Applications and Design of Heterogeneous and/or Broadband Sensor Networks *

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Abstract

With the advances in sensor technologies and its wide application scope, it is likely that sensor networks will consist of heterogeneous classes of nodes, including multimodal sensors, bigger highpower nodes, and smaller lowend nodes. The lowend nodes will use low-energy wireless interface, forming unreliable wireless links. On the other hand, the highpower nodes can be equipped with broadband and more reliable links.

This paper explores the resulting new paradigm, called Heterogeneous and/or Broadband Sensor Networks (HBSN), where the multimodal sensing capability and broadband connections have enabled numerous novel applications. We describe two of these new applications and investigate the special design considerations for supporting each of them. We propose a hierarchical architecture to facilitate the cooperation/interaction between sensor nodes and to optimize HBSN for energy efficiency. Preliminary performance evaluation results are presented.

Keywords: Heterogeneous Sensor Network, Broadband Wireless Network, Multi-modal Sensing, Live Virtual Reality, Wireless Multimedia

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1 Introduction

A sensor network is a collection of sensor nodes deployed in a given space. It bears promises of revolutionizing the interactions between the world of atoms and the world of bits. The applications range from wildlife monitoring to environmental data gathering, from structural defects detection to critical field surveillance, and more. This variety in application has made it increasingly clear that the sensor nodes should as well present variety in size, processing power and radio interface capability. One reason is that different environments for each specific application demands the most suitable and economic form of sensor nodes. Another reason is that the architecture of heterogeneous sensor network will provide potential performance gains, compared to the homogeneous networks. These forms of different sensor nodes, in the currently available products, can range from very small motes of the size of a coin [1], to single board PC-computers equipped with image sensors and WLAN cards.

While the wireless interface at the small sensor motes poses a limit on the bandwidth being less than 100K bps, the high-power sensor nodes can be equipped with full-scale wireless cards, and they are not severely bandwidth constrained. Various broadband wireless technologies can be considered for forming the wireless links between them, which includes the IEEE 802.11.a/g, IEEE 802.16 and possibly UWB. Thus, we can form a broadband wireless backbone between the high-power nodes in a heterogeneous sensor network.

We call this type of sensor networks the HBSN (Heterogeneous and/or Broadband Sensor Networks). The ability of reliably delivering large volume of data has opened a new range of applications for HBSN, which includes video/audio surveillance, monitoring of telemetry data. A new application of *live virtual reality* has also emerged [9]. A *live virtual reality* system, based on a HBSN, can provide user real-time live videos of monitored field, and the ability to let the user move virtually within the field. For example, a security console operator can conduct a virtual fly-through survey of the entire complex using only a joystick.

By combining a few high-power sensor nodes and more low-end sensor motes into one networked system, a HBSN opens another new application opportunity: multi-modal sensor monitoring. The data sources of a HBSN can include image, sound, temperature, electromagnetic filed and other sensors. The interaction between the various types of sensor nodes can be of the following two manners.

1. Master-slave: Assume that sensors of model A are resource consuming, and sensors of model B are not. To achieve longer network life-time, model A sensors operate mostly in sleeping mode, while the sleep and wakeup decisions are based on the clues provided by the continuously working model B sensors. An example is the combination of image sensors and acoustic sensors.

2. Peering: Sensors of all sensing models work in parallel, and the data from all sensing models should be delivered to the sink simultaneously.

The rest of this paper is organized as follows. In Section 2, we describe two type of applications of HBSN, one of which is the emerging new technology of *live virtual reality*. In Section 3, a hierarchical architecture is proposed for conventional multi-modal sensing, which is aimed at intelligent cooperation and energy consumption among the multi-modal sensor nodes. For live virtual reality, we propose system performance metrics and study architecture design issues in Section 4. In Section 5, we present the performance evaluation results for the hierarchical sensor network architecture. The conclusions are given in Section 6.

2 Applications of HBSN

New application opportunities of HBSN have opened due to its two special properties, namely, the broadband backbone and the multimodal sensing. In this section, we envision two types of applications, namely, the conventional multimodal sensing and the novel multimodal sensing.

2.1 Conventional Multimodal Sensing

In the conventional multimodal sensing, the sensors of different modes usually interact in the master-slave manner. The main purposes of integrating different sensors are intelligent data processing and logging, and intelligent power savings for resource limited nodes. The following two examples illustrate the possible scenarios in this type of applications.

In the first example, a HBSN is composed of image sensors at the backbone nodes and acoustic or electromagnetic sensors at the low-end nodes. The application of this HBSN deployment is battle field surveillance and tracking of military vehicles [6]. Collaborative target tracking solutions using acoustic or electro-magnetic sensors are under several on-going study [4, 5, 10, 12]. However, tracking alone may not provide adequate information regarding intruding vehicles. More information such as vehicle type, on-board personals and/or armament, are also desirable to the user. These requirements can only be met by applying image sensors. Since image sensors are expensive and they generate high volume of data to be delivered, it is natural to integrate them with the broadband backbone nodes. However, the following two factors limit the continuous operations of the image sensors. The first factor is the volume of generated data, which not only poses a heavy burden in data delivery, but the useful image frames are also inundated with huge amount of frames of void scenes. The second factor is the considerable power consumption of image sensors. Thus, the image sensors are triggered by the tracking results of the nearby low-end nodes, using traditional tracking algorithms. Using this approach, only the image scenes of intelligence value are generated and delivered.

In the second example scenario, the high-power nodes can have considerable power supply, and the batteries can be replaced when needed. However, the much smaller low-end nodes have very limited power supply and can only be discarded when the battery power runs empty. To have longer network life-time, it is sensible to let low-end nodes keep sleeping during most times, and high-power sensor nodes work continuously. Sensors at high-power nodes have longer sensing range, but they are farther away from the objects of interest. They can wake up the low-end nodes closer to the object, and the network can collect more close-up data.

2.2 A Novel Multimodal Sensing

In this novel multimodal sensing, the sensors of different models usually interact in the parallel manner described in Section 1. The application envisioned for this type of sensing is the *live virtual reality*. In this application, not only the data from sensors of several modals are delivered to the sink node, but also all sorts of data are integrated into a combined source of *virtual reality* in front of the user. This enables the user the possibility of a *live virtual visit* to the monitored field. Since majority of human perceptions about their environment are from visual and auditory data, the sensing modals that should be included are image and auditory sensors. However, sensors that are beyond human perceptibility can also be integrated, such as chemical sensors and electromagnetic sensors. These sensors can provide enhanced *virtual reality*, and could be of importance for certain specific applications. Currently, a similar video surveillance technology is under test by the *Video Flashlight* project [9] in *Southwest Research Institute*. The test system uses a series of strategically placed video cameras, which can be deployed into a building, complex, military base or city. The security console operator sees the complex in real-time video on a monitor and can move through the complex with a joystick control; security personnel can conduct an electronic fly-through survey of the entire complex. The system is currently being tested in several government complexes and buildings.

The major devices involved in a *live virtual reality* system are the panoramic imagers. Moreover, to generate the view of a virtual visitor from an arbitrary location, it is necessary to synthesize video frames from several nearby imagers. This can be achieved by the *image-based rendering* techniques.

In this section we review the availability of enabling devices and techniques, from which we conclude that at the current level of technology advance, it is possible to build an *live virtual reality* system from the COTS (commercial-off-the-shelf) devices.

2.2.1 Panoramic Imagers

To accommodate the user's arbitrary viewing angle, and possibly free turning, the imagers should be able to pan, tilt and zoom. By using a panoramic imager, no moving parts is needed to conduct the necessary orientation. A panoramic image with 360° field of view can be produced from a fisheye lens or imager array. The generated images are similar to the reflection images seen on a silver ball. One can imagine a virtual view-plane placed inside the hemisphere view. It can be placed at any angle and distance from the viewer at the origin. By projection, a perspective-corrected image of any angle and zoom can be extracted.

A type of panoramic image sensor node is developed in MIT *Lincoln Laboratory* [3]. The imager component is a 1 Megapixel, 12 bit color CCD with a view being $-5°$ to $90°$ in elevation and $0°$ to $360°$ in azimuth. Each node is based on a PC-104 form factor, used for industrial embedded computing [2]. In approximately $10cm \times 10cm$ form, each node includes a main-board with Pentium class CPU, 2.5" hard drive and power supply, running Linux with full networking functions.

2.2.2 Computational Creation of Virtual Environment

Currently, *virtual reality* techniques have evolved to render true-to-life images, namely, *image-based rendering* (IBR) [7]. Based on the images from the deployed cameras, one can synthesize them to generate a novel scene in front of the virtual viewer, at arbitrary location, viewing angle and zoom.

The amount of available geometric information about the objects and the monitored field will dictate the IBR method used for rendering. For surveillance within a building, where complete 3D information can be available, the Texture-mapped model method can be used. The advantage of this method is that it only needs a very small number of imagers, which reduces the deployment cost and more important, the load of delivering real-time image data. On the other hand, for city blocks, where topographical data can be obtained by airplane-mounted laser scanners, IBR methods that only require depth map information can be used. Depth information is relatively easier to obtain, and slightly more imagers are needed. Finally, if we prefer a quick deployment into a remote site, we don't have any geometric information of the monitored field at hand. The field could contain natural objects such as plants that are hard to be modeled. We need to use IBR methods with no geometric information requirements. However, more cameras are needed and the load for delivering the image data is also higher.

3 Architecture of Conventional Multi-modal Sensing

In this section, we propose a hierarchical architecture for conventional multi-modal sensing in HBSN. Sensors are logically organized into a higher (H) and a lower (L) layer. The H layer, which serves as a control plane for the L layer, consists of a few large sensors with large sensing and broadcasting range (referred to as H sensors hereafter). The L layer consists of a large amount of small sensors, deployed either randomly or planned.

The introduction of high-power sensors and the hierarchical architecture has several implications on the underlying sensor network. First, the H sensor nodes form a broadband backbone for data delivery. In addition to the much-increased throughput, the large transmission range of H sensors allow them to serve as a bridge between remotely-located L sensors and improve the connectivity of the whole network graph. Second, the control plane formed by H sensors can coordinate the operations of data plane to improve efficiencies of radio transmission and data sensing. H sensors can setup dedicated collision-free transmission path while minimizing overhearing and idle listening. If the H sensors also have a larger sensing range, they can offer meaningful guidance to L sensors to avoid turning on the sensing circuits during a long event-less period.

H sensors are not directly involved in data collection. Instead, their large sensing and broadcasting ranges are ideal to assist L sensors to achieve energy-efficient request dissemination and data collection. The L sensors focus on data collection and work more like a traditional sensor network. However, operation of L sensors are not autonomous. Both data collection (sensing) and transmission functionalities of L sensors are governed by the H nodes. L sensors wake up periodically to listen to instructions from H sensors and perform their tasks accordingly. Otherwise, they keep sleeping for energy-conservation.

We assume H sensors have a sensing range of R. In addition, they have a tunable radio transmission range. The maximum radio transmission range should be large enough for H nodes to communicate with each other. When H nodes need to communicate with L nodes, they tune their radio transmission power such that the radio transmission range equals to their sensing range R. For the L sensors, we assume their sensing and radio ranges are small. In addition, individual L sensors know their own location.

3.1 The Initialization Phase

After the HBSN is deployed, all the L nodes need to discover their relative location with respect to the H nodes, i.e. which area are they located, as shown in Figure 2. This is achieved through an adoption process initiated by H nodes. When new H nodes are deployed in the sensor fields, it broadcasts an "ADOPTION" message that contains its own identification information. L sensors who receive such message will record the H sensor as a parent. Since the coverage area of H have overlaps, one L nodes could have multiple parents. For L nodes located in the center area of Figure 2, all 4 H nodes are their parents. For L nodes located in the lower left corner, H_3 is their single parent. If R is large enough and the grid deployment of

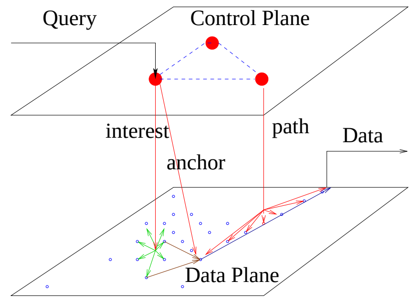


Figure 1. Hierarchical Sensor Network Architecture

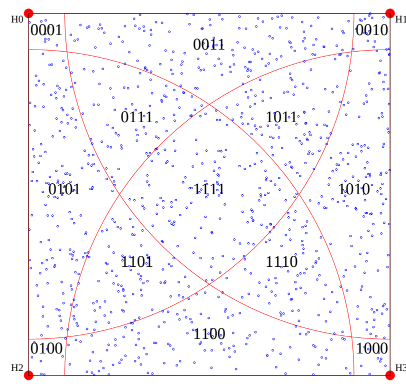


Figure 2. One Grid Cell of HSN Architecture

H nodes ensures a full coverage, every L node has at least one parent.

This "parent-child" relationship is unilateral. Every L node has a list of its own parents. But individual H node is not aware of how many children it has. In fact, given the huge number of L sensors available and their vulnerability, tracking every single child will be resource-demanding. Our design thus avoids establishing a bilateral relationship for better scalability. In addition, the adoption process is needed only once at the beginning of deployment for stationary sensor networks. At the end of adoption process, the entire sensor field is effectively divided into many small regions. In the case of grid deployment with 4 H nodes, as illustrated in Figure 2, the unit square sensor field is divided into 13 pieces. An ID is uniquely created for each region based on the parents information.

3.2 The Operational Phase

3.2.1 Controlled Sleep/Awake/Active Pattern

During the operational phase, L nodes periodically wake up to listen for instructions from their parents, and behave according to the instructions. Should an L node become orphaned at any time, it can resort back to the traditional sensor network protocols and keep functioning. In the operational phase, we assume that the clocks of the H nodes are synchronized properly. In addition, we assume the adopted L nodes can synchronize their clocks during the adoption process.

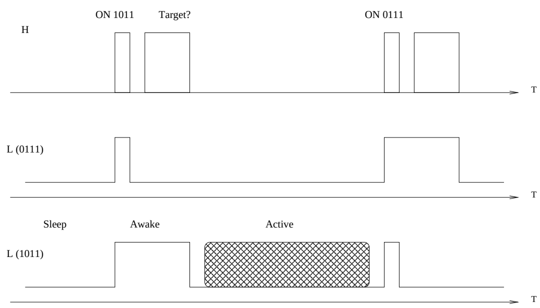


Figure 3. Controlled Sleep/Awake/Active Pattern

Figure 3 illustrates the controlled sleep/awake/active pattern of L sensor nodes. At the beginning of each cycle, all L nodes wake up to listen to the WAKEUP messages. If an L node receives a WAKEUP message that does not match its own area ID, it goes back to the sleep mode immediately. Otherwise, the L nodes will keep listening for the forthcoming instruction information. Based on the instruction received, an L node will determine its appropriate actions and perform the tasks accordingly. However, if a node determines that it plays no role with the instruction, it will sleep until the next cycle.

As illustrated in Figure 4, the WAKEUP message is broadcasted by an H node. Consequently, all L nodes in its coverage area will receive it. This accounts for a total of $\frac{n\pi R}{4}$ L nodes statistically. After receiving a WAKEUP message with area ID 1101, only L nodes in that area will remain awake. This significantly reduces the number of L nodes hearing the INSTRUCTION message, as illustrated in Figure 5. In this particular case, only $0.075n$ nodes will hear the INSTRUCTION message.

3.2.2 Details of INSTRUCTION messages

The INSTRUCTION message can be customized for applications. Currently, we defined three types of INSTRUCTION messages.

INTEREST INTEREST message is used by a H node to inform L nodes about what data is needed. A typical example could be "I'm interested in anything moving faster than 1 MPH". L nodes receiving such message will perform its own sensing to collect data. L nodes receiving the INTEREST message will turn on its radio circuit during the same period to transmit or relay data.

ANCHOR ANCHOR message is used to inform the sensing L nodes about where to send the data if some events of interest are detected. It defines a small area inside the sensing area. L nodes use a position-based protocol to deliver data to any node in the ANCHOR area. The anchor area should be large enough to include at least one L node statistically. If multiple L nodes fall in the anchor area, they will elect a leader or allow data aggregation to avoid redundant copies of data. The leader election procedure works in a similar fashion as cluster head election through a random backoff timer.

The purpose of defining an anchor area is two-fold. First, the control plane does not have the information about the exact location of interesting events. Consequently, the control plane will not be able to setup a dedicated transmission path from the sensor to the receiver. An anchor area thus provide a rendezvous point of sensory data and the dedicated transmission path can then be setup from the anchor area to the destination using the PATH message. Second, the anchor point offers an ideal place to process and aggregate data from multiple sensors. This could reduce the amount of data that needs to be transmitted back to the receiver.

PATH PATH message defines a reserved data transmission path from the anchor area to the destination. It typically describes a straight line from the anchor area to the destination. Upon receiving this message, L nodes that align with this line will turn on their radio circuit to participate in data relaying. The L nodes that are not on the line can safely turn off their radios during this period to avoid idle listening and overhearing.

4 Architecture of the Novel Multi-modal Sensing

For conventional virtual reality, data acquisition devices throughout the monitored field record their environment for certain time. The data are stored in a databank representing the monitored field. Later, when the virtual environment is explored by the user, the static databank is used for representation. Whereas the live virtual reality, on the other hand, combines the data acquisition and the representation into one continuous process. The data acquisition devices form a

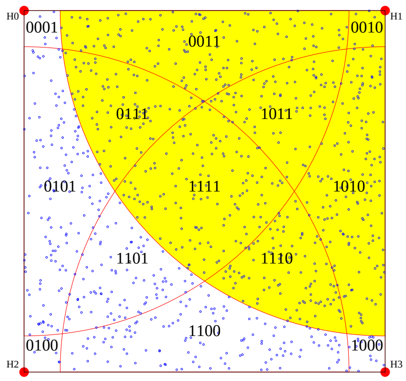


Figure 4. WAKEUP Message is Broadcasted

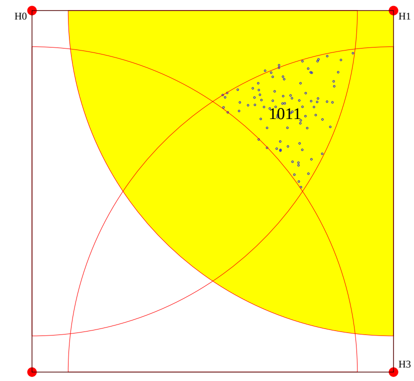
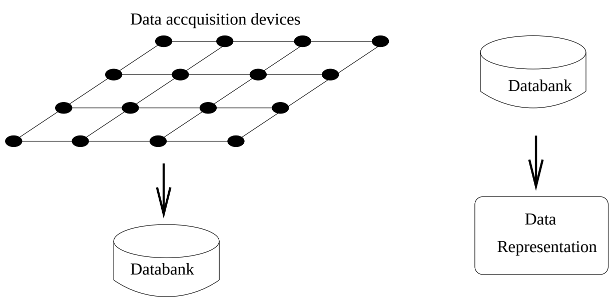
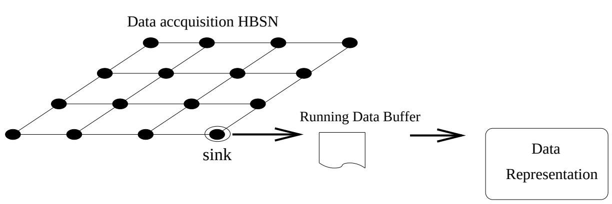


Figure 5. INSTRUCTION message only received by the designated area

HBSN and feed the live data into a running data buffer, which is pulled by the data representation modules to create user experience. Figure 6 shows this difference in the system operation model.



(a) Conventional virtual reality.



(b) Live virtual reality.

Figure 6. Comparisons of system operation models for both conventional virtual reality and live virtual reality.

4.1 Representation Performance

The ultimate goal of live virtual reality is the *embodiment* of the user into a remote environment, the system's performance is defined according to the user's experience. We identify the following two main metrics that contribute to user experience the most.

Representation Fidelity: This metric indicates how accurately the system can represent the real environment. It is composed of the following two factors: the *scene fidelity* and the *time fidelity*. *Scene fidelity* is the difference of the rendered scene and the real scene. It mainly applies to both the static objects and the moving objects in the environment. While *time fidelity* is the freshness of the data being used for the rendering. It mainly applies to the rendering of the moving objects.

Representation Reactiveness: This is the delay from the time when the user changes the view, including viewing position, angle or zoom, to the point when the corresponding new scene is rendered. To achieve a convincing virtual experience, delays longer than a certain threshold will not be tolerated.

4.2 Network Deployment

A live virtual reality system, as shown in Figure 6(b), is composed of a HBSN of data acquisition devices, a data representation module, and the data buffer. Data collected in the HBSN are delivered to one sink node, which feeds the data buffer with fresh data. From a networking point of view, the HBSN's role is data collection and delivery. However, the HBSN performance dictates the whole system's representation performance, namely, the time fidelity and the representation reactiveness.

The HBSN is composed of high-power nodes that are equipped with panoramic image sensors, and the smaller low-end nodes that are equipped with sensors of small form factor. The small and inexpensive low-end nodes can be deployed in an ad hoc manner in the field. To achieve the desired quality of collected data, certain deployment density is required. Furthermore, to achieve longer network life-time, low-end nodes can be over-deployed, and the spare nodes will take the role of the dying nodes [11]. For the high-power nodes, it is desirable to deploy them at planned locations. Since these nodes also form the broadband backbone, it is better to place them into a grid.

4.3 Perception Range

In conventional virtual reality system, data from the entire monitored field is stored into a databank. However, for the live virtual reality system, this may not be the case. Due to the enormous amount of image data generated, and the power conservation requirements, the network only need to gather the sensor data that contributes most to the virtual visitor's perception. In this paper, this set of sensor data is termed as *perception range.*

Perception range is decided by the virtual visitor's location and viewing angle. Humans, with eyes squarely in the front of our head, can see about 180 degrees. The binocular vision, vision in which both eyes are used synchronously to produce a single image, is about 140 degrees. Thus one can imagine a geometric representation of the perception range is a cone zone centered at the viewer's location, oriented along the viewing angle, and with 140° aperture angle. On the other hand, to decide which sensors in the perception range have higher priority in contribution of user perception, the manners are different regarding to different sensing models. For image sensors, the preferred data source are images taken close to the viewer with viewing angle similar to viewer's angle. This is the requirement of many image based rendering algorithms. Thus, the preferred image sensors are *subject centric*. However, for other sensing models such as electro-magnetic sensors or chemical sensors, data source closest to an object will be the most accurate. Thus, the preferred sensors in these models are *object centric* manner. Finally, for auditory sensors, a combined manner can be used. To mimic the sound heard by the viewer, the subject centric manner can be used. On the other hand, it is sometimes desirable to filter the background noises and hear only the sound from a certain object. Then, the object centric manner should be used.

4.4 Implementation Considerations

Except for the image sensors, data volume generate by all other sensors cannot pose much load burden to the broadband backbone. Each sensor in the perception range only needs to find a closest high-power node and upload its data into the backbone for delivery. Thus, we focus on the treatment of the image data.

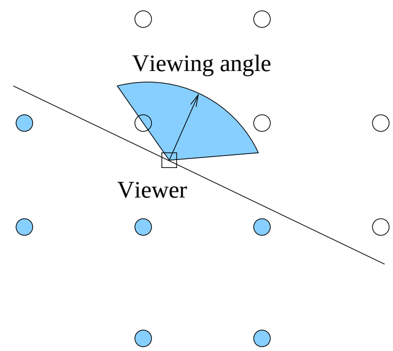


Figure 7. Nodes in perception range for image sensors.

Figure 7 shows the set of nodes in the current perception range. They are 4 nodes at the corners of the grid cell in which the viewer's location belongs to, and 8 more surrounding nodes. Thus, with regard to the viewer's location, the 12 nodes surrounding it need to turn on the image sensors and send its data to the sink node via the broadband backbone. With the image data from these 12 nodes, novel scenes at any viewing angle can be instantly generated using an image-based rendering algorithm. Thus the viewer is free to change viewing angle. The current working set of image nodes needs to change only when the viewer moves into a new grid cell. Figure 7 shows an example viewing angle. Notice that only the shaded nodes in the figure are the image sources for rendering. They are behind the line perpendicular to the viewing angle. The reason is that if we use a image from beyond the perpendicular line, any object between the image sensor and the viewer will be missed.

A live virtual reality system is essentially a streaming multimedia system. The data is routed in the HBSN broadband backbone to the sink. Thus, the quality of service (QoS) routing requirements are still applicable to this novel system. The packet delivery ratio, delay and delay jitter will directly decide the system's representation fidelity. Thus, QoS-awareness in the routing protocol is necessary. However, in this new application environment, novel methods in assigning packet priorities can be derived. The guideline is that the data that the most contributes to the representation quality should have higher priority. For example, the inner four nodes in the 12 perception range nodes should give their packets higher priority. This is because they are closer to the viewer. Besides, the data from small sensors can also help for more intelligent priority assignment. In most cases, moving objects such as vehicles or animals should catch the viewer's attention more than the static objects. Timely representation of dynamic objects is the central goal of a live virtual reality system. Thus, the small sensors can be collaboratively running a target detection and tracking algorithm. Location information of moving objects are disseminated into the backbone nodes. In this way, nodes that are on the direction of moving objects should have higher priority than other nodes.

5 Performance Evaluation

5.1 Optimize HBSN for Energy Ef£ciency

To optimize energy efficiency for HBSN, we focus on a unit-grid cell with one H node on each of the 4 corners. Larger grid structure can always be formed from such unit-grid cell.

5.1.1 Sensing Energy

In many sensor networks, the sensing circuits are turned on using the "every sensor, all the time" (ESAT) approach. If the sensor field are not very active, most sensors are unnecessarily wasting energy during the long eventless period. For acoustic sensors that consumes minimum energy, this inefficiency might not affect the network lifetime very much. However, other types of sensors, such as image sensors, could be affected due to this inefficiency.

Ideally, only sensors near an interesting event should be turned on, and only for the duration of the event. This is not possible without some guiding information from other sources, e.g. the control plane in HBSN. In HBSN, the H sensors can use their sensing capabilities to identify the region of the interesting events. Consequently, only L sensors inside the region need to be turned on.

As shown in Figure 2, if we assume that H sensors are binary sensors with range R, the whole sensor field can be divided into n regions. If a uniform distribution of events location is assumed, the probability of events falling in region i is proportional to A_i, the area of region i. In addition, the number of sensors in any region is also proportional to its area. Therefore, the average proportion of sensors turned on for an event is $P_s \propto \sum_i^n A_i^2$. If we further assume that interesting events only happens a constant β portion of the time, then energy consumed by sensing circuits in HBSN is:

$$E_{HBSN}^S \propto \beta \sum_i^n A_i^2 \times E_{ESAT} \quad (1)$$

5.1.2 Transmission Energy

In HBSN, L sensors in the active region will forward their data to the anchor area first. From data origin to the anchor area, any ad hoc routing protocol, e.g. AODV [8] can be used. The data path bears a few energy inefficiency generic to wireless ad hoc networks, including 1) idle listening 2) overhearing 3) collision and 4) control packet overhead. Idle listening refers to the period of time when a node receive nothing while turning on its circuit for possible traffic. Although there is no traffic received, the node still consumes significant more energy than in sleep state. Overhearing refers to the case that a node receives packets destined to other nodes due to the broadcast nature of the wireless channel. Collision refers to the case that two or more senders within the range of one receiver transmit at an overlapped period of time. This leads to waste of energy at both sender side and receiver side.

In contrast, the path from the anchor area to the destination is setup by the PATH message. This reserved path is collision free. In addition, sensor nodes not on the reserved path are turned to sleep mode to avoid idle listening and overhearing.

Let us indicate the length of the transmission path in the active region i as L_A^i. Statistically, L_A^i is proportionally to A_i, the area of region i regardless of the location of the anchor area. Similarly, the average length of the setup path L_S is proportional to the area, which is 1 in this case. Furthermore, the probability of a particular region i become active is proportional to its area A_i. Therefore,

$$E_{HBSN}^T \propto \sum_i^n A_i^2 \quad (2)$$

In Equations 1 and 2, energy consumption in HBSN is minimized when $\alpha = \sum A_i^2$ is minimized. Considering the constraint that H sensors should fully cover the sensor field, and the location of H sensors are on the 4 corners of the grid, we formulate a constrained nonlinear programming problem as in Equation 3

$$Objective: \quad Min \ \ E = \textstyle\sum_i^n A_i^2 \quad (3)$$

$$s.t. \quad R \geq \tfrac{\sqrt{2}}{2} \quad (4)$$

This problem can be solved considering the symmetric property on the graph. $E_{min} = 0.1089$ when $R = 0.8956$. Numerically, one can expect spending 1% energy on sensing but expect the same accuracy if interesting events happens only 10% of the time. On average, only 10% of the nodes will waste energy on idle listen, overhearing and collision.

5.2 Connectivity

In most cases, data collected by sensors need to be delivered to a designated receiver, either inside or outside of the sensor fields. Disconnected sensor nodes or segments are as well as dead from the application's perspective. To improve connectivity, one can either increase the deployed sensor density or the radio transmission range. However, radio interference and the probability of collision will also increase with density or transmission range. In addition, increasing sensor density is not cost effective and increasing radio transmission range is not power-efficient. In HBSN, remote L sensors could reach each other through H sensors, which have much larger transmission range.

In this paper, we choose "bi-connectivity" as a measure of the sensor network connectivity. A biconnected graph $G(V, E)$ is a graph that remains connected if any vertex (V) and all edges associated with it (E_V) are removed. Since sensor nodes are susceptible to failures, an ideal sensor network should not become disconnected with any single node failure. We randomly deploy 1000 sensor nodes, with transmission range r in a unit square. These 1000 nodes forms the vertex V of the graph G. To obtain the connectivity graph, a link is inserted if a pair of nodes are within the communication range. We then use Depth-First Search (DFS) algorithm to determine how many biconnected components the graph G contains. For a graph G with fixed number of vertex, a less number of biconnected components indicates a stronger connectivity. We then deploy H nodes using different grid architecture in the same graph to study the effect of HBSN on network connectivity.

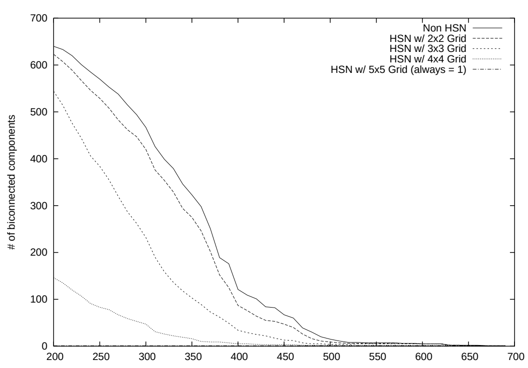


Figure 8. HBSN Improves Bi-connectivity

Figure 8 presents the study on the number of biconnected components versus the transmission range r. When the transmission range of sensor nodes, or from another perspective, the node density, is increasing, the number of biconnected components is reducing. Without deploying HBSN, the graph becomes full biconnected (number of biconnected components equals 1) when $r \geq 670$. With 25 H nodes deployed (5×5 grid), the graph is full biconnected when $r = 200$. Therefore, a few number of H nodes can reduce the requirement on node density more than 10 fold.

5.3 Path Cost

To understand the impact of HBSN on network throughput and delay, a similar graph is constructed as in Section 5.2. Links involving any L nodes ($L \longleftrightarrow L$,$L \longrightarrow H$ and $H \longrightarrow L$)are assigned a cost of 1 and the links among H nodes are assigned a cost of 0.1 to reflect the fact that H nodes have a broadband link among themselves.

Based on such graphs, we construct the minimum-cost spanning tree (SPT) from every L nodes. This SPT is the ideal case of network routing that might not achieved. Nonetheless, it reflects the network property without considering the actual routing protocol being used.

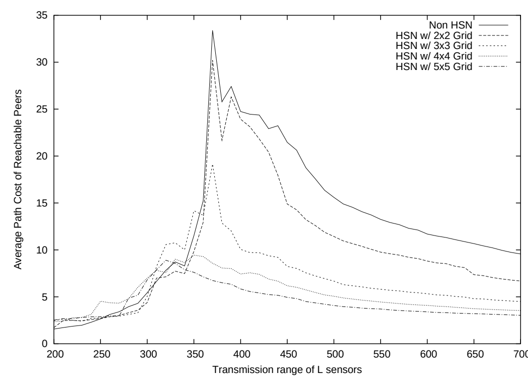


Figure 9. HBSN Reduces Path Cost

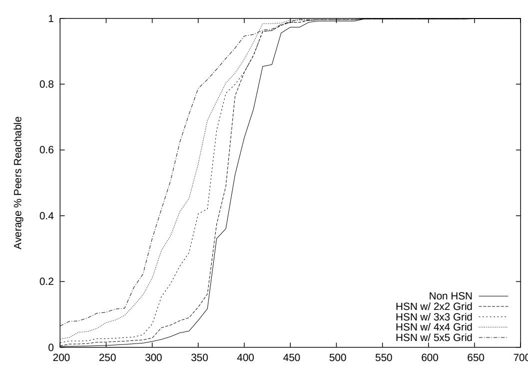


Figure 10. HBSN Improves Reachability

Figure 9 shows that with the increased deployment of H nodes, the average path cost among any two L nodes decreasing. Ideally, this translates to larger throughput and smaller end-to-end delay.

One might observe that the average path cost increases with the transmission range r of L nodes at the beginning. This is due to the fact that the increasing transmission range will connect those originally disconnected network segments, but at a high path cost. This is confirmed by Figure 10, which shows the average percentage of reachable peers.

6 Conclusion

Broadband wireless backbone and multimodal sensing are two new features of a Heterogeneous and/or Broadband Sensor Network (HBSN). To study the interaction and cooperation between the different model sensors, we have identified two manners of interaction in architecture design, namely, the *master-slave* and the *peering* manner. The two manners are applied in the two applications described in this paper. For the conventional multi-modal sensing, we have proposed a hierarchical architecture in order to achieve new types cooperation and better energy conservation among the sensor nodes. For the novel multi-modal sensing, we envisioned the new application of *live virtual reality*. This application integrates data from all sensor models into a virtual live environment. The metrics of system performance and the architecture design issues are discussed.

7 Acknowledgment

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