time the network developeds its topology and indicates how nodes correlate their observations. This again helps other nodes to draw conclusions about their environment.

This approach is flexible, since it does not rely on predefined network topologies or predefined correlations between node. It also reduces the amount of commissioning for the whole system, since nodes are able to gather the necessary configuration information over time.

2 COMMUNICATION INFRASTRUCTURE REQUIREMENTS

A smart sensor network has to be able to be flexible in its communication requirements and be able to detect the network structure without extended need for configuration. The following requirements have been identified as key issues to a well-tuned network.

At start up each node shares information with any accessible node to detect relationships among the local views of each nodes. After this self-adaptation process the neighborhood of a node is established and semantic information about events detected in one node are augmented with the information provided by the neighborhood nodes.

Once the nodes have learned about their neighborhood, the communication can be logically restricted to the nodes in its (communication) neighborhood. The concept of node neighborhoods can also be used to establish ad-hoc wireless connections among nodes in order to save communication resources, isolate the information and deal with communication infrastructure failures. Network re-configurability allows a new node that is plugged into the network to join the neighborhood of all nodes and to learn its correct neighborhood. This finally results in updated neighborhood relationships. A permanent failure of a node will, on the other hand, result in updated neighborhoods among the other nodes.

Nodes in the network need to be able to do self calibration. This means that sensor modality modules (i.e. camera and audio sensors) support self-calibration by digital filtering and dynamic background learning. On the other hand, the network of SENSE nodes calibrate by learning symbol correlations among nodes.

Sensor modalities within a node create Low Level Symbols (LLS), which are combined and aligned in different processing layers of the semantic processing module [9] to produce High Level Symbols (HLS). This information enhancement process is done by using statistical techniques. In the upper layers of semantic processing the correlation of HLS between nodes is learned. This knowledge is then used to establish neighborhood correspondences. Once established, HLS are enriched with the information gathered by other nodes. By using object categories the nodes are able to recognize identical objects in different nodes, which is used to establish objects paths over sensing areas of different nodes.

The methods for establishing semantic knowledge about the environment within a node as well as for inter-node views do not depend on the sensor modalities (i.e. audio and video). If, for example, temperature and humidity sensors are used instead, the same approach will be appropriate for learning normality of the environment with respect to these sensor modalities. This portability allows identifying unknown behavior as well as predefined alarm scenarios, and to establish a common view between neighboring nodes.

3 LOOPY-BELIEF PROPAGATION

Communication of semantic information between nodes is based on the Loopy-Belief Propagation (LBP) algorithm. LBP is used to form collections of neighboring nodes and to map events detected by one node to another node's view. This information can be used to store paths or trajectories of persons that appear on multiple nodes, or to detect if somebody tries to avoid surveillance by disappearing unexpectedly from view.

Belief propagation in general is an iterative algorithm for computing marginal distributions of functions on a graphical model. Examples are pair wise Markov random fields or Bayesian networks. Loopy Belief Propagation (LBP) is an extension of the belief propagation framework from polytrees to general networks and was developed by Pearl [1]. Such generalized graphs can have loops, which gave the algorithm its name.

Aside of local learning the nodes learn a global view of normality, i.e. the system learns not locally in a node, but globally the common behavior. The nodes have partially overlapping sensing areas and have a symbolic statistical representation of normality in their local views. For establishing global views about normality in a "stochastic" environment the following requirements occur: it has to be based on statistical methods, decentralized, and computationally inexpensive.

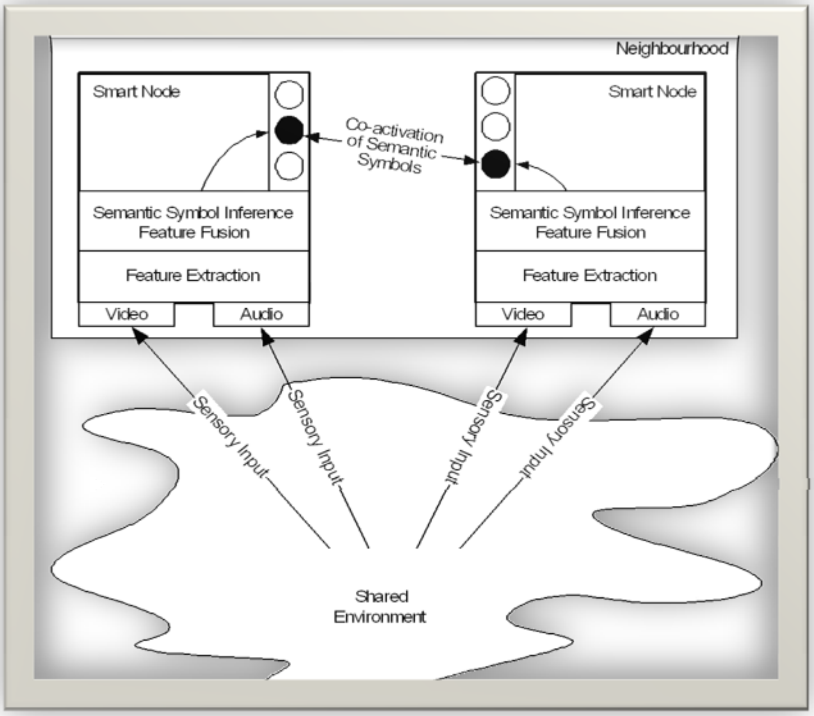

Fig. 1 Symbol inference between neighboring nodes

The belief propagation algorithm for loopy graphs is based on statistical methods and is decentralized. Since it is an "old" algorithm (it was developed about 20 years ago), it is today computationally inexpensive. Among the different areas of usage are error correcting codes (e.g. the "Turbo code" [2], [3]) or machine learning [4]. Recently it has been a candidate for sensor networks communication [5] as well as image understanding [6].

The Loopy Belief Propagation updates stochastic variables in nodes by iterations and appears to be suitable for the described system since it employs decentralized processing. It has been shown that the LBP algorithm performs well in learning contexts, where the Expectation-Maximization (EM) algorithm is used to learn model parameters and LBP is used to perform an approximate calculation of the required expectations.

During operation the system has two states: first the system starts up and infers correlations between different nodes, that is, between different semantic symbols in the nodes. It transmits broadcast messages to all nodes in range. After this state the system has learned or inferred all the correlations and sends messages only to those nodes that are really neighbors – semantic neighbors. Semantic neighbors now have semantic symbols that are correlated with the local semantic symbols).

The nodes therefore communicate by sending and receiving messages from and to other nodes, where the nodes must be reachable by their neighboring nodes. The information of neighborhood is stored as a matrix with the HLS and is therefore a parameter that varies over time. Another task is to update the correspondences and therefore the weights between HLS. The results are matrices on each node that represent correlations between the node's own HLS and those of reachable neighbors. Fig. 1 shows two neighboring nodes that detect co-activation of symbols. They use this knowledge to gain information about their environment and about their overlapping sensing areas.

The information exchange between nodes contains the exchange of *beliefs* about the current state of the observed area. A belief object, which is encoded in XML, is exchanged between the nodes. Each belief object consists of a label and a set of probabilities. There are two sub-types of "belief" communications, which are explained in the following.

Evidence communications contains estimates sent by every neighbour of a certain node about the probability that HLS in the node itself are active. These estimations are computed using both local information and evidence communications from other nodes. The comparison of external beliefs with the beliefs computed inside the node results in an estimation of the correlation between HLS belonging to different nodes.

An example evidence message shows activation evidences for four symbols: two persons *SMP01* and *SMP02*, one luggage *SML01* and one human scream *SMS01*:

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<protocol>1.0</protocol>
<!--Encoding of inter-node evidence message-->
<ev nodeid="NODE01">
	<ts>20076-20-10 19:23:33.42</ts>
	<objlist n="4">
		<ob1>
			<id>SIMP01</id>
			<prob>0.87</prob>
		</ob1>
		<ob2>
			<id>SMIP02</id>
			<prob>0.76</prob>
		</ob2>
		<ob3>
			<id>SMIL01</id>
			<prob>0.99</prob>
		</ob3>
		<ob4>
			<id>SMIS01</id>
			<prob>0.88</prob>
		</ob4>
	</objlist>
</ev>
```

Posterior communications are sent by all neighbouring nodes. For a given node a posterior represents the probability that every single HLS of the node itself is active (according to the information gathered by every neighbour).

The example message below contains posterior probabilities for the same symbols as in the above described evidence message:

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<protocol>1.0</protocol>
<!--Encoding of inter-node posterior message-->
<post nodeid="NODE01">
	<ts>20076-20-10 19:23:33.42</ts>
	<objlist n="4">
		<ob1>
			<id>SMIP01</id>
			<prob>0.879</prob>
		</ob1>
		<ob2>
			<id>SMIP02</id>
			<prob>0.8706</prob>
		</ob2>
		<ob3>
			<id>SMIL01</id>
			<prob>0.99</prob>
		</ob3>
		<ob4>
			<id>SMIS01</id>
			<prob>0.4088</prob>
		</ob4>
	</objlist>
</post>
```

4 SETTING UP SEMANTIC NEIGHBORHOOD COMMUNICATION

Before the nodes can establish semantic neighborhoods it is necessary to find possible candidates for semantic neighborhoods. Therefore the nodes look for nodes that are in range of the wireless network. When the neighborhoods have stabilized, a node communicates mainly on semantic level, that is, with neighbors that have overlapping sensing areas, e. g. overlapping camera views. To reduce resource usage, a maximum of four semantic neighbors per node is assumed. This is backed by the assumption that no node has more than four neighbors which have overlapping sensing areas. In case this assumption is violated, the number of possible semantic neighbors has to be increase, but in the application of surveillance and security this is unlikely.

Configuration of neighborhoods is performed only by detection of correlation and not by predefined configuration. Aside of the reduction of communication to nodes that have semantic relations, it shall still be possible to reach any node (e.g. for network management or maintenance). Thus the combination of wireless and wired network allows conceptually any-to-any node communication.

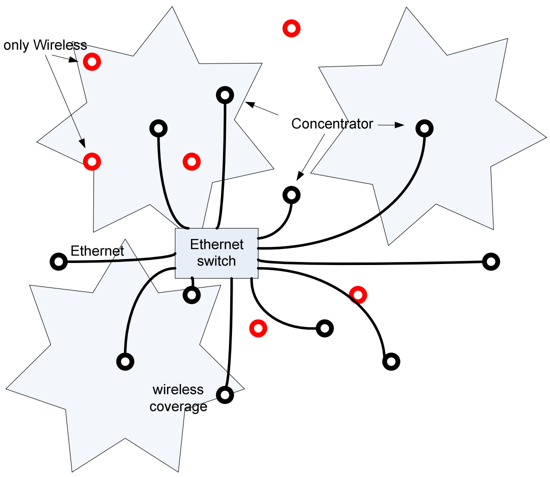

Fig. 2 Unconfigured system. For clarity, all figures show more concentrators than simple nodes.

When the system starts, each node contacts all other nodes within reach. Fig. 2 shows wireless coverage (that is, reception range) depending on environmental conditions. Since reception is not necessarily symmetrical (i. e. circular), the figure indicates coverage areas as stars. Since we assume primarily wireless communication, directly reachable nodes are a superset of nodes with overlapping sensor views. This assumption is true, because of the large coverage of the wireless module; on the other hand reachable nodes are always only a subset of all nodes in the network. We differentiate between two kinds of nodes with respect to communication: *Concentrators* perform local communication between wirelessly connected nodes and they can communicate with other, far away nodes via an Ethernet connection. This allows them to transmit images or videos from sensor nodes to a central machine that renders the user interface. Ethernet is also used to communicate with other concentrators. *Simple nodes* are able to communicate directly only with one concentrator node. These are nodes that are equipped only with wireless connection. Simple nodes can exchange data between each other, they only need to be within wireless range. If it turns out that they have semantic correlation to nodes that are not reachable by wireless connection, they can use the concentrator to which they are connected. The concentrator takes care that the message reaches the destination node.

4.1 Initialization

At the beginning of initialization each concentrator creates a local cluster with its wirelessly associated nodes.

Next, each concentrator detects up to four neighbor concentrators to which it communicates information from its local cluster. These will be learned via wireless communication as in simple nodes. During the learning phase, nodes detect their real neighbors (i. e. in range of wireless communication). This information is used to restrict communication among those nodes by the concentrators.

Now semantic neighborhoods are established by finding correlations between locations in the local views of nodes on the semantic level. In a real world environment such as the airport, which is the testbed for the SENSE system, this learning of local normality takes about three days; LBP afterwards will take another three days for establishing neighborhoods.

The initialization procedure consists of the following steps:

- A node requests an IP address from a DHCP server, which is installed in the network.

- Each node tests, if it is connected to the Ethernet network. If it has network connection and got an IP address, it sets it status to be a concentrator, otherwise it is a simple node. When being a simple node, it sends a broadcast wireless message to all reachable nodes asking for a concentrator (Fig. 3).
- If there is no concentrator available, it builds a micronet with its reachable neighbors and let the loopy belief propagation algorithm find a maximum of 4 neighbors with the highest area of overlap and good connectivity. In the prototype installation this case is considered a configuration error and should not happen. One node is negotiated to control the message flow and thus substitutes the concentrator. Additionally, periodic broadcasts from the nodes in the micronet are used to find a concentrator node as soon as it comes in reach (e. g. when powered on).

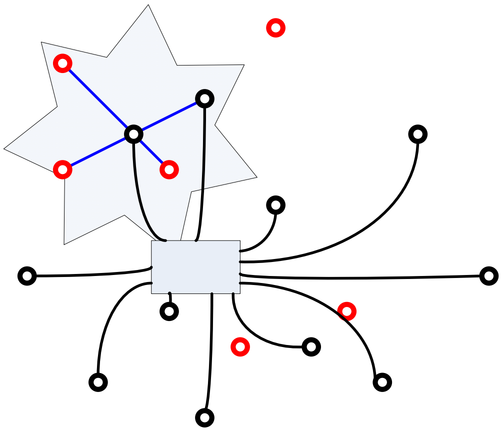

Fig. 3 Wireless coverage of one concentrator node

If there is just one concentrator available, the new node connects to that one and starts to look for semantic overlap with it. If there is more than one, it has to find the concentrator with best connectivity. After having found its wireless neighbors the nodes reduce their transmission power in order to avoid disturbance of other nodes. Fig. 4 shows how a concentrator keeps contact to only two simple nodes and letting the third simple node out of reach. A last method of finding neighbors is to check on the nodes which are connected by Ethernet connection.

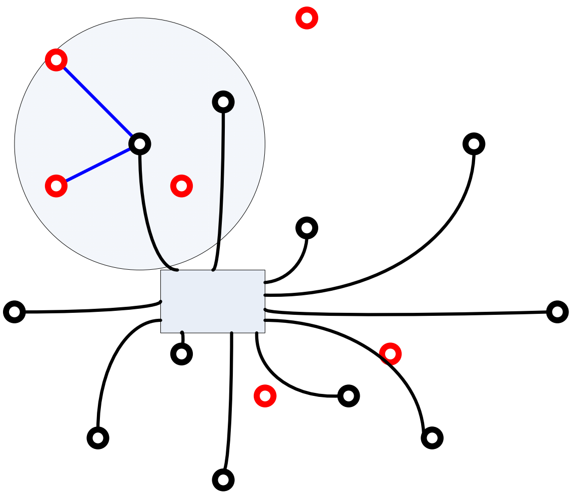

Fig. 4 Neighbouring nodes of one concentrator with strongest connection

4.2 Finalization

After the correlations between wired connected nodes and between concentrators and simple nodes have been found, correlations between simple nodes connected to different concentrators have to be found. The concentrator nodes forward LBP messages from their wireless nodes via other concentrators to simple nodes that are not in physical neighborhood. Due to wireless bandwidth restrictions this task is of lower priority than transmitting normal LBP messages between concentrators and wireless nodes.

This is the reason that at startup a slightly different negotiation procedure takes place than with a purely wireless network. But having more bandwidth available on Ethernet eases the wireless communication load.

After neighborhoods are recognized, communication is restricted among "overlapping" nodes on a semantic neighborhood; the network topology is opaque for the semantic application.

When the network changes by adding a simple node, the above mentioned procedures are also executed, meaning the concentrator to which the node is connected distributes its messages to the local nodes and the neighbor concentrators, which causes re-configuration using the loopy belief propagation algorithm. When a simple node is removed, the neighbors which communicate with it detect it, report it, and then re-adapt their correlation information.

When a concentrator is removed, this corresponds to the loss of a bridge node in Fig. 2, together with the associated cluster. This triggers reconfiguration of the wireless network topology. Either all simple nodes are able to find another concentrator – which will be the normal case because of the high wireless range of the chosen transceivers – or the remaining simple nodes form a micronet and wait for a concentrator. The other nodes in the SENSE system which had overlap with one of the lost nodes will eventually find out about the broken network connection and inform the user.

Finally it is possible that the lost network has no overlap with the remaining network; to cover this case the messages are broadcasted periodically for updating the network. Lost connections will therefore be reported to the user.

5 CONCLUSIONS

A network of smart sensor nodes that is capable of dynamically detecting the network topology and establishing network connections is the key factor for low configuration efforts in sensor networks. We have shown how such a network can be established by using high-level semantic knowledge that is gathered by loopy belief propagation between sensors with overlapping sensing areas. Based on a multi-step process each node detects neighbors with or without wired connection and builds semantic neighborhoods, which are in the first step related to nodes within wireless communication range and are then refined to include only nodes who are actually semantically related. Ongoing research will continue to improve the semantic algorithms and do further research on system stability, expecting that the system remains stable as long as the ratio of new nodes or disconnected nodes remains low. In case of the prototype installation this is guaranteed, since node setup only changes slowly.

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