Multimedia Communication in Wireless Sensor Networks

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***Abstract*— The technological advances in Micro Electro-Mechanical Systems (MEMS) and wireless communications have enabled the realization of wireless sensor networks (WSN) comprised of large number of low-cost, low-power, multifunctional sensor nodes. These tiny sensor nodes communicate in short distances and collaboratively work toward fulfilling the application-specific objectives of WSN. However, realization of wide range of envisioned WSN applications necessitates effective communication protocols which can address the unique challenges posed by the WSN paradigm. Since many of these envisioned applications may also involve in collecting information in the form of multimedia such as audio, image, and video; additional challenges due to the unique requirements of multimedia delivery over WSN, e.g., diverse reliability requirements, time-constraints, high bandwidth demands, must be addressed as well. Thus far, vast majority of the research efforts has been focused on addressing the problems of conventional data communication in WSN. Therefore, there exists an urgent need for research on the problems of multimedia communication in WSN. In this paper, a survey of the research challenges and the current status of the literature on the multimedia communication in WSN is presented. More specifically, the multimedia WSN applications, factors influencing multimedia delivery over WSN, currently proposed solutions in application, transport, and network layers, are pointed out along with their shortcomings and open research issues.**

***Index Terms*— Wireless Sensor Networks, Multimedia Communications, Application Layer, Transport layer, Network layer.**

I. INTRODUCTION

THE technological advances in Micro Electro-Mechanical Systems (MEMS) and wireless communications have enabled the realization of wireless sensor networks (WSN) comprised of large number of low-cost, low-power, multifunctional sensor nodes. These tiny sensor nodes communicate in short distances and collaboratively work toward fulfilling the application-specific objectives of WSN. The existing and potential applications of WSN span a very wide range including environmental monitoring [73], biomedical research [68], human imaging and tracking [30], and military applications [52]. It is envisioned that the WSN paradigm will inevitably be an integral part of our surroundings and daily lives [11]. However, efficient communication protocols are imperative for the realization of this vision.

WSNs are generally built up by dense deployment of a large number of sensor nodes either inside a physical phenomenon or very close to it. The main objective of any WSN deployment can be stated as to enable reliable and efficient observation and initiate right actions by reliably detecting/estimating the physical phenomenon features from the collective information provided by sensor nodes [11]. The intrinsic features and limitations of sensor nodes, however, impose significant challenges for the reliable communication in WSN. In fact, sensor nodes carry limited and generally irreplaceable power sources. Therefore, the existing WSN applications and communication protocols are mainly tailored to primarily assure high energy efficiency. Furthermore, short radio ranges of sensor nodes mandate the development of efficient multi-hop communication protocols, which can also effectively operate in densely deployed sensor networks.

Recently, considerable amount of research efforts have yielded many promising communication protocols to address the challenges posed by the WSN paradigm [11], [12]. These solutions have contributed to the actual implementations of sensor networks tailored to the unique requirements of certain sensing and monitoring applications. The common feature of the vast majority of these research results is that they mainly address the communication problems of the WSN applications which primarily require conventional data communications. However, there exist many proposed WSN applications which require efficient multimedia communications such as observing and gathering audio, image and video information from the event field.

Many of the potential WSN applications such as target tracking, process control, source localization, discovering and following rare animal species, controlling the vehicle traffic in highways and railways necessitate efficient multimedia communication in sensor networks. For instance, a human tracking sensor network is introduced in [29] to demonstrate the feasibility of visual monitoring a hot spot by using the current off-the-shelf (COTS) components. Similarly, the accuracy and effectiveness of military WSN applications such as border surveillance and intrusion detection may also be strengthened by incorporating visual monitoring via deployment of COTS components. On the other hand, industrial process control applications of WSN may also require multimedia information to be collected from the event area by incorporating diverse imaging sensors to visualize, monitor and control time-critical processes [35].

Multimedia WSN scenarios may also be observed in health monitoring and support applications such as detecting elderly people's behavior for proactive health care purposes [19]. In one such multimedia WSN application called *Health Smart Home* [26], it is intended to provide patients receiving remote health care with more freedom by use of image capturing sensors to spread the application area to the street from the house. Furthermore, since traumas are mostly experienced far from hospital and the following first hour in trauma care is vitally important, efficient application of a multimedia sensor network can increase survival rates [43]. With the arrival of the paramedics, a multimedia WSN can be established in ad hoc manner between the paramedic Body Area Network (BAN) [27]; ambulance-based Vehicle Area Network, which supports multimedia streaming; the remote hospital network and the patient's BAN as well as with the health smart home elements. The overall system is also called as *Healthcare Personal Area Networks (PAN)*.

In addition to the challenges due to the unique characteristics of the WSN paradigm discussed above, the additional challenges posed by the intrinsic features of the multimedia communication must be addressed in order to realize these multimedia applications with WSN deployment. Unlike the conventional data communication required for reliable transport of event features from the field, multimedia traffic does not require 100% reliability and mostly has strict requirements on bounded delay, jitter, minimum bandwidth, and smooth change of the transmission rate. These additional requirements inevitably amplify the challenges for multimedia communication in sensor networks. Especially, high bandwidth demand and strict time-constraints of multimedia communication bring significant challenges for sensor networks in matching the energy and processing capacities and the level at which the application objectives are met. While there exist significant amount of research results on communication problems of WSN [11], [12], multimedia communication in WSN is vastly unexplored. On the other hand, multimedia communication problems have been largely investigated and many solutions exist for wireless environments and the Internet. However, these solutions cannot be directly applied to the WSN scenarios due to its unique characteristics and resource constraints. Consequently, there exists an urgent need for research efforts in order to address the challenges for multimedia communications in WSN to help realize many currently envisioned multimedia WSN applications. In this paper, we present a survey of the research challenges and the current status of the literature on the multimedia communication in WSN. More specifically, the multimedia applications of WSN, basic design constraints, currently proposed solutions in different communication layers for WSN and their shortcomings when applied to multimedia WSN applications, and open research issues for multimedia delivery in WSN are pointed out. The objective of this survey is to capture the current state of the art of multimedia communications in WSN and point to the open research avenues in this field.

The remainder of the paper is organized as follows. In Section II, we discuss the major factors influencing multimedia communication in WSN corresponding basic design constraints of WSN deployments for multimedia applications. The existing work on the application, transport, and network layers are surveyed in Sections III, IV, and V, respectively. Their shortcomings for multimedia communication requirements in WSN as well as the open research issues are discussed for each of these protocol layers. We conclude our paper in Section VI.

II. FACTORS INFLUENCING MULTIMEDIA COMMUNICATION IN WSN

Design of a sensor network for a certain application is influenced by several factors such as fault tolerance; scalability; production costs; operating environment; sensor network topology; hardware constraints; transmission media; and power consumption [11]. These factors are addressed by many researchers as comprehensively surveyed in [11], [12]. Here, we discuss some of these basic design constraints considering the unique requirements and challenges for multimedia communication in WSN. On the other hand, there exist additional factors which affect the efficiency of multimedia communication in WSN such as *high bandwidth demand, multimedia coding techniques, application-specific QoS requirements and delay bounds*, which will be elaborated in this section as well. These factors are of great importance as they serve as a guideline to design communication protocols and an multimedia applications/algorithms for efficient multimedia communications in sensor networks.

A. High Bandwidth Demand

Real-time multimedia applications are well known with their high bandwidth requirements and stringent delay constraints, which may be hard to satisfy even on wired links. In the design of multimedia WSN, high bandwidth requirements of multimedia traffic should be taken into account. For example, the size of a typical uncompressed video sample, i.e., frame, in QCIF format (144x176) is approximately 25 Kbytes. In addition to the transmission of their own data, sensor nodes also relay the packets coming from other nodes due to the intrinsic low range, multihop communication strategy of WSN. Therefore, for multimedia capable WSNs, data transmission rates of sensor nodes need to be sufficiently high to accommodate the high bandwidth demand of multimedia information. Consequently, the *Ultra Wideband* (UWB) or impulse radio technologies may be considered as a promising communication technology to provide high bandwidth capacity for multimedia applications in WSN, especially in indoor wireless sensor networks [53].

B. Multimedia Coding Techniques

Since sensor nodes in a multimedia WSN capture and compress multimedia signals, processing and communication efficiency of the compression algorithms is clearly a design constraint, which need to be carefully addressed.

1) Processing Efficiency: Predictive encoding is known to be an effective way of obtaining good rate-distortion performance for signals with temporal correlation which is inherent to multimedia. However, computational complexity of these algorithms is unacceptably high for power constrained sensor nodes. On the other hand, using all intra frame coding is efficient in terms of energy spent on processing, however, it is inefficient in terms of communication cost due to its low rate-distortion performance.

2) Communication Efficiency: Predictive coding can reach high compression ratios and dramatically reduce the bit rate of a source signal. However, as will be discussed in Section III, it is error sensitive and should be properly handled while transmitting over lossy channels. Many techniques are proposed in order to tackle with this problem, all of which are based on adding some redundancy with the cost of increased bandwidth demand reducing the communication efficiency. Using channel codes is inefficient for the case where losses exceed the correction capacity of the code, e.g., burst losses, and cause a *cliff* effect. Unequal protection solves this cliff effect problem, however, layered representation has a serious rate-distortion penalty that results in a communication inefficiency. Multiple description coding (MDC) [34] is another approach which removes the cliff effect and has acceptable rate-distortion performance (except MD-FEC [60]). Note that all of these solutions are based on predictive coding and they are inherently inefficient in terms of dissipated processing power.

On the other hand, as discussed in Section III, a new family of multimedia encoders, *Wyner-Ziv encoders*, is proposed which may be acceptably efficient in terms of both process and communication power, and should be considered as a promising coding technology for multimedia WSN.

C. Power Consumption

The severe power constraints of sensor nodes require sensor design with low-complexity and high compression efficiency in order to prolong the lifetime of a wireless sensor node. In this way, both processing and communication power consumption can be reduced to acceptable levels which make the multimedia transport over WSN feasible. Power consumption due to communication in WSN has been widely investigated [11], [12]. Hence, here, we mainly focus on the energy-efficiency issues related to the multimedia processing at sensor nodes.

The state of the art video encoders have very good rate-distortion characteristics by following the classical complex encoder and simple decoder balance. However, such complex encoders are not implementable on resource constrained sensor nodes. On the other hand, intraframe coding is a low-complexity compression scheme that can provide a low rate-distortion performance. For example, an unoptimized H.264 [42] interframe encoder can reach very high compression rate, however, even on today's powerful PCs a frame rate of 2-3 frames/second can be obtained, where the intraframe coding of the same encoder can work at a rate of 20-25 frames/sec. The new distributed source coding techniques may find a good tradeoff between processing and communication cost by reverting the traditional balance of complex encoder and simple decoder in order to fit to the power constraints of sensor nodes.

An application-specific approach for energy conservation is introduced in [48] which can be used in *state change detection* of a hot spot. The buffering of the previously gathered image is performed according to the current one to find out the changes in the hot spot which results in considerable amount of energy saving. However, this brings a challenging tradeoff between energy-efficiency and required memory capacity.

In [83], processing and communication power consumption are considered simultaneously by incorporating an adaptive sender buffer in order to decrease both the CPU idle time and transmit radio idle time. In this approach, when the video sensor captures the event, firstly, the processor encodes a frame as the transmitter waits for it in the idle mode. The finished frame is transmitted by the radio while the processor is in idle mode. Then, it generates the next frame and continues this cycle until no data is available. However, the efficiency of this approach in sensor networks must be thoroughly investigated considering both energy and processing constraints of sensor nodes.

On the other hand, as will be discussed in Section III, distributed coding of the multimedia source is another promising approach which may also contribute to significant energy savings in WSN. In fact, it is shown in [49] that there exists an optimal number of nodes involved in the distributed coding process, which minimizes the total energy consumption.

D. Production Cost

In general, sensor nodes are low capacity devices equipped with a simple sensing circuitry which may have seismic, magnetic, thermal or acoustic data capture capabilities. In addition to the low profile hardware of a sensor mote, usage of above mentioned simple sensing equipment enables to reduce the costs. However, for the case of multimedia WSN, sensing circuitry becomes an audio, image, or video capturing hardware, e.g., camera, which is a considerably expensive device. In addition to the costly sensing circuitry of a multimedia sensor node, usage of multimedia encoders such as predictive encoders, e.g., H.263, MPEG-1, H.264/AVC, MPEG-4/AVC, necessitates higher processing and memory capacities. Consequently, the sensor node hardware cost is much higher in multimedia WSN scenarios.

On the other hand, newly emerging low complexity encoder designs will decrease the need for faster CPUs and larger memory requirements even by reaching a close rate-distortion performance of the legacy predictive coding systems. For example, the pixel-domain Wyner-Ziv encoder [33] can encode frames in 2.1 msec on the average, while average time for interframe coding takes 227 msec/frame with an H.263+ encoder. Furthermore, since motion estimation is eliminated, there is no need to store previous frames which means savings from the required memory. With the emergence of low-complexity encoders cheaper multimedia nodes will be viable, although they will still be much more expensive than simple heat, seismic or acoustic sensors.

E. Application-Specific QoS Requirements and Delay Bounds

The delay introduced to the data stream either by processing time or by the communication latency are of great importance in multimedia communication. Delay due to multimedia processing is usually aimed to be addressed by the efficient compression and decoding techniques, which results in another balanced system from the delay point of view. The insufficient conformation of sensor processing units force a trade-off between the computation time to compress data and the gained latency.

One of the proposed techniques to save energy in Section II-C is to turn the sensor radio off when no communication is needed. The procedure to re-power on a radio is called *wakeup scheme*, which significantly contributes to total end-to-end delay. In some proposed wakeup schemes [56], [67], the energy saving and delay are not simultaneously considered, which contributes to the failure to find an optimum point for meeting the application-specific QoS requirements with minimum energy expenditure. On the other hand, in [91], another wakeup scheme is proposed, which tries to balance the energy and delay constraints. This procedure enables the radio switching techniques to be applicable to strictly delay intolerant multimedia WSN applications.

In addition to the above reasons, delay may be introduced due to the applied error control mechanism to recover from packet losses. As discussed in Section II-B, predictive coding is the legacy coding standard applied to multimedia streams, however, it is well known with its high sensitivity to packet losses. In the multimedia streaming literature, many approaches exist in order to control the distortion while transmitting this loss sensitive signal over a lossy packet network. As will be discussed in detail in Section III, all of these techniques introduce a delay either due to retransmission or increased bandwidth demand due to redundancy imposed by the applied loss resilient source or channel coding. Hence, application-specific delay bounds should also be taken into account when selecting appropriate multimedia error resilience techniques at the application layer.

On the other hand, delay jitter is a more general problem for systems involving with continuous media such as audio and video. Generally, effects of delay jitter is tolerated by client side buffering which is bounded by the real-time requirements of the application. Thus, in a multimedia WSN scenario, sink may handle the jitter problem by employing an efficient receiver-side buffer to maintain the application-specific QoS requirements.

In summary, all of these factors should be considered in order to design an efficient sensor network deployment for multimedia applications.

III. APPLICATION LAYER

In a multimedia WSN, application layer should represent the captured signal properly to transport over lossy channels by using algorithms that minimize both process and communication power as discussed in Section II-B. While there is a significant amount of research on multimedia compression and transmission, these techniques do not fit well to the unique characteristics of the WSN paradigm. For example, the new video coding standard H.264/AVC [42] provide very good rate-distortion performance due to advanced techniques [84] it incorporates to exploit the signal statistics, e.g., spatial prediction for intra coding, multiple reference frames motion compensation, small and variable block-size intra/inter block coding, and advanced entropy coding schemes. However, predictive encoders are designed to work on high-end systems which do not have any energy and processing limitations. This is mainly because while the advanced techniques incorporated in predictive encoders help increase the coding efficiency, they also introduce excessive processing and energy requirements. Therefore, they do not stand as a practical application layer solution for energy and capacity limited sensor motes.

In order to achieve the distributed sensing in a WSN, compressed bit stream should be communicated over lossy channels. Packet losses should be properly handled by means of additional source and/or channel coding schemes since all popular predictive coding schemes obtain good rate-distortion performance under no loss conditions. In lossy environments, controlling the distortion is handled with using automatic repeat request (ARQ), forward error correction (FEC) codes or hybrid schemes [46]. ARQ mechanisms [22] use bandwidth efficiently with the cost of additional latency due to the packet retransmissions. Hence, such approaches are simply impractical since WSN applications generally require real-time delivery of data. On the other hand, FEC systems work by imposing redundant packets [28], [17], [74]. For a given estimate of available bandwidth, this will obviously cause a decrease in the message rate. This additional redundancy helps recover packet losses such that a (n, k) code can recover $n - k$ losses. However, if the channel exceeds the correction capacity of imposed FEC codes, a "cliff" effect is observed in the rate-distortion performance. Therefore, priority encoded transmission (PET) [14] idea is applied by means of applying varying degrees of FEC to different parts of the video bit stream depending on their relative importance. In [39], [55], [60], this idea is applied to layered coded streams and provides graceful degradation in observed image quality in the presence of error losses. However, layered representation of video signals has a significant rate-distortion penalty, which prevented wide use of such schemes that depend on layered representation.

Another approach is using multiple description coding (MDC), in which each received description results in a decrease in signal distortion and overcomes the undesired cliff effect of FEC codes as observed in Fig. 1 [34]. In [82], state of the art MDC techniques for video are analyzed in detail. A new family of video encoders based on the *Distributed Source Coding* (DSC) theory is proposed [1], [2], [89], [69] which is called *Wyner-Ziv* video encoders. Wyner-Ziv encoders remove the need for a layered representation, and provide a substantial rate-distortion gain as compared to the classical layered representation. It assumes a coarse quantized version (base layer) is completely received, and rate-distortion gain is achieved by exploiting the correlation between the original image and coarsely quantized version. However, all of the schemes overviewed in this section are based on predictive coding, which dominates the total energy consumption of each encoder. Either due to low rate-distortion performance or high power requirements, none of the classical video compression schemes can be implemented on energy and capacity con-

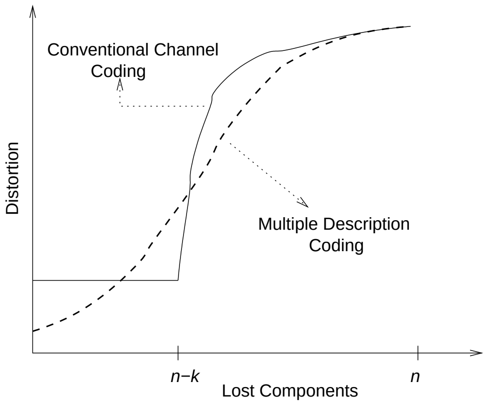


Fig. 1. FEC coding vs. MDC.

strained sensor nodes.

According to the target application, collected sensor signals have their own special characteristics. For example, signals may take continuous or discrete values, or may be both spatially and temporally correlated. Both for digital audio and video case, source signals are discrete valued and each individual signal source is assumed to have temporal correlation inherently. On the other hand, spatial correlation depends on the deployment strategy, i.e., whether the network is densely deployed or not, and the sensing capability of nodes, which may be able to sense near or far field data. Audio data can be assumed to be isotropic, and hence, this class of sensors can be classified as near field sensors. However, video data is anisotropic and its sensors have both far and near field sensing capabilities provided that the event is in the line of sight.

The main goal of the application layer in WSN is to process the collected signals in order to achieve a proper representation so that it can be properly transported via the underlying protocol stack in a multihop fashion over wireless links. One approach is to make minimum processing at this layer, and using *cooperative communication* (in-network processing) at the network layer [76] in order to aggregate data for achieving an energy efficient representation. In this communication model, observer is not interested in the exact readings of each sensor, instead an aggregate value of sensor readings from a region is sufficient for the observer. This approach does not suit to multimedia sensors from the following aspects:

1) Local Communication: Local short distance communication to the aggregator node, e.g., cluster-head, is necessary. Hence, transporting uncompressed multimedia may result in high communication cost even in short ranges. On the other hand, transporting compressed data from the sensors will reduce the communication cost, however, it will require extra energy at the aggregator nodes for decompress-aggregate-compress process.

2) Source Aggregation: Simple aggregation functions such as averaging, does not apply to multimedia signals. Joint encoding can be applied as an aggregation function of multiple correlated multimedia signals. However, this may yield very marginal gains especially for the video signals where the correlation between sources is low. This is, in fact, due to anisotropic nature of video signals and far field sensing capabilities of video sensors. Even in the case of high spatial correlation between source signals, distributed source coding framework showed that separate encoders with joint decoding can reach the performance of joint encoding/decoding with optimal codes that work at the Slepian-Wolf limit [70].

On the other hand, the second approach is based on a *non-cooperative communication* model [76], where signals are processed (compressed) separately in an energy efficient manner immediately at the sensing nodes for a specific event capture rate which is sufficient to reliably represent the event. In this approach, possible methods of energy efficient representation of event signals from the event field are outlined below:

(1) Spatio-temporal Correlation Approach: In this approach [79], the main goal is to properly represent the event rather than the signal itself. It is assumed that in order to reliably observe the event, the overall data generated by this event may not be needed at the sink. To this end, spatio-temporal correlation is captured by a theoretical model. Results reveal that, by properly reducing the reporting rate, f, and selecting representative nodes, M, from an event area, great power savings are achieved with an allowable amount of distortion $D(f, M) < D_{max}$.

(2) Distributed Source Coding (DSC): In this approach, the ultimate goal is to represent the signal optimally, i.e., minimum power consumption with maximum compression. In the classical sense of DSC, each correlated signal is independently compressed by a standard encoder, but they are jointly decoded to obtain an increased signal quality at the decoder. In [70], Slepian and Wolf showed that for the lossless compression separate encoding with a joint decoding is as efficient as joint encoding and decoding.

The application layer solutions presented above are appropriate for non-cooperative networking model and depends on both spatial and temporal correlation models. However, they are generic solutions and applicable to audio, video or ordinary data transport scenarios. DSC is a very active research area, and many research studies have been done to achieve near limit codes in [47], [57], [87], [92], [94]. Despite that the DSC technique is a an efficient way of representing correlated data at the Slepian-Wolf or Wyner-Ziv limit, it suffers from finding an explicit correlation model [33], between sources to be compressed in a distributed manner. This is why applications of classical DSC to the real world images or videos are limited. In [31], DSC is used to exploit spatial correlation in real-world images by using geometric information to estimate the correlation function of the visual data.

In [32], multimedia transport over WSN is addressed and a hierarchical network infrastructure is proposed in order to handle high bandwidth and low delay requirements of multimedia data by means of deploying a limited number of high capacity mobile nodes which are called *mobile swarms*. On the other hand, there are numerous work in the literature that process acoustic signals captured by the sensors [23], [24], [78]. However, all of them are focused on the problem of *location finding* using time delay between data captured from different sensors. In all of these works, sink is totally

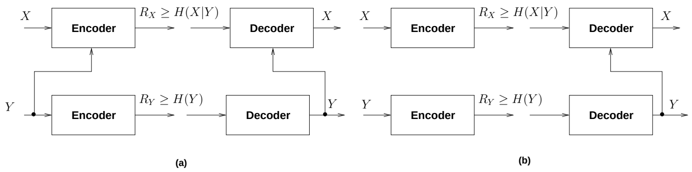


Fig. 2. Lossless compression schemes for (a) joint encoding and decoding, (b) seperate coding and joint decoding (Slepian-Wolf).

uninterested in the content of the audio data captured at the sensors. For the applications, where the sink is interested in the content of the captured audio signal from the field, energy efficient representation techniques discussed here apply to the audio capturing scenarios as well.

A new encoding scheme that can find a good tradeoff between communication and processing cost is mandatory for efficient multimedia communication in WSN. For example, predictive coding increases the processing cost while minimizes the communication cost due to its good rate-distortion performance. On the other hand, encoders that do not exploit temporal correlation, e.g., intraframe coding of video, has minimal processing cost. Nevertheless, due to its low rate-distortion performance, it suffers from high communication cost. New encoding schemes that make use of DSC can find a good tradeoff between processing and communication cost. Therefore, we first introduce the theory behind DSC and its connection to channel coding. In the rest of this section, we overview the principles of Slepian-Wolf and Wyner-Ziv coding that lead to the current practical distributed source coding schemes and its applications for video coding. We then point out open research issues for their application in multimedia WSN.

A. Slepian-Wolf Coding

Slepian-Wolf coding is basically a lossless source coding technique for compression of correlated sources, X, Y, with separate encoding of each source, i.e., without knowledge of the other sources, and a joint decoding.

Let X, Y be a pair of correlated random variables where their drawings are $\{(X_i, Y_i)\}_{i=1}^{\infty}$ are independent and identically distributed. Define the total rate for the entropy coding of two correlated sources, X, Y as $R = R_X + R_Y$. In the joint coding case as given in Fig. 2(a), from Shannon's source coding theory, rate given by the joint entropy $R \geq H(X,Y)$ is sufficient. This may simply be obtained by compressing Y with a rate of $R_Y \geq H(Y)$, and X with $R_X \geq H(X|Y)$ bits per sample which requires full knowledge of Y at the encoder of X as represented in the encoder part of Fig. 2(a). Hence, the total rate is obtained to be $R_X + R_Y \geq= H(X|Y) + H(Y) = H(X,Y)$

Slepian-Wolf theorem says that $R \geq H(X,Y)$ is sufficient for the seperate encoding of correlated sources, which in turn means $R_X \geq H(X|Y)$ is achievable by only knowing the joint statistics of X and Y and without explicit knowledge of Y at the encoder Fig. 2(b). The achievable rate region for Slepian-Wolf coding is given in Fig. 3. Note that for proper decoding, Y should be available at the decoder and is called as the *side information*. However, Slepian-Wolf coding is basically a source coding problem, Wyner first realized the close connection to channel coding and suggested the use of linear channel codes as a constructive approach to Slepian-Wolf coding in [86].

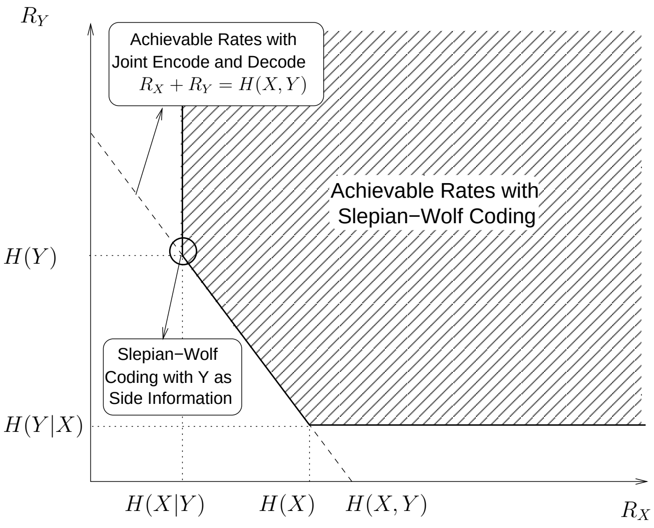


Fig. 3. Rate region for Slepian-Wolf coding.

In the very recent papers [47], [57], direct link between Slepian-Wolf source coding problem and the channel coding is established through the use of syndromes and the coset codes.

B. Wyner-Ziv Coding

Wyner-Ziv coding [85] is an extension of Slepian-Wolf coding in order to compress discrete correlated signals with respect to a fidelity criterion rather than losslessness, i.e., lossy coding. In [85], it has been shown that there exists *rate loss* in distributed coding for a given fidelity criterion, D, which can be represented as $R_{WZ}(D) - R(D) \geq 0$, where $R(D)$, $R_{WZ}(D)$ are the achievable joint encoding rate and Wyner-Ziv coding rate, respectively.

Wyner-Ziv encoders can be thought as a quantizer block followed by a Slepian-Wolf encoder, where the decoder should have access to the side information, Y uncoded. Since it was shown in [94] that linear codes and nested lattices may approach Wyner-Ziv limit for jointly Gaussian signals, practical Wyner-Ziv coding schemes that use nested lattice quantizers [87] and trellis-coded quantizers [57], [92] are proposed.

C. Applications of DSC for Video

There is a well developed theory behind the distributed source coding for nearly 30 years, and recently, many practical Wyner-Ziv encoders are proposed. They are generally restricted with the underlying spatial *correlation model* between the sources. In [88], binary symmetric case (BSC) proposed as a more practical model since it is a well-studied channel model with available capacity-approaching codes. However, the recent reviews of DSC [33], [88], pointed out that it is difficult to obtain a joint probability density function in sensor networks.

Using Wyner-Ziv coding for compression of spatially correlated data in a distributed manner has resulted in a radical conceptual change in data compression. Since by joint decoding and by seperate encoding of correlated sources (for a given correlation model) with properly designed Wyner-Ziv coders, the performance of joint encoding/decoding can be approached, simple encoders which do not need to exploit the spatial correlation can be designed with the cost of a more complex joint decoder at the receiver. This is the main revolutionary idea that that swaps encoder/decoder complexity and lead us to design of low cost and capacity video encoders.

For sources with high spatial correlation and with either no (still images) or low (low frame rates) temporal correlation [95], the above spatial compression approaches result in a noticeable performance gain. In a WSN, the amount of spatial correlation between sources is directly related to the density of the deployment. Thus, in densely deployed networks spatial correlation can be reduced by allowing transmission of only less correlated data gathered from representative nodes [79]. On the other hand, independently from the WSN deployment strategy, captured video signals are assumed to have high temporal correlation where all conventional predictive coders aim to exploit it. For the cases where little spatial correlation exist, applying the Wyner-Ziv idea for compression of temporally correlated samples of a single signal source is more adequate.

In [3], [4], [5], [6] using the Wyner-Ziv idea frames are separately coded (intra coded) and jointly decoded at the decoder. Since frames are separately coded there is no predictive coding (motion estimation and compensation) which means a great power saving (intraframe coding). However, frames are jointly decoded at the decoder and their rate-distortion is superior to the performance of intra coded frames but worse than interframe coding.

This Wyner-Ziv coding architecture may alleviate us to design of low power video encoders which can achieve better rate-distortion performance than intra coding in WSN. Shifting complexity from encoder to the decoder side is common for all Wyner-Ziv encoders (spatial or temporal), however, this scheme has the advantage of being independent of an explicit correlation model. This property enables the design of practical distributed source coders.

Pixel-domain distributed video encoder [3], [4], [5] is given in Fig. 4 in order to illustrate a practical distributed video encoder scheme that exploits temporal correlation. The seperate encoding concept of DSC corresponds to the intraframe coding and similarly joint decoding corresponds to the interframe decoding in the figure. Key frames may be selected as the first frame in a group of pictures (GOP) and the rest are the Wyner-Ziv frames. Furthermore, if turbo decoder cannot reliably decode the original symbols, it makes a “request bits” call until an acceptable probability of symbol error is reached. The other proposed schemes such as transform-domain DSC [6], [58], [59] and joint decoding with motion estimation [7] can reach up to 2dB of the rate-distortion performance of interframe coding.

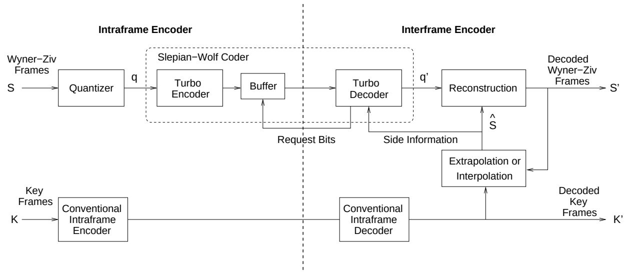


Fig. 4. Pixel-domain distributed video encoder

D. Open Research Issues

In multimedia WSN scenarios, extra care should be given to the application layer due to both energy and capacity constraints of sensor nodes and requirements of multimedia data. The open research issues on the application layer design for efficient multimedia communication in WSN can be outlined as follows:

- **Distributed Source Coding (DSC):** Available state of the art video encoders are designed to work in a balance of complex encoder and simple decoder and can achieve very good rate-distortion performance, which is reasonable for a single encoding and multiple decoding scenario such as video-on-demand. However, real-time applications especially running on low capacity and energy constrained devices do not favor this balance. DSC approach may revert this balance and hence stands as a promising approach for multimedia applications in WSN. There are basically two DSC approaches based on whether the event samples are correlated or not.
    - **DSC with Spatial Correlation:** The classical approach aims to represent the spatial correlation between two sources by assuming that samples of each source is i.i.d. Since this approach assumes that no temporal correlation exists between the samples, i.e., independent samples, it is well suited for the distributed compression of correlated images rather than video [47], [57], [87], [88], [94]. The major drawback of this approach is the need for the explicit correlation model between sources. Therefore, it is still a very challenging open research problem to develop the most appropriate correlation model for DSC application in multimedia WSN scenarios.
    - **DSC with Temporal Correlation:** Another DSC approach is exploiting the correlation between the samples of a single source, which fits very well for video applications. It provides significant energy gain at the encoder, and can reach a rate-distortion performance between the intraframe and interframe coding. There exist significant amount of research on Wyner-Ziv video encoders which aims to find a good tradeoff between processing and communication costs in multimedia WSN application [3], [4], [5], [6], [7]. Wyner-Ziv encoders [2], [1], [59], [69], [89] may also stand as an alternative of the layered representation and forward error correction

coding of bit streams for the legacy video streaming applications in multimedia WSN scenarios.

- **Multiple Description Coding (MDC):** Using MDC over a multipath transport provides significant resilience against burst losses and delay due to route recovery in case of a node failure. It also removes the cliff effect of classical channel coding schemes. Hence, new multiple description coding schemes that can provide the similar process and communication efficiency tradeoff should be investigated for multimedia WSN applications.

IV. TRANSPORT LAYER

In order to realize efficient multimedia communication in WSN, a reliable transport mechanism is imperative. In general, the main objectives of the transport layer are (i) to bridge application and network layers by application multiplexing and demultiplexing; (ii) to assure reliable data delivery between the source and the sink according to the specific reliability requirements of the application layer; (iii) to perform congestion control by regulating the amount of traffic injected to the network. However, the required transport layer functionalities to achieve efficient multimedia communication in sensor networks are subject to significant modifications in order to accommodate both the unique characteristics of WSN paradigm and multimedia transport requirements.

The energy, processing, and hardware limitations of wireless sensor nodes bring significant constraints on the transport layer protocol design [12]. For example, these limitations render the conventional end-to-end retransmission-based error control and the window-based additive-increase multiplicative-decrease (AIMD) congestion control mechanisms adopted by the vastly used TCP protocols inapplicable to WSN domain as they would lead to waste of scarce wireless sensor resources. Furthermore, wireless sensor networks deployed for different applications may require different reliability level as well as different congestion control approaches. On the other hand, in addition to the challenges for reliable data transport in WSN, there exist additional challenges due to the unique requirements of the multimedia transport. These challenges can be outlined as bounded delay and delay variation, minimum bandwidth demand, smooth traffic variation for multimedia streaming, and error control according to the specific requirements of multimedia WSN application.

Due to the application-oriented and collaborative nature of the wireless sensor networks, the main data flow takes place in the *forward path* where the wireless sensors are the source nodes transmitting their data to the sink. The *reverse path*, on the other hand, carries the data originated from the sink such as programming/retasking binaries, queries and commands to the sensor nodes. Consequently, here, we mainly focus on the forward path where multimedia communication takes place in WSN.

In [40], [77], [80], the need for a transport layer with efficient congestion control and reliability mechanisms for reliable data delivery in the wireless sensor networks was clearly pointed out. Although an end-to-end reliability may not be necessary due to the presence of correlated data flows, an event in the sensor field needs to be captured with a certain accuracy at the sink. Consequently, unlike traditional communication networks, the sensor network paradigm dictates an *event-to-sink* reliability notion at the transport layer [9]. This involves in reliable communication of the event features to the sink rather than conventional packet-based reliable delivery of the individual sensing reports/packets generated by each sensor in the field. Such *event-to-sink reliable transport* notion based on collective identification of data flows from the event to the sink is illustrated in Fig. 5.

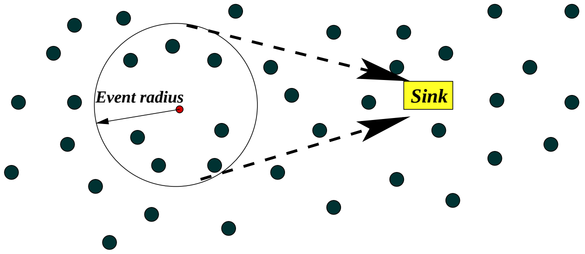


Fig. 5. Typical sensor network topology with event and sink. The sink is only interested in collective information of sensor nodes within the event radius and not in their individual data [9].

For reliable multimedia communication in WSN, possible congestion in the forward path due to high bandwidth demand should be also addressed by the transport layer. Once the event is sensed by a number of sensor nodes within the coverage of the phenomenon, i.e., event radius, significant amount of multimedia traffic is injected to the network by these sensor nodes and may easily lead to congestion. It has been shown in [77] that exceeding network capacity can be detrimental to the observed goodput at the sink. Moreover, although the event-to-sink reliability may be attained even in the presence of packet loss due to network congestion thanks to the correlated data flows and intrinsic properties of multimedia traffic, a suitable congestion control mechanism can also help conserve energy while maintaining desired accuracy levels at the sink.

Many multimedia transport protocols are proposed to control the flow of multimedia traffic in terrestrial networks [20], [36], [62], [75], [63], [54], which can be categorized into two types of rate control schemes, i.e., AIMD-based (Additive Increase Multiplicative Decrease) and equation-based. AIMD-based rate control schemes [20], [62], [75] are TCP-compatible, i.e., they compete reasonably fairly with the existing TCP by following TCP behavior to conservatively update the sending rate based on feedback information. On the other hand, the equation-based rate control schemes [36], [54] are proposed in order to provide relatively smooth congestion control for multimedia traffic in the terrestrial networks. The idea of the equation-based congestion control is to adjust the transmission rate no more than the estimated throughput of the corresponding TCP counterpart experiencing the same packet loss rate, round-trip time, and packet size. TFRC (TCP Friendly Rate Control) [36] is an equation-based rate control scheme which adopts a simple TCP throughput model in its congestion control mechanism. MPEG-TFRCP (TCP Friendly Rate Control Protocol for MPEG-2 Video Transfer) [54] is another equation-based rate control scheme designed for transporting MPEG2 video in a TCP-friendly manner. However, none of these solution proposals considers the WSN characteristics discussed in Section II, and hence cannot be used for efficient and reliable multimedia communication in WSN.

On the other hand, although the transport layer solutions for multimedia communication in conventional wireless networks are relevant, they are also inapplicable to WSN domain. These solutions mainly focus on efficient rate control for real-time multimedia streaming and fair network resource utilization following end-to-end TCP semantics and are proposed to address the challenges posed by wireless link errors and mobility [8], [13], [16]. The primary reason for their inapplicability is their notion of end-to-end rate control which is based on end-to-end acknowledgments. Furthermore, these solutions do not consider application-specific reliability requirements, which may be of great necessity in multimedia WSN applications.

There also exist some transport layer solution proposals in the literature specifically tailored to address efficient congestion control and reliable data delivery in sensor networks. In [72], the Reliable Multi-Segment Transport (RMST) protocol is proposed to address the requirements of reliable data transport in wireless sensor networks. RMST utilizes in-network caching and provides guaranteed delivery of the data packets generated by the event flows. However, event-to-sink reliable multimedia communication does not require guaranteed end-to-end data delivery since the individual data flows are correlated loss tolerant. Moreover, in-network caching for end-to-end strict reliability may bring significant processing and power overhead for resource constrained sensor nodes. The congestion detection and avoidance (CODA) protocol for sensor networks is presented in [81]. CODA mainly aims to detect and avoid congestion on the forward path in WSN. However, the CODA protocol does not address the reliable event transport in the sensor networks. In contrast to the transport layer protocols for conventional end-to-end reliability, Event-to-Sink Reliable Transport (ESRT) protocol [9], [65] is based on the event-to-sink reliability notion and provides reliable event detection with minimum energy expenditure without any intermediate caching requirements. It includes a congestion control component that serves the dual purpose of achieving reliability and conserving energy. It mainly exploits the fact that the sheer amount of data flows generated by the sensor nodes toward the sink are correlated due to spatial and temporal correlation among the individual sensor readings [79]. However, none of these transport layer protocols devised for WSN consider multimedia transport requirements such as application-specific QoS requirements, delay-bounds, and high bandwidth demand.

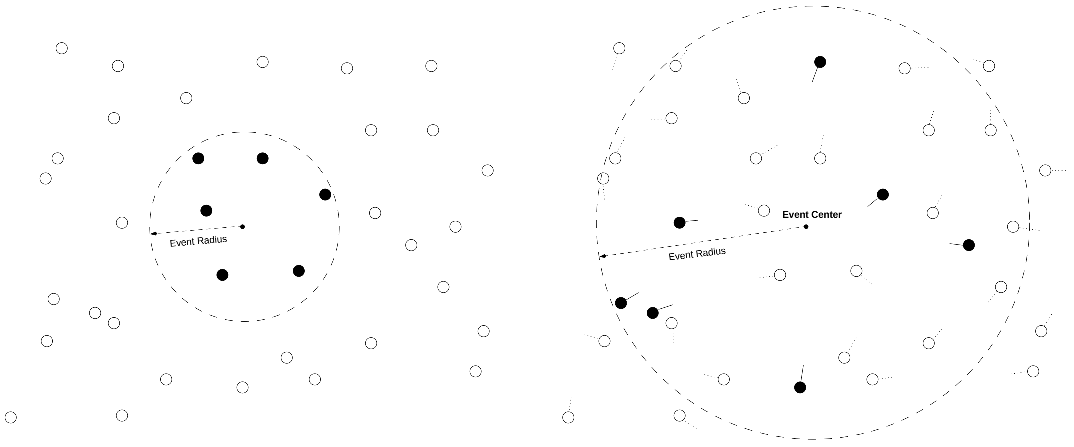
A. *Open Research Issues*

In summary, the transport layer mechanisms that can simultaneously address the unique challenges posed by the WSN paradigm and multimedia communication requirements are essential to achieve efficient and reliable multimedia communication in WSN. As we discussed above, while there exist promising solutions for event-to-sink reliable data transport in WSN, new transport protocols for multimedia delivery over WSN are yet to be developed. Hence, the summary of the open issues to be researched for multimedia transport in sensor networks are outlined below:

- **Reliable multimedia delivery over WSN:** In multimedia WSN applications, the data gathered from the field may contain multimedia information such as target images, acoustic signal, and even video captures of a moving target. However, the multimedia traffic has significantly different characteristics and hence different reliable transport requirements compared to conventional data traffic. Therefore, new transport layer solutions which address the requirements of multimedia delivery over WSN must be developed.
- **Real-time communication support:** Despite the existence of reliable transport solutions for WSN as discussed above, none of these protocols provide real-time communication support for the applications with strict delay bounds. Therefore, new transport solutions which can also meet certain application deadlines must be researched.
- **Relation between Multimedia Coding Rate and Reliability:** The success in energy-efficient and reliable delivery of multimedia information extracted from the phenomenon directly depends on selecting appropriate coding rate, number of sensor nodes, and data rate for a given event [79]. However, to this end, the event reliability should be accurately measured in order to efficiently adapt the multimedia coding and transmission rates [9]. For this purpose, new reliability metrics coupled with the application layer coding techniques should be investigated.
- **Cross-layer optimization:** Due to the severe processing, memory and energy limitations of sensor nodes, it is imperative that multimedia communication must be achieved with maximum efficiency. With this respect, cross-layer optimization of multimedia coding, transport, link and physical layer algorithms must be investigated and the theoretical results must be applied to develop new cross-layer communication protocols for reliable and efficient multimedia transport in WSN.

V. NETWORK LAYER

Network layer is mainly responsible for routing packets, both in fixed and mobile networks either it is wired or wireless. However, wireless mobile ad hoc networks or WSNs require *infrastructure communication* as well as the *application communication* referring to the basic packet routing task [76]. Infrastructure communication refers to the network layer communication needed to discover initial routes or repair failing routes due to changing topology. Although in mobile ad hoc networks topology changes are due to either mobility or leaves/joins of nodes to the network, it is generally due to node failures in WSN. In addition to the changing topology problem, WSN poses more stringent limitations due to scarce power and computational capacities and inability to use global identification (ID) due to extra overhead introduced by large number of nodes [11].



(a) (b)

Fig. 6. Shows event area in (a) typical WSN, (b) video WSN, with same node deployment

Therefore, WSN requires power efficient self-organizing routing protocols that take the above limitations into account. Furthermore, application communication is analyzed as either cooperative or non-cooperative communication. Cooperative communication is achieved by making *local communication* between sensors and *source aggregation*. Typically, sensors within a bounded locality communicate with an aggregator node in order to achieve an efficient representation of their data by means of some aggregation function, which is named as in-network data processing. Recently, numerous researchers have proposed energy efficient routing solutions for WSN [10], [15].

Multimedia delivery in WSN has the following limitations and characteristics, which should be taken into account during the design of a routing protocol.

L.1) Data Delivery Model: According to data delivery strategy WSNs are classified into three main groups, namely continuous, event-driven, and query-driven (observer initiated) [76]. Continuous delivery model requires continuous transmission of sensor data generated at a specified rate independent of the existence of an event or a user query emanating from the sink.

This delivery model is not suitable for efficient multimedia communication in WSN as the continuous compression and transport of multimedia is a highly power consuming task and may immediately drain the total energy in the sensor network. For this reason, practical multimedia communication in WSN should be activated in either event or query-driven manner.

L.2) Source Aggregation: Some routing solutions are based on aggregation of sensed data from a locality according to a certain aggregation function. However, simple aggregation functions such as averaging, max, thresholding is not feasible for multimedia data as stated in Section III. A possible aggregation function may be joint encoding of the incoming multiple correlated video signals at an aggregator node. However, distributed source coding theory revealed that spatial correlation can be represented as efficient as joint encoding by using seperate encoding with joint decoding principle. In addition to these discussions, small spatial correlation between sources may further reduce the importance of in-network aggregation or efficient representation of spatially correlated sources with DSC. This makes sense when the anisotropy in video capturing and far field sensing capabilities of video sensors are taken into account as illustrated in Fig. 6(a).

L.3) Local Inter-Sensor Communication: Local communication between sensors are generally necessitated by the source aggregation idea in L2. Local communication of multimedia data is not feasible due to reasons given in the *Local Communication* item in Section III. In addition to these discussions, definition of event area is somehow different than the classical sensor networks, because sensing capabilities of video sensors are different from typical sensors. A typical thermal, audio, acoustic or seismic sensor gathers data of its very close proximity, hence, sensors in a small event area around the event center wake up and sense the event as given in Fig. 6(a). However, video sensors, provided that it is in the line of sight, has far field sensing capabilities, e.g., from few ten meters to few hundred meters depending on the target application, and this data may be still valuable at the sink. On the contrary, if the event is out of the sight of a video sensor, no matter how close the camera to the event is, captured video signal may be assumed to be useless for the observer at the sink. A sample video WSN example designed as a surveillance system is given in Fig. 6(b), where dashed lines at each node show the line of sight of that node. Note that according to the far field sensing nature of video sensors, radius of an event area may be considerably larger than the traditional case. In addition to larger event area, active nodes within an event area is sparsely distributed. Consequently, inter-sensor communication becomes much more power consuming, and event samples observed by different sensor nodes become less correlated due to the sparse distribution.

L.4) Quality-of-Service: Multimedia data delivery is bound to the QoS requirements discussed in Section II-E such as high bandwidth and low error rate. Direct communication from a sensor node (a cluster head) to the sink in a single hop results in the usage of low bandwidth and high error rate communication channel (due to fading and multipath).

Therefore, for the case of multimedia transport, it is desirable to use multihop communication over short distances using high bandwidth and low error rate channels rather than the lower quality single hop communication. However, multihop communication results in a latency due to introduced channel access and queuing delay at each hop. Therefore, efficient routing protocols are required to satisfy the delay constraints of the application.

In the case of multimedia over WSN, network layer protocol should be designed to support either query or event based delivery models (L1). In accordance with the above limitations, network protocol should work in a multihop fashion (L4) where the local communication (L3) and source aggregation (L2) is disabled. In addition, using multipath is favorable since alternative paths may be used to increase effective connection capacity and provide error resilience, and network survivability [61]. In the rest of this section, routing algorithms proposed for WSN are analyzed in terms of their suitability for multimedia WSN applications by following a similar taxonomy in [10], [12].

A. Data-centric and flat-architecture protocols

This class of routing protocols gather or route data based on the attribute of the data, i.e., data centric, rather than using routes based on the unique identities (ID) of nodes in the sensor network.

Sensor Protocols for Information via Negotiation (SPIN) [37] is a negotiation-based event-driven protocol. Sensors generate meta-data descriptions in order to represent their data about an event, and broadcast advertisement message, ADV, for it. If a neighbor is interested in the data it sends back a REQ message and DATA is sent upon the reception of the REQ message as illustrated in Fig. 7. The neighbor node repeats the same process

SPIN is not suitable for the multimedia since generating meta data descriptions for multimedia data is not a practical task on capacity and power limited nodes. Furthermore, the ADV, REQ and DATA mechanism at each node is not well suited to the delay restrictions of real-time applications. Moreover, SPIN's advertisement mechanism cannot guarantee delivery of data due to uninterested nodes on the path between source and the sink.

Directed Diffusion [41] and its variants such as Rumor routing [18] and Gradient-based routing [66] are all query-based protocols and based on the idea described below with some slight modifications.

The sink makes a query by sending out an *interest*, which is a task defined by attribute-value pairs. Each sensor node stores this interest and relays it to some or all of its neighbors. In this way, a query is diffused into the network as shown in Fig. 8(a). As soon as a sensor node detects an event that matches one of the interests in its cache, it calculates a gradient for each neighbor node that delivers the matching interest. Thus, the gradients are setup from sensors to the sink as shown in Fig. 8(b). At the third stage in Fig. 8(c), the sink reinforces one or more paths by sending the same interest on the selected paths with a higher event rate. Note that in Fig. 8(d), two paths are reinforced rather than a single one. After path establishment is completed, data transport starts as defined in the matching interests. In addition to route discovery mechanisms, in-network processing may be employed to aggregate data to increase efficiency [41].

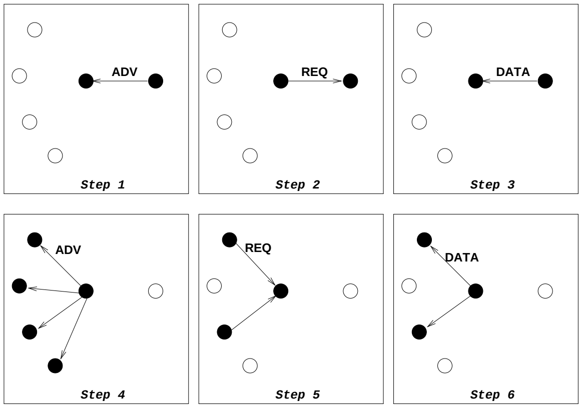
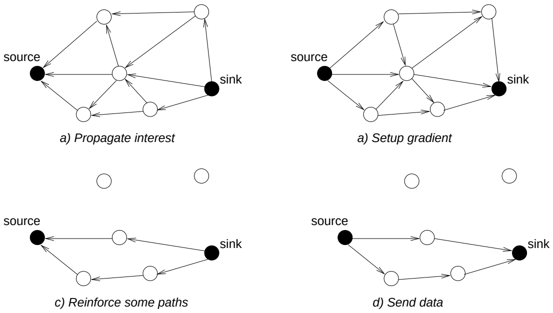


Fig. 7. The SPIN protocol [37].



a) Propagate interest

a) Setup gradient

c) Reinforce some paths

d) Send data

Fig. 8. Directed diffusion.

Although this is an efficient routing protocol for query-based data delivery, usage of in-network processing is a drawback in terms of multimedia transport (limitation L2). If source aggregation is disabled, it becomes suitable for multimedia due to its multipath property as well as the other properties that satisfy the limitations given in L1-L4. Even if in-network processing is disabled, it is still a complex algorithm for practical use in multimedia WSN applications.

B. Hierarchical routing protocols

The basic goal of hierarchical (cluster-based) routing protocols is energy-efficient transport of sensed data within a cluster to the sink. These protocols generally utilize in-network processing at the cluster-heads in order to achieve high efficiency, which is not practical for multimedia traffic (limitation L2). The other drawback of this class of protocols for multimedia WSN case is increased local communication cost between sensors due to communication and processing cost of multimedia information gathered and processed at a cluster-head (limitation L3). The other drawback is in terms of QoS requirements of multimedia (limitation L4) since generally cluster-heads are assumed to be capable of accessing the sink directly over longer distances, which results in a low quality channel.

In all of the following protocols, a node is selected in order to collect data from its proximity and make direct communication with the sink. For example, LEACH (Low-Energy Adaptive Clustering Hierarchy) [38] clusters the sensors in the field and achieves fair distribution of power consumption among the nodes in the cluster by randomly reassigning one or more cluster-heads. PEGASIS [45] has the same approach, however, it allows a single aggregator node and defines a chain in order to avoid using clustering algorithms. TEEN [50] and its adaptive version APTEEN ((AdaPtive) Threshold sensitive Energy Efficient sensor Network) [51] have the similar approach with LEACH, i.e., both designate the transmitting nodes by using thresholding mechanisms.

This family of protocols are mainly focused on application communication rather than infrastructure communication. Primarily due to the conflicts with the basic limitations of multimedia WSN, these protocols cannot be considered as an efficient way of routing multimedia data.

C. Location-based protocols

Typically, there is no IP-like addressing in sensor networks. Therefore, if location information is known, routing protocols can utilize it to reduce the latency and power consumption of the sensor network. For example, in Directed Diffusion, queries may be broadcast to the neighboring nodes that are on the way of the interested region as proposed in Geographical and Energy Aware Routing (GEAR) [93]. The following protocols aim to make energy efficient routing by using location information and without making any type of aggregation. Geographic Adaptive Fidelity (GAF) [90], is mainly designed for mobile ad hoc networks, and it utilizes a virtual grid and therefore may be classified as a hierarchical routing protocol. It saves energy by turning off unnecessary nodes without loosing any routing fidelity, and it communicates in a multihop manner. Minimum Energy Communication Network (MECN) [64], and its variant Small MECN (SMECN) [44] based on local algorithms aim to compute a network with minimum energy. This is achieved by using the location information and finding relay regions that minimize the energy. Both MECN and SMECN can be classified as proactive routing protocols since an up-to-date routing information is maintained in the network. However, the computed network topology provides the minimum energy paths, and hence, the proactive routing protocols are ineffective due to the need of reconfiguration of the network in case of a topology change.

Location-based protocols, except MECN [64] and SMECN [44], generally follow the ideas developed in other protocol classes previously overviewed in this section. However, location awareness provides a reduction in latency and energy consumption which are very crucial for multimedia applications that work on energy constrained WSN. Consequently, this class of protocols suit to the multimedia WSN applications provided that they obey the limitations given in L1-L4.

D. QoS-based protocols

This class of protocols aim to minimize a cost function as a metric of optimization which may capture features such as node residual energy, link latency, hop count, and bandwidth usage.

Sequential Assignment Routing (SAR) [71] is the first proposal that addresses the QoS issue in WSN. It expands multiple trees, where the root of each tree seeds from the neighboring nodes of the sink and they are expanded by avoiding nodes that provide low QoS and energy reserves. In this manner, multiple paths with different QoS levels are obtained from a source to the sink. In *maximum lifetime routing* [21] a cost function is defined as a combination of transmission and reception energy and residual energy levels of neighboring nodes. IDSQ/CADR [25] is both location and query-based protocol, where querying and routing are handled by *information driven sensor querying* (IDSQ) and *constrained anisotropic diffusion routing* (CADR) modules, respectively. Its main objective is to increase the information gain by selecting the routes that minimizes a composite cost function of the link delay and bandwidth. However, it is not suitable for multimedia delivery in WSN, since quantifying the contribution of each sensor's measurement to the overall information gain is not practical for the multimedia. Furthermore, it is not designed to establish multiple paths between the sink and a sensor node. *Energy aware routing* is a destination initiated protocol, where the basic idea is to increase the *network survivability* rather than using only the lowest energy paths [61]. Link costs are defined as a function of transmit/receive energy and residual energy normalized to the initial energy similar to the definition in [21]. The interesting feature of this protocol is establishing multiple paths (optimal and sub-optimal) with different energy metrics and assigned probabilities. Packets are routed on one of the randomly selected multiple paths in order to prevent the depletion of the optimal path, which results in an increase in network survivability. Hence, it is inherently a multipath protocol with QoS measurements and a good fit for routing of multimedia streams in WSN.

This class of protocols, in general, are well suited for multimedia delivery in WSN since they comply with the limitations L2-L4, i.e., no data aggregation, no local communication of data, and multihop routing. Protocols that support multipath together with QoS-based routing are the best fit for multimedia transport. Since different priorities can be assigned to different partitions of multimedia data, using higher QoS paths for high priority partitions may yield a better overall network performance.

E. Open Research Issues

Despite the existence of significant amount of research results on routing protocols for WSN, there is no solution proposal specifically tailored to address the routing problems of multimedia streams in WSN. Hence, the open research issues in this direction can be outlined as follows:

- **Reactive Routing:** Reactive routing schemes that do not rely on source aggregation and local communications would basically fit to the requirements of a multimedia WSN, and hence, must be investigated for routing protocol design for multimedia WSN applications.
- **Location-aware QoS-based Routing:** As discussed in Sections V-C and V-D, location awareness and QoS-based

protocols may further improve the energy-efficiency in routing of multimedia streams in WSN. Hence, these classes of routing protocols must be thoroughly investigated in order to develop a complete solution for routing problem in multimedia WSN applications.

- **Multipath Routing:** Multipath routing protocols are also a important class since it provides load balancing, and reliable communication. This approach must be also pursued in order to develop routing solutions which also comply with the application layer design methods such as multiple description coding.

VI. CONCLUSION

Wireless sensor networks has a wide range of potential applications which strengthen the human interaction with the physical environment. While vast majority of the research studies have focused on the applications requiring conventional data communications, there exist many WSN applications which directly involve multimedia communication such as target tracking and surveillance, disaster relief, homeland security, proactive health care, smart homes. In order to realize these multimedia WSN applications, effective communication protocols, which address the unique challenges posed by the WSN paradigm and multimedia transport requirements, are mandatory. In the current literature on WSN, the research efforts have been focused on addressing the problems of conventional data communication. In this paper, we surveyed the research challenges and the current status of the literature on the multimedia communication in WSN. More specifically, the multimedia applications of WSN, basic design constraints, currently proposed solutions in different application, transport and network layers, and open research issues for multimedia delivery in WSN are pointed out. The main results of this survey reveal that there exist a clear need for a great deal of research effort to focus on developing efficient communication protocols and algorithms in order to realize multimedia WSN applications.

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