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A REPORT ON DATA TRANSMISSION AND VISUAL CODING IN VSNS

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ABSTRACT
Wireless sensor networks are an important research area that has attracted considerable attention. Most of this attention, however, has been concentrated on WSNs that collect scalar data such as temperature and vibration. Scalar data can be insufficient for many applications such as automated surveillance and traffic monitoring. In contrast, camera sensors collect visual data, which are rich in information and hence offer tremendous potential when used in WSNs. However, they raise new challenges such as the transmission of visual data with high computational and bandwidth requirements in mainly low-power visual sensor networks. In this case study we highlight the challenges and opportunities of VSNs. We discuss major research issues of VSNs, specifically camera coverage optimization, network architecture, and low-power visual data processing and communication and identify enabling approaches in this area.
Keywords: WSN, bandwidth, network architecture.

INTRODUCTION
Wireless sensor networks (WSNs) connect small devices, each of which has its own sensing, computation, and communication components and power source. The task of such networks, which are distributed and ad hoc, is generally to monitor the environment and collect specific data about it. WSNs are viewed as a disruptive technology that could change the way we collect data from and interact with the physical world similar to the way electronic messaging and mobile communication changed the way we communicate with each other. Hundreds of papers have been published in this research area [1].

Most of this research, however, has focused on wireless networks of sensor nodes that collect scalar data such as temperature, pressure, and humidity sensors. Such sensors generate a limited amount of information, which can be insufficient for many applications even if a large number of sensors is deployed. Hence the need arises for WSNs with multidimensional data sensors, such as camera sensors, to which we refer as visual sensor networks (VSNs). With the recent advances in imaging technologies and micro-electro-mechanical systems, producing small, low-power, and low-cost image/video capture devices at a large scale may be within reach in the foreseeable future. An obvious example of the advances in building small and cheap camera sensors is that almost all mobile phones in the market today incorporate tiny cameras with increasing quality over time. For a survey of publications that have started to emerge about VSNs, we refer to [2]. VSNs offer a wide range of applications. *Remote and distributed video-based surveillance* systems represent a large set of these applications. These are systems that collect visual data from networked smart distributed camera sensor nodes, process it collaboratively, and transmit useful information to the control center. Depending on the application, these networks may be connected to a mobile phone network, an intranet, or the Internet. These systems are useful in a wide range of applications including environmental monitoring, surveillance of sensitive headquarters, and industrial control. For example, by deploying such systems in factories run by industrial robots, engineers can remotely monitor the factories and adjust the robots when necessary.

Ambient assisted living and personal care applications of VSNs have great commercial and societal potential. In such applications, networks would include a variety of sensors (e.g., camera, temperature, blood pressure) and personal computing devices (e.g., laptops, PDAs). They may also be connected to other commodities such as TVs and personal robots. The data recorded by the sensors would be accessed by users who would be able to control the connected devices. Such networks would be used, for example, to improve quality of life or remotely monitor and assist elderly and disabled people.Other applications of VSNs include *virtual reality*, where Internet users can remotely visit interesting locations, such as museums equipped with camera sensors, and navigate through their attractions choosing the camera view angle and the zoom range they prefer.As VSNs offer new opportunities for many promising applications compared to scalar sensor networks, they also raise new challenges that are not fully addressed by current research on WSNs. Camera sensors generate a huge amount of data compared to scalar sensors. Processing and transmitting such data by generally low power sensor nodes is challenging due to their computational and bandwidth requirements.In this article our aim is to discuss the challenges and opportunities of VSNs, overview the early approaches, and identify research issues that are crucial to VSNs. The rest of the article is organized as follows. In the next section we discuss the issue of camera coverage in VSNs and how it differs from coverage in generic WSNs. We then compare the merits of homogeneous and heterogeneous VSNs and show why a multitier architecture is suitable for heterogeneous VSNs. We overview the different techniques that can be used for data processing and

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coding in VSNs, and point to the importance of low-power collaborative data processing and distributed source coding for VSNs. We then discuss data transmission in VSNs and the trade-offs that have to be made between the transmission reliability and energy cost depending on the application's requirements and resources. We give our conclusions in the final section.

CAMERA COVERAGE

The issue of ensuring and preserving coverage of an area with controlled redundancy using WSNs has been widely investigated, and efficient algorithms have been proposed [3, 4]. The main goals of coverage optimization algorithms is to preserve coverage in case of sensor failure and to save energy by putting redundant sensor nodes to sleep. Choosing which nodes to put in sleeping or active mode should be done carefully to prolong the network lifetime, preserve coverage and connectivity, and perform the task at hand (e.g., data gathering). However, when camera sensors are involved, three-dimensional coverage of space is required, which increases the complexity of the coverage issue. By reducing the 3D coverage problem to a geometric problem, Huang *et al*. [5] showed analytically that verifying 3D coverage can be done within polynomial time. However, they did not treat the issue of coverage optimization. Coverage of networked cameras can be simplified by assuming that the cameras have a fixed focal length lens, are mounted on the same plane, and are monitoring a parallel plane. An example of this scenario is monitoring the floor by cameras mounted on the ceiling and directed toward the floor, where a camera coverage area is generally represented by a rectangle (or a circle) in the field of view (FoV) plane, as illustrated in Fig. 1. With this simplification, coverage optimization algorithms devised for generic WSNs can be applied to VSNs. However, one should not expect similar performance to that achieved for traditional WSNs. The reason is that most coverage preservation mechanisms of traditional WSNs are related to the routing protocol since coverage and connectivity are coupled issues [4] . In contrast, in VSNs they are completely separated; two cameras that cover the same area may be far from each other since a camera's FoV is unpredictable. Note that unlike scalar sensor nodes, which collect data in the area around them, camera sensors can capture images from areas that are not necessarily in their vicinity.

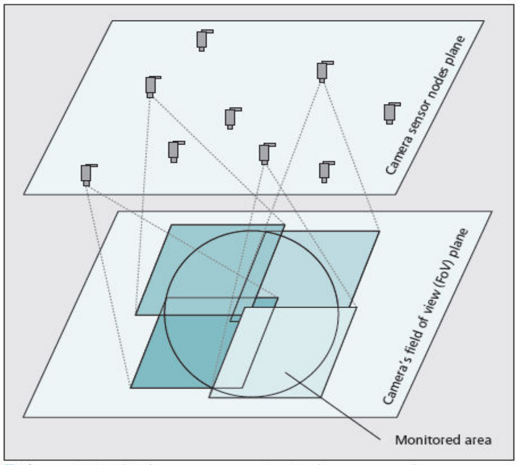

Figure 1. *Simplified camera coverage in visual sensor networks.*

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In [6] Soro and Heinzelman applied an application aware routing and coverage preservation protocol called DAPR, designed for traditional WSNs, to VSNs. DAPR [7] determines the sensor nodes that should be active or sleeping to ensure full coverage of the monitored area with minimal energy cost. The authors of [6] found that DAPR behaves differently for VSNs. This shows that specific protocols should be designed for VSNs. In fact, research is starting to emerge in this direction. For example, Yoshida *et al.* proposed a cooperative control model that let pan-tilt-zoomcameras dynamically adjust their coverage areas to ensure and maintain full coverage of the whole observation area without any central control [8].It is obvious that coverage optimization of VSNs is more complex than that of traditional WSNs due to the way cameras capture data and the higher number of control parameters. This is challenging since coverage optimization mechanisms should have low complexity due to the energy constraints of VSNs. Also, this is application dependent, and different solutions should be found depending on the network scale and the task at hand.

NETWORK ARCHITECTURE DESIGN

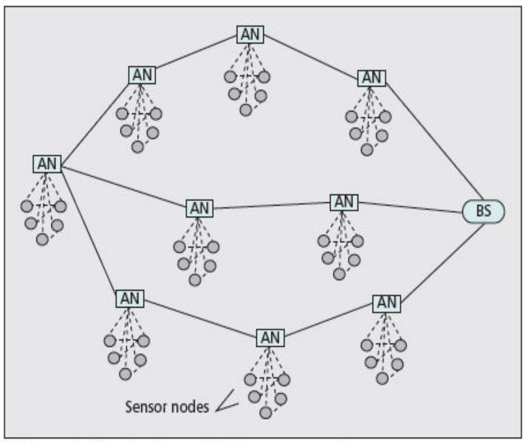
Given the various types of camera sensor nodes with different costs, power requirements, and processing and communication capabilities in addition to the different optical and mechanical properties of camera nodes, the choice of which type or types of camera sensor nodes to use in designing VSNs is not straightforward. While the choices depend on the application requirements and constraints, we can classify them into two categories: homogeneous VSNs and heterogeneous VSNs, described below.

HOMOGENEOUS VISUAL SENSOR NETWORKS

A homogeneous VSN is composed of camera sensor nodes that have the same or similar capabilities and one or more base stations (BSs). We believe that a homogeneous design is suitable for large-scale VSNs since it reduces the complexity of the network. It also supports scalability to a larger number of nodes and self-organization with no central control. Potential applications include habitat monitoring, where possibly hundreds of camera sensors could be deployed to monitor wildlife in remote natural reserves and send collected data to the BS.

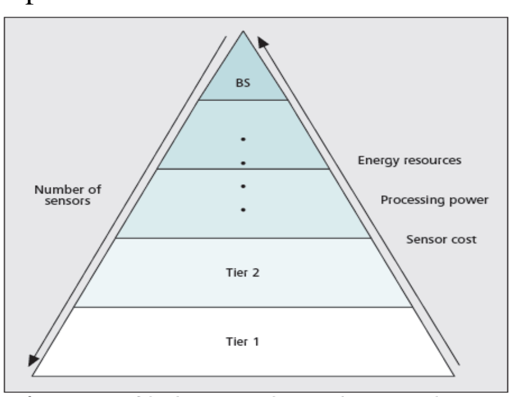
HETEROGENEOUS VISUAL SENSOR NETWORKS

These networks are composed of camera sensor nodes with different capabilities. They may also include actuators or other types of sensors. While heterogeneous design provides better functionality (in terms of assigning different types of sensor nodes to perform different sensing and processing tasks according to the sensors' capabilities) than homogeneous design, it also results in networks with greater complexity. To handle the complexity of heterogeneous sensor networks, a multitier architecture is emerging as a popular paradigm that organizes sensor nodes in a number of tiers, where each tier is composed of homogeneous sensor nodes. A basic example of this design is clustered networks composed of two tiers where the first tier comprises sensor nodes, while aggregation nodes (ANs) constitute the second tier (Fig. 2).



■ **Figure 2.** *Two-tier clustered visual sensor networks.*

First tier nodes would be separated into a number of clusters. Each cluster would collect visual or scalar data and send it to an aggregation node from the upper tier that would be the cluster head. The role of the cluster head is to process the data collected by the sensor nodes and send important information to the BS.



■ **Figure 3.** *Pyramidal architecture of multitier visual sensor networks.*

An illustration of the pyramidal architecture of multitier VSNs is depicted in Fig. 3. The figure shows a general multitier architecture that should be adapted to the application at hand. The first (bottom end) tier would be composed of a large number of low-cost sensor nodes that have low power requirements. Communication between the first tier and the BS is done through the upper tiers. Going from the first to the upper tiers, the number of sensor nodes decreases while their processing capabilities and power requirements increase.A representative example of the multitier architecture design is the SensEye, a multitier VSN designed for surveillance applications [9]. In Sens-Eye three tiers are used: the first tier is composed of low-end QVGA camera sensor nodes to carry out the basic task of object detection, the second tier is composed of VGA sensor nodes for object recognition, and the third tier is composed of pantilt- zoom cameras that have the ability to track moving objects and communicate with the BS. The main idea is that the sensor nodes' capabilities should be in line with the requirements of their performed tasks. Kulkarni *et al*. showed in [9] that SensEye achieves significantly lower-power lower latency operations than a single-tier network.Note that homogeneous VSNs can also be organized in multiple tiers using clustering. In such networks nodes would be organized in a number of clusters where the role of the head of a cluster can be taken by any node in the

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considered cluster.A major research challenge for multitier VSNs is how to design interaction and communication protocols between the different tiers of the network. There is a need for protocols that support both vertical inter-tier traffic and horizontal intra-tier collaboration. Two main issues can be identified here. The first issue consists of finding efficient collaborative image processing and coding techniques that exploit correlation in data collected by adjacent camera sensor nodes. The second issue is how to reliably send the relevant visual data from the camera sensor nodes or aggregation nodes to the BS in an energy-efficient way. These issues are discussed in the next two sections.

COLLABORATIVE DATA PROCESSING AND COMMUNICATION IN VSNS

Visual data collected by camera nodes should be processed and all or relevant data streamed to the BS. It is largely agreed that streaming all the data is impractical due to the severe energy and bandwidth constraints of WSNs. And since processing costs are significantly lower than communication costs, it makes sense to reduce the size of data before sending it to the BS [10]. However, visual data processing can be computationally expensive. Therefore, there is no easy answer to the questions of how and where visual data should be managed. By *where*, we mean whether at a given tier, at the BS, or at all of them. By *how*, we mean which kind of processing (compression, fusion, filtering, etc.). As an example, we illustrated in Fig. 4 a clustered VSN for surveillance applications where camera nodes are triggered by a vibration or sound sensor and collaboratively start sending data to the aggregation node. The latter then processes the received images and only sends valuable information to the BS. While the focus should always be on attaining the application's goals taking into consideration the VSNs constraints, below we give some insights through possible partial answers. One of these answers or a combination of them could offer a complete answer given that the details of the application at hand are known.

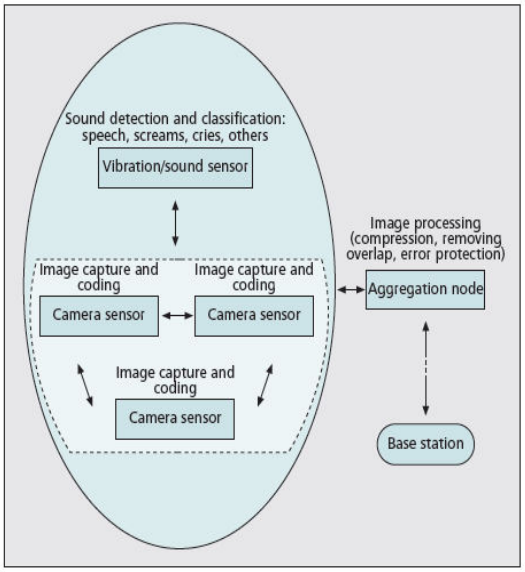


Figure 4. *Example of data processing tasks in visual sensor networks.*

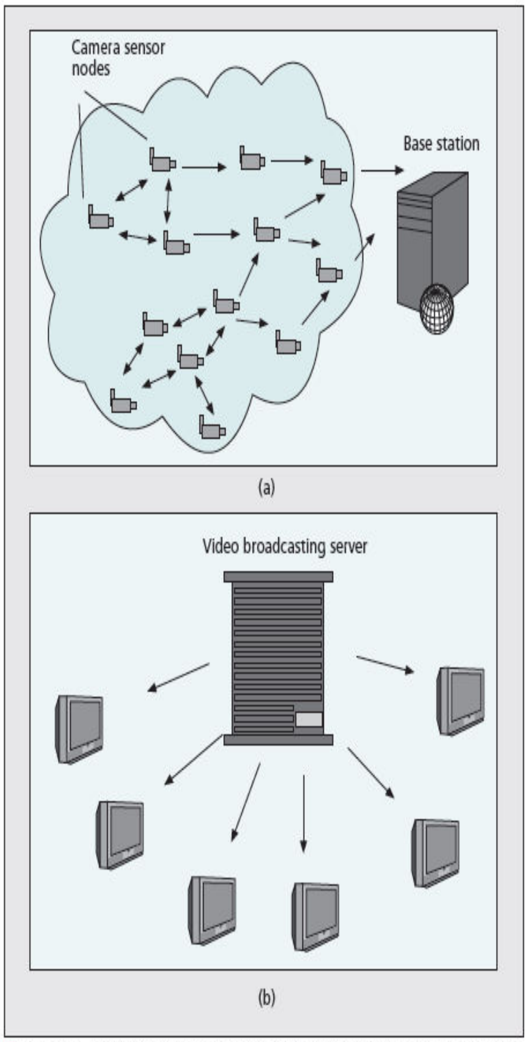
VISUAL DATA FILTERING

Visual data filtering refers to the techniques that act on the visual data gathered by a camera sensor node and extract data that is both relevant to the application and in a compact form suitable for transmission. Filtering can be done by either the sensor node itself or nodes from an upper tier. Filtering techniques include projecting the 2D visual data into 1D, reducing the resolution of data, removing overlap, and filtering out images that do not show any change in the observed scene. Image fusion can also be used where pictures of an area taken by several sensors may be sent to an aggregation node, which would then fuse these pictures into a single image. As an example of visual data filtering techniques, we cite the work of Wu and Chen [11], who proposed a collaborative scheme for VSNs based on exploiting spatial correlation between images taken by neighboring cameras using image matching and removing temporal correlation via background subtraction.

As mentioned previously, the low energy cost and processing power are major constraints of WSNs. And since most image processing algorithms were designed for workstations, which do not have any energy constraints, there is a need for work on low-power image filtering for VSNs.

VISUAL DATA CODING

Source coding can be used for VSNs in order to minimize the size of data collected by sensor nodes before sending it to its destination. Source coding is a relatively mature research area. Among the traditional source coding approaches, the one suitable for VSNs is quality scalable coding. A coder is said to be quality scalable if it generates a bit stream that can be decoded at multiple transmission bit rates. The wavelet based SPIHT and JPEG2000 are among the most popular quality-scalable image coders [12, 13]. Recently, different schemes for error protection of quality scalable bit streams have been proposed, mainly for binary symmetric channels and packet erasure channels. The most popular of them is multiple description coding, which is based on coding the data bit stream using a number of complementary and independent descriptions (packets) for transmission over packet networks [14]. The reconstruction quality at the receiver improves with the number of received packets. Although these systems were designed for image/video streaming over the Internet and mobile networks, their quality scalability and bit rate adaptability are useful for VSNs. In [15] Wu and Chen used the SPIHT coder and unequal error protection for image transmission in VSNs and showed that it provides graceful degradation in reconstruction quality at high bit error rates. Due to the severe energy constraints and low processing power of sensor nodes, the encoder should have very low energy consumption. However, this is generally not the case for traditional image/video codecs, including the ones discussed above. The reason is that since they were designed for multicasting/broadcasting (one-to many/ one-to-all) applications, where the emphasis is logically put on designing low-complexity decoders, the encoder bears the computational burden of the process. In VSNs the complexity requirements are reversed due to their mostly many-to-one information flow (Fig. 5).



■ Figure 5. *Illustration of the contrasting information flows in a) visual sensor networks vs. b) traditional broadcasting applications.*

A paradigm that fits the requirements of VSNs is distributed source coding (DSC), which refers to separate encoding at a number of sensor nodes and joint decoding at the BS. Under this paradigm, every encoder should operate with low power consumption and independent of other sensor nodes, while the decoder has enough resources to exploit the correlation existing between the different encoded bit streams. The old famous Slepian-Wolf and Wyner-Ziv theorems show that DSC can achieve the same or similar rate-distortion performance to traditional (non distributed) source coding [16, 17]. Motivated by these theorems and the emerging applications, DSC has recently attracted a lot of interest [18, 19]. However, most of the work has focused on analyzing DSC under many asymptotic assumptions. Also, the difficulty in finding explicit models that efficiently and accurately represent the spatial correlation in real-world images is still a major obstacle against using DSC in practical applications [20]. Therefore, more attention should be given to finding practical image/video distributed coders.

DATA TRANSMISSION IN VSNS

Reliable data transmission is an issue that is more crucial for VSNs than for conventional scalar sensor networks. While scalar sensor networks can rely on redundant sensor readings through spatial redundancy in the deployment of sensor nodes to compensate for occasional losses of sensor measurements, this solution is impractical for VSNs, which are characterized by higher cost and larger data traffic. Moreover, most reliable transmission protocols proposed for conventional scalar data WSNs are based on link layer acknowledgment messages and retransmissions [21, 22].

They are therefore not suitable for visual data transmission due to their stringent bandwidth and delay requirements.

Data transmission techniques in VSNs can be classified in three categories. The first category includes works that only consider image/video transmission over a single hop. Techniques that consider multi hop transmission where the transmission strategy is determined on a hop-by-hop basis belong to the second category. Finally, the third category includes end-to-end multi path transmission techniques. Representative works from the three categories are highlighted below. In the first category, we find the work of Yu *et al*. [23], who proposed a system for JPEG-2000 image transmission over VSNs that minimizes energy consumption while satisfying quality of service (QoS) guarantees. Also, in [24] Lecuire *et al*. proposed a mechanism for wavelet-based image transmission in VSNs based on decomposing a source image using a discrete wavelet transform and packetizing it into packets of different priorities. The transmission then starts with the high-priority packets, and subsequent packets are only forwarded by a node if its battery level is above a given threshold. This mechanism sacrifices a certain amount of reconstruction quality to prolong the VSN's lifetime. Note that both [23, 24], make use of wavelet image compression to provide quality or resolution scalability.

A representative example in the second category is the work of Wu and Abouzeid [25], who proposed a hop-by-hop reliability scheme based on generating and sending multiple copies of the same data bit stream after encoding it using Reed-Solomon (RS) codes. The data transits through cluster heads and other relaying nodes that are randomly chosen within every cluster. RS encoding and decoding are done at each relaying node, which chooses the strength of the RS code according to the estimated channel error probability. This scheme increases error robustness and does not rely on probing the reliability of multihop paths. However, it does not optimize the end-to-end performance and introduces additional energy cost and delay due to the extra processing performed at the relaying nodes.In the third category, many works combine error correcting codes and path diversification to provide end-to-end reliability in multihop networks, where multiple transmission paths are used to increase reliability. An efficient multipath transmission mechanism splits the data bitstream into small packets, say L packets, adds a number of redundancy packets using forward error correction, and transmits all packets over a numberof paths from a source node to the BS. The information bitstream can be reconstructed successfully at the destination if any L of the transmitted packets are received. Fast algorithms to find the number of channel packets and the transmission paths that optimize the reliability-energy cost trade-off have been proposed [26, 27]. However, these algorithms require that the success probabilities and energy costs of packet transmission over the available paths be known a priori at the source node, which may affect the practical implementation of this mechanism and its performance, especially in highly dynamic networks.

CONCLUSIONS

In this article we highlight the potential applications of visual sensor networks and discuss the challenges that should be met to enable these applications. Research on VSNs is just at its beginning. Optimizing camera coverage, designing scalable network architectures, building practical distributed source coders, and optimizing the trade-off between QoS requirements and energy cost are key research issues in VSNs. Also, due to the different elements in the design of VSNs, multidisciplinary collaborative research is highly needed to design future VSNs.

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