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Review

Routing in wireless multimedia sensor networks: A survey and challenges ahead

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ABSTRACT

Wireless Multimedia Sensor Networks (WMSNs) have drawn tremendous attention because of their potential impact on scientific research and their numerous attractive applications. Routing in WMSNs has been an active area of research in the past few years. The transmission of multimedia data depends on a routing protocol to determine stable and resource-efficient path, and to provide varying levels of Quality-of-Service (QoS)/Quality-of-Experience (QoE) guarantee for multimedia. However, it is a challenging problem due to the limited network resources and complicated operations of multimedia applications as well as dynamic changes of network condition. This paper begins with the challenges and requirements in the design of WMSN routing, followed by an exhaustive survey on routing from the perspective of application requirements and key techniques. In particular, the existing routing solutions are classified into five major categories based on their design and optimization objectives, that is, QoS provisioning, multimedia awareness, energy efficiency, congestion avoidance, bandwidth optimization. Finally, we will discuss the open research issues in routing metrics and several potential research areas regarding routing in emerging WMSN application scenarios.

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1. Introduction

Wireless Sensor Networks (WSNs) (Yick et al., 2008), a type of physical monitoring system, consist of a self-organized and linked sensors widely dispersed in a coverage area. The collection, communication, and treatment of sensed information among various sensors is achieved through specific communication protocols, and the data is transmitted via multi-hop routing to the sink. The sink functions as the data, computation and control center of the entire network. The administrator can communicate with the sink through conventional networks such as the Internet.

Traditional WSNs only gather, process, and transmit scalar data (i.e. temperature, pressure, humidity, or location) across a network with lower bandwidth in transmission. However, as the monitoring environment has been getting increasingly complex, the scalar data could not meet the demands for fine-grained environmental monitoring. Thus, it has become necessary to support media rich content such as images, video and audio, in order to refine the data collection and more accurately monitor the environment. Recent technological developments have significantly reduced the cost of hardware, like cameras and microphones, which have gradually increased in application; bandwidth capabilities have increased as well improving wireless communication capabilities. In such a context, WSNs have started to evolve into Wireless Multimedia Sensor Networks (WMSNs), which can store, process in real-time, correlate and fuse multimedia data originated from heterogeneous sources (Akyildiz et al., 2007). Research indicates that such networks can significantly improve the sensing ability on environments and description ability on environmental events.

WMSN is an important and exciting new technology with great potential for strengthening the traditional WSN applications, as well as creating a series of new multimedia applications such as multi-camera surveillance (Natarajan et al., 2015), visual target tracking (de San Bernabe et al., 2015), location-based multimedia services (Akhlaq Ahmad et al., 2015), and situation awareness (Wang, 2015). With the deployment of WMSN which provides the majority of hardware infrastructure support, and to provide access to sensors, it has become an important supportive platform for sensing and transmission of Internet of Multimedia Things (IoMT) (Alvi et al., 2015). Many applications in IoMT benefit from WMSN technology, such as wearable devices (Weitao Xu, 2015) and crowd sensing (Ramesh et al., 2014). As WMSN has come into existence with the development of various types of multimedia sensors, search volumes of video sensor and camera sensor measured by the Google search trends are consistently increasing with the falling trend for wireless sensor in recent years (see Fig. 1), demonstrating a high level of concern.

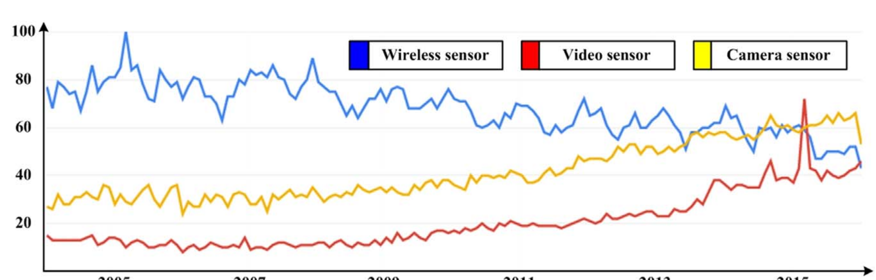

Fig. 1. Google search trends in the last 11 years for terms wireless sensor, video sensor and camera sensor.

High-efficiency routing with multimedia support has become an important research focus in WMSNs. In the past few years, extensive research works on traditional WSN routing algorithms, protocols, and techniques have been done based on the requirements of application and the architecture of the network. The intent behind these solutions is to provide best-effort services to ensure normal operations of network systems, in which energy conservation is major concern. However, because WMSNs have heterogeneous media, large data volume, complex data formats and operations, and need high-rate transmission in real-time, their requirements on processing and storage, as well as bandwidth, are beyond the competence of typical WSN platform such as MICA (Hill and Culler, 2002). The multimedia transmission in WMSNs depends on a routing protocol to determine stable and resource-efficient path, and to provide varying levels of QoS/QoE based on different requirements. The resource efficiency not only includes effective bandwidth utilization, but also includes reduced energy consumption. As a result, there are many special considerations in routing design and development.

This paper intends to present a comprehensive and state-of-the-art survey on routing in WMSNs. The main contributions are as follows:

- The differences between WMSN routing and WSN routing are explained. On this basis, we elucidate the technological challenges routing design faces in WMSNs, while outlining the main design principles.
- An exhaustive survey on routing and their classification into five main categories (QoS provisioning, multimedia awareness, energy efficiency, congestion avoidance, bandwidth optimization) are presented. Many emerging routing techniques (such as coding-based, spectrum-efficient) are covered.
- We highlight the relative advantages and disadvantages of many of prominent routing approaches, and provide a comparison of each solution including various parameters in order for researchers to understand the various techniques, thus to choose the most appropriate one based on their needs.
- This paper points out the open research issues in routing metrics and protocols faced by WMSNs, while discussing trends of routing development for emerging WMSN application scenarios (e.g., IoMT, cloud/fog-assisted, underwater, flying, software-defined WMSNs).

The remainder of this paper is organized as follows. We briefly introduce the related works and motivation in the next section. Section 3 discusses routing design issues along with their limitations. In Section 4, current state-of-the-art of WMSN routing is surveyed and categorized with a discussion on the advantages and limitations. A detailed comparison in a tabular form is brought in Section 5. Some important development trends and challenges that need to be further considered are addressed in Section 6. We present the conclusion in Section 7.

2. Motivation

Relatively little surveys in the literature have focused on routing in WSMNs. One of the most important surveys in this field has been presented in Ehsan and Hamdaoui (2012). The authors describe many energy-efficient QoS routing protocols, but some of emerging routing techniques are not covered.

In another survey (Abazeed et al., 2013), the summarized works are mostly published before 2010, which cannot reflect the research progress made during the past few years. A survey on QoS routing protocols in WMSNs is presented in Aswale and Ghorpade (2015) in which the protocols are reviewed and categorized based on the number of routing metrics. This work also misses many emerging routing methods.

A comparison study of QoS-aware single-path vs. multipath routing protocols for WMSN-based image transmission is performed in Macit et al. (2014). The experimental results demonstrate that: under low and moderate traffic loads, multipath routing is better than single-path routing in terms of reliability; at high traffic loads, multipath routing may perform worse in terms of delay due to extra overhead.

Another performance comparison study on WMSN routing is presented in Alanazi and Elleithy (2015), in which the real-time QoS routing protocols are categorized into probabilistic and deterministic protocols. The authors use simulation method to compare their advantages and disadvantages of these protocols.

After studying existing surveys, we realize that there is no comprehensive paper that surveys all the WMSN routing protocols in a suitable classified manner, as well as the future trends and challenges. This motivates us to perform this survey paper with focus on the latest research progress on WMSN routing while analyzing the development trends and problems to be solved in the future.

3. Routing design issues

In general, routing in WSMNs can be classified as flat routing and hierarchical routing, depending on the network architecture, shown in Fig. 2. In flat architecture, the network is deployed with homogeneous sensors of the same capabilities and functionalities. In cluster-based architecture, the network is divided into clusters. Heterogeneous sensors are deployed in each cluster, where different kinds of sensors relay data to a cluster header (CH) that has more resources and is able to perform intensive data processing. The CH is connected with the sink either directly or through other CHs in multi-hop fashion.

Providing an efficient routing for WMSNs is a complex issue. In this section, we provide an overview of routing design issues. The particularity of routing in WMSNs are explained in Section 3.1. There are several factors that mainly influence the design of WMSN routing, which are outlined in Section 3.2. Section 3.3 outlines the main design principles.

3.1. WMSN routing vs. WSN routing

Both WMSNs and WSNs are wireless ad hoc networks because of their distributed nature. They usually employ battery powered nodes and therefore there is a common concern on energy optimization in the design of routing protocols. Apart from these similarities, there are also fundamental differences especially in terms of multimedia support capabilities.

First, typical WSN routing is not designed for multimedia applications that require high-bandwidth, high-fidelity and processing energy, and real-time transmission. In WMSNs, as heterogeneous sensors may be deployed, video streams, still image, audio and scalar data may be available, which impose additional challenges for routing. Second, there is a trade-off between energy efficiency and multimedia QoS/QoE when making a routing decision. For instance, the routing schemes for data aggregation and compression are widely applied to save energy, but they may cause unacceptable delay in WMSNs. Third, the multimedia sensing and delivery model impact the routing performance, especially for energy consumption rate and frequency of route changes, i.e. when a node is continually capturing and transmitting a multimedia content, more energy will be consumed, and therefore the routes will continually be calculated. Last but not least, widely used predictive video encoding (e.g., MPEG-4 Part 2, H.264/MVC

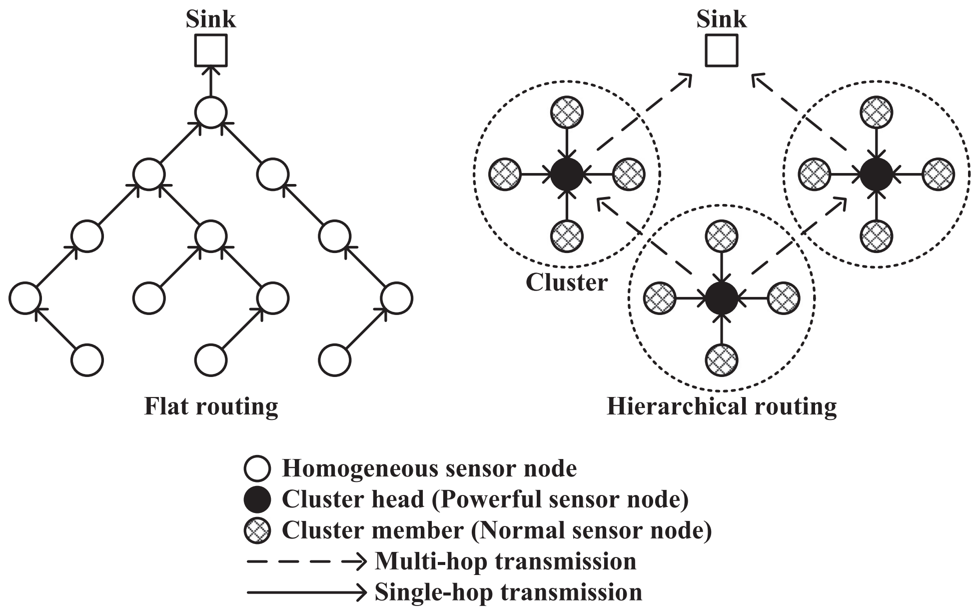

Fig. 2. Flat routing & Hierarchical routing.

(Pan et al., 2015)) leads to significant energy consumption and therefore results in degradation in routing efficiency. These constraints and challenges, in combination with the bandwidth-intense and delay-sensitive nature of multimedia applications, make routing over WMSNs a challenging proposition.

3.2. Technological challenges

There are numerous challenges and difficulties in WMSN routing design and its performance optimization, including:

1. *Limited node energy*: Multimedia represents a resource-consuming application, but WMSNs are limited by their non-rechargeable or replaceable battery supply. Although energy harvesting allows sensors to power themselves, there are many difficulties and limitations in its practical application.
2. *Coexistence of multiple business requirements*: WMSNs handle heterogeneous data which can consist of scalar, audio, video, image and acoustic data, all of which have varied QoS requirements. Various services with a diverse set of requirements present a significant challenge to routing design.
3. *Bursty of multimedia traffic*: Compressed video often exhibits significant burstiness on a variety of time scales, due to the frame structure of the encoding scheme and natural variations within and between scenes (Leland et al., 1994). This greatly increases the difficulty of analysis and evaluation for routing performance in WMSNs.
4. *Redundancy in multimedia traffic*: To obtain visual information of multi-view, high signal-to-noise ratio (SNR), and fine grain, some redundant video sensor nodes are often placed in the monitoring areas. Although this approach helps to reduce coverage-blind areas, the redundant video information it has caused inevitably consumes network resources.
5. *Network dynamics*: A node might stop working because of energy depletion or malfunctions, or be temporarily added into a network due to application demand; thus, the number of nodes in the monitoring area is dynamic. The network topology structure could also change because of mutual interferences, terrain factors and so on; therefore, the expansibility and flexibility should be considered.
6. *Complexity of monitoring environment*: Events at the monitoring area often exhibit dynamic characteristics in spatiotemporal dimensions, increasing event capture difficulty and communication expenses (Shen et al., 2015). The monitoring system must provide timeliness and coverage support. The former needs to control the delays in data processing and transmission, whereas the latter involves coordination and cooperation among nodes.
7. *Network heterogeneity*: Different types of nodes are required to communicate in order to facilitate data collection, processing, and transmission in an effective and efficient manner. Differences in functionality make it impossible to have a uniform communication protocol platform, separating them from traditional wireless networks.
8. *Communication congestion*: The characteristic of many-to-one and mutual interference between wireless links as well as limited WMSN resources leave the network prone to congestion. If a node is overwhelmed by multiple high-rate streams, it will result in decreased network performance and increase the chances of node failure from energy depletion.
9. *Limited communication ability*: The radio frequency signal coverage of sensor nodes is typically below one hundred meters. If it is required to communicate with nodes outside of its coverage range, then a signal relay is needed. If the coverage range is extended by increasing transmission power, then it will consume more energy.
10. *Limited computation and storage ability*: Multimedia sensors are small, micro-embedded devices with a limited-capability processor and reduced storage capacity. However, in addition to data collection and transmission, nodes also are responsible for QoS provisioning as well as other tasks.

3.3. Design principles

WMSN routing can be considered as the inheritance and development of QoS routing in traditional WSNs. The design principles include the following items:

1. *Energy efficiency*: Energy-constrained WMSNs are expected to run autonomously for long periods, but it may be cost-prohibitive to replace exhausted batteries or even impossible in

hostile environments (Rault et al., 2014). This requires a routing protocol with energy efficiency.

2. *Provisioning of QoS guarantees*: WMSNs have increased information gathering capacity; it is able to provide more services, including real-time video. Because of stringent multimedia QoS requirements, routing mechanism not only needs to take energy conservation, scalability and fault tolerance into consideration, but also should provide QoS guarantees.
3. *QoE awareness*: QoS is not accurate or satisfactory enough to guarantee wireless video quality in many cases, whereas QoE is more suitable scheme to overcome the main drawbacks of QoS based on the perspective of the user. This metric has played an important role in measuring the quality level of multimedia content.
4. *Provisioning of service differentiation*: Due to heterogeneous traffic flows and their differentiated requirements, supporting differentiated services becomes crucial for WMSNs. A routing protocol of diffserv is able to adapt to environments where multiple businesses coexist.
5. *In-network multimedia processing*: The nodes using in-network processing are able to compress and filter the redundancy to lower network load, saving bandwidth and energy. Thus, it has become necessary to set aside a certain operational space for in-network processing in routing design.
6. *Link quality awareness*: It is difficult to provide good routing performance consistently because the quality of an unstable link often changes dramatically (Lin et al., 2015). Accurately capturing link quality can help choose those good links for routing, especially in reliability and latency.
7. *Bandwidth efficiency*: Multimedia transmission with large amounts of data requires high bandwidth, depending on frame rate, resolution, and compression format. This requires a routing protocol with capabilities of preventing disorderly competitions for bandwidth, and achieving load balancing.
8. *Congestion avoidance*: Because of bursty traffic, WMSNs are more prone to traffic congestion, and consequently, a large number of lost packets result in poor quality of reconstructed video (Aghdam et al., 2014). So, it is necessary to consider congestion control and fairness in the design of routing protocol.
9. *Low cost and low complexity design*: Routing protocol design should follow flexible and simple principle to simplify as much as possible the expenses of computation and information exchange. In addition to adopting approximate or heuristic routing algorithms, it is worth investigating computation offloading in routing for energy-traffic tradeoff.
10. *Cross-layer cooperation*: Researchers have systematically studied QoS architecture of WMSN and the inherent relationship to various QoS parameters. The independent operations of various protocol layers are integrated into a unified design framework, facilitating cooperativity with each other to achieve optimal system performance.

4. The state-of-the-art in WMSN routing

Since WMSN is highly related to application, specific routing protocols need to be designed according to specific demands. As shown in Fig. 3, from the perspective of application requirements and key techniques, this section provides an exhaustive survey of recent research progress on routing. The existing routing solutions are classified into five main categories: QoS provisioning, multimedia awareness, energy efficiency, congestion avoidance, bandwidth optimization. The routing solutions belonging to each category are further classified based on their design and optimization objectives. Under each category, we introduce the working principles and execution details of the representative routing solutions, at the same time analyze their merits and disadvantages.

4.1. QoS provisioning

Unlike the traditional WSNs aimed at maximizing network lifetime by decreasing energy consumption, the main objective of WMSNs is to optimize delivery of multimedia content with a predetermined level of QoS in terms of delay, reliability, accuracy, quality of video perception, and coverage preservation.

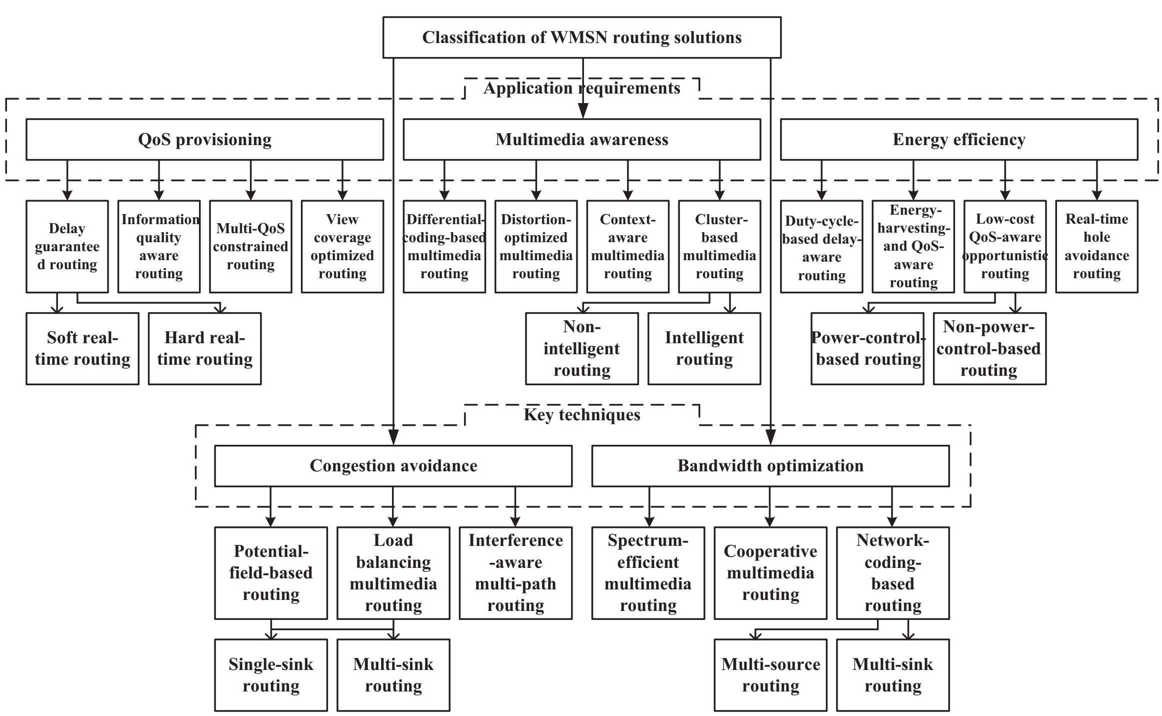

Fig. 3. Classification of WMSN routing solutions.

4.1.1. *Delay guaranteed routing*

Delay guaranteed routing protocol utilizes transmission delay as the path selection basis. This type of protocol generally combines with specific link quality measurement, queue management, flow distribution, and other mechanisms to improve real-time transmission. Next, we survey the routing solutions based on the type of delay guarantee, i.e., soft and hard real-time bounded delay.

(1) *Soft real-time routing*: Energy-Aware QoS routing (EAQoS) (Akkaya and Younis, 2003) has been proposed to identify a low energy-consuming and reliable route while taking the end-to-end delay into consideration. Utilizing a hierarchical queuing model, EAQoS accounts for non-real-time data stream throughput by adjusting service probability. However, EAQoS fails to consider the delays of channel access and queuing. Moreover, it requires entire network topology information to support multiple path computation and decreases the flexibility.

Real-time Power Aware Routing (RPAR) (Chipara et al., 2006) could dynamically adjust transmission power and routing decision according to network load and data packet size. Its unique forwarding and neighbor management mechanism could effectively save energy while meeting real-time constraints. Moreover, RPAR accounts for variability in link quality in order to improve transmission reliability. Despite its advantages, RPAR fails to consider hole and congestion issues.

He et al. (2005) propose SPEED, a distributed QoS routing protocol based on geographic location, aimed at providing end-to-end soft real-time assurance for businesses by exploring the spatiotemporal characteristics. To compute the forward speed, which should be greater at the selected node than the threshold, and forward time, adjacent nodes needed to exchange position information and loading status in real-time. Despite its advantages, pitfalls of SPEED encompass a lack of consideration for energy efficiency and a lack of reliability.

Li et al. extend the one-hop-based protocol SPEED, and propose THVR (Li et al., 2009), a Two-Hop real-time Velocity-based Routing protocol. An adaptive packet drop mechanism is introduced to enhance energy efficiency while reducing packet deadline miss ratio. However, the packet drop during a crisis state is undesirable since it violates reliability requirements.

Dynamic Hybrid Geographic Routing (DHGR) (Chen et al., 2009) utilizes both distance- and direction-based strategies for flexible energy-delay tradeoff. This scheme can satisfy average end-to-end delay constraint while reducing energy consumption. In particular, a node can perform a dynamic adjustment without any feedback from the sink or knowledge with respect to global topology. However, it fails to consider reliability in its tradeoff mechanism.

Cross-layer channel Utilization and Delay Aware Routing (CUDAR) (Hamid et al., 2015) protocol enables cross-layer information exchange between network and MAC layers for choosing potential forwarding nodes in WMSNs. The purpose is to provide soft end-to-end delay guarantee along with efficient resource utilization. The relationship between packet service time and channel utilization is analyzed to evaluate its effect on network performance. Nevertheless, it is difficult to evaluate overhead from cross-layer design.

Spachos et al. (2015) improve the ADRS (Spachos et al., 2014), which is usually used to provide source location secrecy against an adversary. The focus is on demonstrating how the scheme can be employed to extend network lifetime of a WMSN under delay constraint. The advantage conferred by this scheme is of low complexity, and the capacity to adapt rapidly to changes in topology.

(2) *Hard real-time routing*: An energy-efficient routing algorithm is proposed in Ergen and Varaiya (2007). The purpose is to maximize the lifetime by adjusting the number of packets traversing throughout the network. The end-to-end delay constraint is excluded and lifetime maximization is formulated as a linear programming problem, and a distributed solution is implemented which uses an iterative algorithm to approximate the optimal solution. The protocol incorporates delay guarantee into routing framework by adjusting path length to the collection node. However, it cannot meet application-specified delay bound.

Delay Guaranteed Routing and MAC (DGRAM) (Shanti and Sahoo, 2010) protocol depends on contention-free TDMA-based MAC protocol, and can support hard real-time applications in an energy-efficient manner. While the reduced latency is achieved by slot reuse, it does not require a centralized controller, different from many TDMA-based MAC protocol. However, it makes too many assumptions to ensure correct operation, e.g., all nodes are synchronized; the coverage area of the network is circular, and so on. These assumptions limit the applicability.

A self-stabilizing hop-constrained energy-efficient (SHE) clustering and routing protocol is proposed in Chen (2016) that supports hard real-time application. This protocol constructs multi-hop paths within a cluster, where the number of member nodes is under control in order to satisfy the deadline. The aggregate packets are forwarded from CHs to the sink through different paths. However, it fails to support the heterogeneous nodes with various energy capacities.

4.1.2. *Information quality aware routing*

Providing acceptable information quality (IQ) (i.e., reliability, accuracy, and consistency of information) is essential for many WMSN applications. The design of IQ aware routing with data aggregation, transmission rate control, or sampling rate control has been explored to optimize overall performance.

IQ Aware Routing (IQAR) protocol (Tan et al., 2010) aims at finding the least-cost routing tree subject to IQ constraint in event detection. It constructs an initial distance based aggregation tree that spans all the sensors, and collects sufficient data for a phenomenon of interest (PoI) to be detected accurately. Through redundancy suppression, IQAR significantly reduces energy and delay. However, the realistic characteristics of WMSNs should be considered when applied.

Li et al. (2012)propose ILSR, a localized Integrated Location Service and Routing scheme to a mobile sink with guaranteed delivery rate. This scheme utilizes a controlled flooding to update node location when a link is broken or is created. The authors consider both unpredictable and predictable sink mobility, both of which can guarantee delivery in a connected network modeled as unit disk graph. The energy efficiency and routing delay issues need to be further considered.

A distributed probabilistic routing (ProHet) (Chen et al., 2013) is proposed to provides guaranteed delivery for heterogeneous sensor networks with different transmission ranges. As a reactive protocol, ProHet is more suitable for large and more dynamic networks. The authors further propose two types of performance guaranteed routing protocols LayHet and EgyHet (Chen et al., 2013). The former is based on the shortest path, which saves energy by minimizing the number of broadcasts and the probability of forwarding. The latter is energy-optimized LayHet.

4.1.3. *Multi-QoS constrained routing*

Multi-QoS constrained routing simultaneously considers multiple indices, providing dynamically adjustable QoS assurance.

As a great improvement of SPEED, MultiPath and Multi-SPEED Routing (MMSPEED) (Felemban et al., 2006) takes a cross-layer design approach between network layer and MAC layer in order to distinguish the communication flows with different delay and reliability demands, and to provide end-to-end QoS guarantee.

While this protocol provides reliability assurance in the form of expectation redundancy forward, it introduces a new metric, ON-Time Reach-Ability, to represent the probability to reach destination within the limit of the required delay. The primary problem for MMSPEED is that it lacks a control for redundant data, so there is a decrease in energy efficiency, and an increase in communication congestion.

The work in Razzaque et al. (2008) defines the aggregation multipath routing function and probabilistic model for route decision, building upon which it designs selective greedy forwarding and prepares different transmission rules for real-time and non-real-time packets. Real-time data can be forwarded from nodes farther away. A Distributed Aggregate Routing Algorithm (DARA) is designed to determines the multiple paths for multiple sinks while ensuring reliability. However, this algorithm has the issue of redundant data.

Huang and Fang (2008) propose a multi-constrained QoS multipath routing that utilizes local link state information to map soft-QoS into links on a path. The end-to-end QoS guarantee problem is formulated as a stochastic programming, building upon which a distributed routing algorithm is designed by the estimation and approximation of path quality. However, there is a need to improve the estimation accuracy thus strengthening its robustness.

Energy efficient and QoS aware multipath Routing (EQSR) (Ben-Othman and Yahya, 2010) constructs multiple paths through broadcasting, and considers node energy, storage space and link quality during path selection. Moreover, it adopts the concept of diffserv to spread high priority data into multiple paths, thus improving reliability and throughput. However, it fails to consider multimedia context mapping.

An energy-aware routing protocol (EARQ) is proposed in Heo et al. (2009) that provides real-time, reliable and energy-aware data delivery in industrial WSNs. A node estimates the energy cost, delay and reliability of a path based on local information. The estimation value is used to calculate the probability of route selection. On this basis, a path that has lower energy cost and meets deadline would be chosen. Redundant packets can be transmitted through an alternate path to enhance reliability. However, it lacks a method for optimizing delivery of multimedia data.

Liu et al. (2012) propose QoS-PSO, an agent-assisted QoS-based routing algorithm, which uses Particle Swarm Optimization (PSO) algorithm to compute the synthetic QoS value (including delay, bandwidth, and packet loss rate) to determine an optimal path. Intelligent software agents are introduced to monitor changes in network topology, communication flow, and routing table. Despite its advantages, it lacks a trade-off mechanism to coordinate multiple QoS metrics.

Parallel Elite Clonal Quantum Evolutionary Algorithm (PECQEA) (Zhou et al., 2014) aims at minimizing energy consumption while providing QoS guarantees including delay, jitter, bandwidth, and packet loss rate in WMSNs. It has fast search speed and global search ability in complex search spaces, and can avoid the local optimum and rapidly towards the optimal region during the search process.

Operator Calculus based Routing Protocol (OCRP) (Nefzi et al., 2015) utilizes Operator Calculus methods on graphs to solve the multi-QoS constrained routing problem. In this protocol, a node chooses the set of eligible next-hops based on the given constraints and the distance to the sink. However, it ignores the impact of estimation accuracy on delay and reliability.

4.1.4. View coverage optimized routing

View coverage of the monitored area is a fundamental problem in WMSNs, and should be considered in routing design.

A distributed coverage-preserving routing algorithm is proposed in Li et al. (2011) to maximize the coverage scope of path area under the application-specified delay. This algorithm estimates sensing area scope by monte-carlo integration, and then utilizes label setting strategy for selecting paths. The advantage conferred by this algorithm is the capacity to get rid of GPS dependence. However, if applying this algorithm into a WMSN, the omnidirectional sensing model needs to be changed into the directional sensing model (generally adopted by multimedia sensor).

An offline coverage-aware multipath selection algorithm (Costa, 2011) is proposed to distribute multimedia traffic over multiple paths based on the coverage relevance. Despite the improvements in energy utilization and load fairness, it cannot meet application-specified end-to-end delay.

4.2. Multimedia awareness

Recent advances in WMSNs have led to many new routing techniques specifically designed for voluminous multimedia data management, control, and transmissions, where multimedia awareness is an essential consideration.

4.2.1. Differential-coding-based multimedia routing

WMSNs allow performing lightweight in-network processing on the raw multimedia data transmitted from environment. Considering that the radius of FoV is generally greater than the distance between adjacent nodes, combining in-network processing with routing is a practical solution. A number of routing approaches have been proposed to reduce load and save energy (Villas et al., 2013), but lack of consideration for the characteristics of multimedia data. Meanwhile, many correlation models have been proposed to extract the spatial correlation of camera sensors (Mowafi et al., 2014), but lack of the collaboration with routing. Here we choose differential-coding-based routing for in-network video processing in WMSNs.

Dai et al. (2012) explore in-network video processing during route selection, and achieve a dynamic compression on redundant video data using differential coding (DC) (Dai and Akyildiz, 2009). Take Fig. 4 as an example to explain the effect of DC. Node v_i needs to find a route, via v_j, for its intra frame (I-frame) to the sink. If the size of the I-frame is I, the saved bits from DC is $I \times (1 - \eta)$. Video sensors with large overlapped FoVs are likely to have high DC gains.

Our previous study (Shen et al., 2014) shows that the multi-sink environment can provide much more opportunities to reduce redundancy with DC. Fig. 5 illustrates such an example. Video sensors v_i and v_j need to transmit I-frames to the sink. If only one sink s_1 exists, the redundancy elimination opportunities may be lost, because the chosen next-hop must be closer to the sink. When introducing two sinks s_1 and s_2, v_i can find an acceptable path to the sink via v_j, thus eliminating redundancy. In such a scenario, the optimal route selection is not only related to the distance between sensor and sink, but also related to the energy

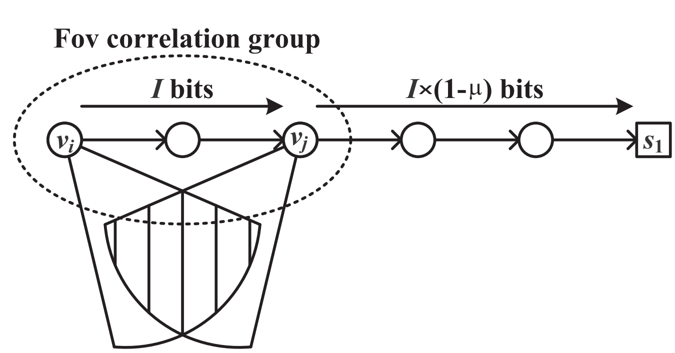

Fig. 4. Correlation-aware differential coding (redrawn from Dai et al. (2012)).

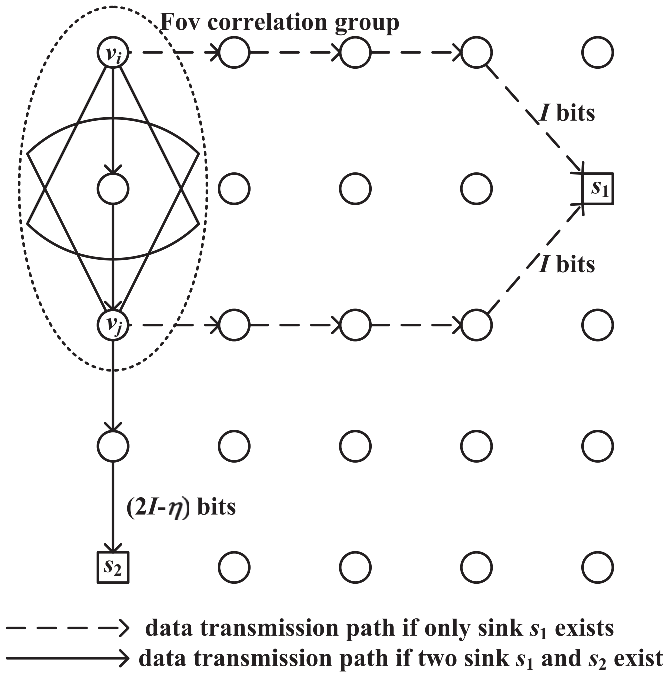

Fig. 5. An example of reducing data redundancy in a multi-sink environment.

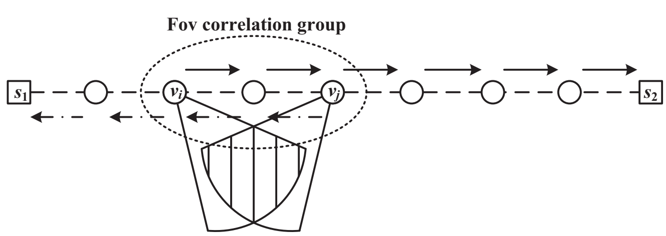

Fig. 6. Source and intermediate nodes selection for a multi-sink environment.

gain towards different sinks. Take Fig. 6 as an example. There are two sinks (s_1 and s_2) and two video sensors (v_i and v_j). The roles between a video source and an intermediate node can be exchanged. Correspondingly, two possible routes can be selected, i.e., $v_i \to v_j \to s_2$ and $v_j \to v_i \to s_1$. The latter may be a better selection.

4.2.2. Distortion-optimized multimedia routing

Multipath transmission helps to improve bandwidth utilization. Chen et al. analyze the performance bottleneck of video communication in WSNs, and propose Directional Geographical Routing (DGR) (Chen et al., 2007). In this approach, source nodes distribute data processed by Forward Error Correction (FEC) into multiple paths to improve load balance and bandwidth utilization for video transmission. This approach has a strong fault tolerance, but it has the following disadvantages: redundant data is often produced during transmission, additional control and processing expenses are needed during route selection.

As an improvement of DGR, the authors further design a multiple-priorities-based path-scheduling algorithm (Chen et al., 2008) to guarantee the end-to-end delay while balancing energy and bandwidth usage among all the node-disjoint paths in WMSNs. A cross-layer-based adaptive coding is explored addressing the issue that the aggregate bandwidth is not enough to satisfy the required coding rate.

The work in He et al. (2009) investigates the error remedy techniques with routing and source coding for large-delay and small-delay WMSN applications. A Lagrangian duality based distributed algorithms is introduced to maximize network lifetime, but it fails to consider QoS provisioning.

Image Quality-Aware Routing (IQAR) (Sarisaray et al., 2014) supports multiple image sources and a single sink operating in large-scale WMSNs, focusing on reliable, energy- and delay-efficient data delivery. In IQAR, each node independently decides on the best next hop to forward the image packet. In order to provide acceptable perceptual quality at the end user, an analytical model is used to predict the image distortion resulting from any given error pattern. The reduced energy consumption may be achieved if an error correction method is introduced.

4.2.3. Context-aware multimedia routing

WMSNs handle heterogeneous data which can consist of scalar, audio, video, image and acoustic data, all of which have varied QoS requirements. Due to heterogeneous traffic flows, and differentiated requirements of these flows, provision of service differentiation becomes crucial to achieving QoS routing in WMSNs.

QoS-based geographic routing (Savidge et al., 2005) constructs weighted cost function according to node locations, queue length and residual energy to provide delay adjustable path for event-driven WMSNs. The concept of diffserv is introduced, where data packets are stored into two independent queues with different priorities. Based on the number of data packets in the queue, nodes dynamically adjust the priority orders achieving the adjustability of real-time transmission. However, factors such as available bandwidth and link error rate also affect real-time performance.

Multi-Priority MultiPath Selection (MPMPS) (Zhang et al., 2008) scheme separates multimedia streaming into two parts consisting of audio and video. Fig. 7 shows the routing framework. The transmitted data would then be recombined at the receiving station. However, potential drawbacks of this method include that communication streams might not be synchronized, and the decomposition and combination of multimedia streams also increase processing expenses.

Lari and Akbari (2010) investigate multipath video transmission, focusing on improving the quality of video while considering energy efficiency, bandwidth and delay constraints in WMSNs. Video packets are classified depending on their types and importance. Packets with high priority are transmitted through paths with larger buffer size, higher residual energy, and lower error rate. Nevertheless, this method cannot assure that all the computed paths meet QoS requirements.

A QoS based routing protocol that supports event and periodic-based data reporting is proposed in Fonoage et al. (2010). This protocol introduces multiple queues for different types of packets and assigns them with different priorities. The neighbor with higher residual energy, higher link quality, and lower load would be chosen for forwarding. It allows aggregation data to be sent over multiple paths to enhance reliability, and introduces a mechanism to prevent congestion. Compared with SPEED (He et al., 2005), it achieves performance improvement in energy and reliability.

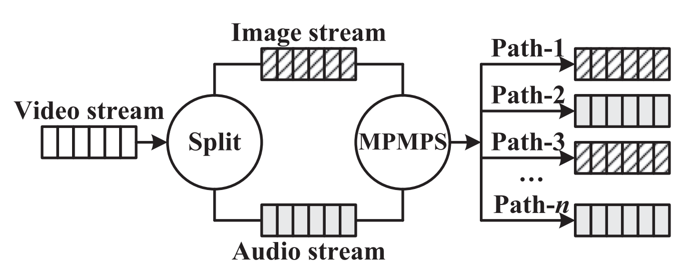

Fig. 7. Multi-priority multipath routing framework (redrawn from Zhang et al. (2008).

Traffic-differentiation-based modular QoS localized routing (LOCALMOR) (Djenouri and Balasingham, 2011) can work with any acknowledgment-based MAC protocol. Fig. 8 shows its system framework. Data traffic is classified into several categories. Different routing metrics are used according to their required QoS. In addition, a multi-sink single-path transmission approach is used to increase reliability.

A cross-layer-based differentiation routing is proposed in Al-malkawi et al. (2012), considering the types of data in WMSNs. Compared with still images and scalar data, time-critical multimedia data is assigned with higher priority. In addition, the received signal strength is utilized to cluster the nodes. A TDMA-based scheduling is introduced within clusters and among CHs in order to improve delay. However, this approach cannot assure that all the computed paths meet application requirements.

The work in Shah et al. (2012) investigates a cross-layer design framework to enhance the number of video sources under the satisfied distortion constraint in WMSNs. It consists of a source directed multipath routing (SDMR) algorithm that interacts with the underlying MAC protocol and maintains three disjoint directed paths subject to QoS constraints. The ratio of the different kinds of video frames is maintained as a trade-off between distortion and source bit rate.

4.2.4. Cluster-based multimedia routing

Clustering sensors into groups is a popular strategy to prolong the network lifetime. In this section, we survey cluster-based WMSN routing, categorized into two classes: Non-intelligent and Intelligent.

(1) *Non-intelligent routing*: A two-hop clustered image transmission scheme is proposed in Zuo et al. (2012). While utilizing redirectors to compress the images to save energy and thus to avoid energy hole, it introduces adaptive transmission radius adjustment and energy-aware tasks allocation to balance energy consumption. However, it does not consider any QoS metric in multimedia transmission.

A selective encryption and energy efficient clustering scheme is proposed in Varalakshmi et al. (2014), achieving joint optimization on network lifetime and video distortion in WMSNs. The H.264/AVC reference codec is used to compress and perform selective encryption scheme, thus reducing extra encryption overhead.

Energy-Efficient QoS Assurance Routing (EEQAR) (Lin et al., 2011) achieves energy efficiency and meets QoS requirements in WMSNs. This protocol adopts cellular topology to form the cluster structure and balance the energy consumption by structure movement. Nodes use a QoS trust estimation model based on social network analysis to measure the supplied QoS of their neighbors and update the monitoring results. However, EEQAR fails to consider how to select reliable routes, and lacks a method to evaluate the quality of video.

Kandris et al. (2011) present PEMuR, a cluster-based energy-efficient multimedia routing for WMSNs. The sink upgrades and maintains cluster structure, and energy threshold to the entire network. If energy consumption exceeds the threshold, it would notify the CH. PEMuR introduces a predictive model to assess the impact of lost packet on video distortion. If transmission rate exceeded the available bandwidth, it could selectively discard some video packets with a rule that reduces video distortion as much as possible. However, the centralized clustering scheme increases control overhead and therefore decreases network lifetime.

A smart multi-hop hierarchical routing protocol (MEVI) is proposed in Rosário et al. (2012) that provides QoS/QoE support for multimedia transmission in WMSNs. The cross-layer parameters from physical, MAC and network layers are taken into account in route selection. MEVI introduces an opportunistic scheme to create clusters while performing a smart solution to trigger multimedia transmission according to the sensed data.

(2) *Intelligent routing*: Ant-based QoS routing model (AntSensNet) (Cobo et al., 2010) provides diffserv and QoS guarantees in WMSNs. Before route selection, nodes perform a distributed algorithm to form a virtual backbone that covers the entire network. During route discovery phase, when a CH needs to transmit data, a certain amount of forward ants are generated to search routes if not found to meet the constraints. During route reply phase, the sink judges if a path meets QoS constraints depending on the information carried by the forward ants. If so, then backward ants will be generated towards source node. During route maintenance phase, source nodes periodically generate forward ants to upgrade and maintain route. However, this algorithms will inevitably increase protocol's complexity.

Huang et al. (2014) propose two ant-cluster-based WMSN routing algorithms IPACR and ICACR. The former improves the typical ant colony routing algorithm by adjusting the initial pheromone distribution, thus to accelerate the algorithm convergence and to increase the probability of path searching. The latter is suitable for large-scale scenarios. However, the algorithms may not be applicable in some real-time scenarios because of slow response.

4.3. Energy efficiency

Energy efficiency is crucial in designing WMSN routing. In this section, we categorize the literature into four categories: Duty-cycle-based delay-aware routing, Energy-harvesting- and QoS-aware routing, Low-cost QoS-aware opportunistic routing, and Real-time hole avoidance routing.

4.3.1. Duty-cycle-based delay-aware routing

Nodes in low-duty-cycle WSNs periodically schedule themselves to be active for work and then stay dormant at other times to reduce the energy consumption. Nevertheless, communication in such networks has a non-negligible delay (Xiao et al., 2015). The delay-aware duty-cycle routing solutions are discussed in this section.

Hop-by-hop geographic routing (DCR) (Hao et al., 2013) pursues the near minimum energy consumption subject to given delay constraint in duty-cycled WSNs. In DCR, when a next-hop candidate wakes up, a node that holds a packet first re-computes its optimal next-hop and then decides whether to wait for a next-hop or transmit to the best next-hop based on a Markov decision process. Despite delay guarantee, it does not consider any reliability metric.

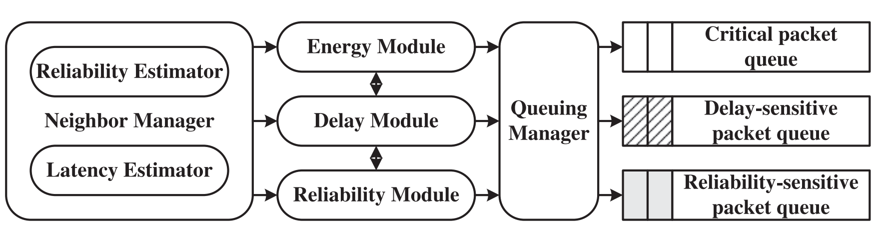

Fig. 8. Traffic-differentiation-based QoS routing framework.

Deadline-aware scheduling and forwarding (DASF) (Dao et al., 2016) algorithm focuses on maximizing the duty cycle while meeting the required delay-constrained success ratio in duty-cycled WSNs. The end-to-end delay distribution with the given network model and parameters is estimated in order to determine the maximum duty cycle interval. This algorithm makes a forwarding decision based on distance between nodes and the sink, without time synchronization.

4.3.2. Energy-harvesting- and delay-aware routing

Recent advances in the areas of solar, piezoelectric, and thermal Energy Harvesting (EH) will soon enable the realization of perpetual EH sensors (Gorlatova et al., 2013). When applied to WMSNs, energy from external sources can be harvested to power the nodes, thus increasing lifetime.

The work in Noh et al. (2007) presents a QoS-aware geographic routing based on a solar-cell energy model. It consists of two algorithms APOLLO and PISA, aimed at maximizing scalability and minimizing memory in a localized manner. The former is used to compute the topological knowledge range according to an estimated energy budget in the next period. The latter uses its knowledge range to determine a route meeting delay, reliability and energy constraints. However, it fails to consider the characteristics of energy supply in a realistic environment.

Energy-Rich-backbone-based Geographic Routing (ERB-GR) (Noh and Hur, 2012) scheme provides low-latency and energy-rich paths while considering the duty-cycle of each node. In particular, ERB-GR can achieve reliable data transmission as long as the network remains connected.

Kwon et al. (2007) propose a low-latency routing algorithm for EH-WSNs. A random graph in which a node may have multiple parent nodes is constructed, so that a faster path can be chosen to avoid lazy nodes. Different cost-aware path selection schemes are designed but lack of flexibility.

Noh et al. (2008) propose a duty-cycle-based low-latency geographic routing for solar-powered WSNs. The transmission ranges are periodically determined based on the available energy, the predicted energy consumption, and the energy expected from the harvesting device. The purpose is to provide a desirable transmission with low latency and high reliability. However, its performance is not always satisfactory since the predictions of variables are inevitably inaccurate.

4.3.3. Low-cost QoS-aware opportunistic routing

Retransmission-based reliability assurance could generate more expenses. Opportunistic Routing (OR) (Chakchouk, 2015) technique is able to take advantage of diversity and broadcast features of wireless link to combine multiple unreliable links into a single reliable link. Nevertheless, traditional OR protocols, which require support from global link status information, may not be applicable for WMSNs. Researchers have improved the traditional approach in terms of QoS and energy conservation, which are discussed in this section.

(1) *Power-control-based routing*: Opportunistic Real-Time Routing (ORTR) (Kim and Ravindran, 2009) balances transmission delay and energy consumption through power control, and introduces a new routing metric, called Expected Real-Time Guarantee Region (ERTGR). If real-time demand is relatively lenient, ERTGR is relatively small, meaning that the forwarding distance would be limited, but energy consumption would be low. Packets with a higher real-time demand would obtain larger ERTGR, with more forwarding nodes to select. This obviously helps to improve the forwarding speed, but would consume more energy.

Transmission power Control-based Opportunistic Routing (TCOR) (Coutinho et al., 2014) protocol saves energy by reducing the transmission power, considering the energy cost relative to the packet reception of the neighbors. This protocol can maintain the reliability, but does not consider any metric in delivery delay .

(2) *Non-power-control-based routing*: Cheng et al. formulate the multi-QoS constrained OR selection as a multi-objective multi-constraint optimization problem, and propose an Efficient QoS-aware Geographic Opportunistic Routing (EQGOR) (Cheng et al., 2014) that guarantees both reliability and delay in WSNs. The advantage is the capacity to efficiently select forward list, achieving significant improvement in terms of energy efficiency, latency, and time complexity. However, EQGOR is not compatible with some special features of multimedia traffic.

Spachos et al. (2014) propose a Content Relevance Opportunistic Routing (CROR) protocol, in which a generic packet relevance level scheme is designed considering the needs of any human-centric QoS prioritization. This protocol can adequately adapt to changes in the density of a given WMSN, thus improving the scalability and reliability of prioritized multimedia content transmissions.

In Shen et al. (2014) we propose a QoS-aware Multi-sink Opportunistic Routing (QMOR) to achieve an energy-efficient delivery of video under QoS constraints in WMSNs. In the estimation of reliability, the dependency among video frames in a group of pictures (GOP) is taken into account. We then further propose L2OR (Shen et al., 2015), a low-cost low-complexity opportunistic routing to solve the issue of duplicate transmissions. A heuristic algorithm is designed to approach optimal forward list while reducing the search space to the size of candidate relay set.

4.3.4. Real-time hole avoidance routing

Holes is one of the key challenge issues for routing. In a WMSN with holes or obstacles, it is prone to problems of overuse of a single node or no route to select, resulting in energy waste and congestion.

Two-phase Geographical Greedy Forwarding (TPGF) (Shu et al., 2010) routing algorithm aims at finding multiple node-disjoint paths capable of bypassing holes. If a hole is found during forwarding then the node closest to the sink of adjacent nodes can be selected as the forwarding node. TPGF uses the shortest path principle, while considering minimal delay and energy conservation, to find as many disjoint paths as possible, but it cannot assure that all the generated paths meet delay constraint.

Pair-Wise Directional Geographical Routing (PWDGR) (Wang et al., 2015) strategy takes advantage of the nodes that around sink through pair-wise node in order to solve the energy bottleneck problem in WMSNs. This strategy selects transmission angle of paths within the 360° scope, in which pair-wise node is chosen as destination node around sink. In this way, the serious energy burden around sink can be eased, thus achieving energy-delay trade-off.

Service-Differentiated Real-time Communication Scheme (SDRCS) (Xue et al., 2011) utilizes greedy forwarding to deliver packets while providing an effective and efficient hole avoidance approach. It strips the sensing field into layers by using a received signal strength based node grouping method. Each node can obtain a group ID assignment, which adapts to the hole.

A localization-free and energy efficient hole bypassing is presented in Yilmaz et al. (2014) for fault–tolerant multi-hop clustered topology. The proposed solution consists of an intra-cluster bypassing mechanism to recover path and an inter-cluster bypassing to make the down clusters keep relaying message to sink. With these techniques, the cost of localization and topology recreation can be avoided. However, it fails to consider the trade-off between energy and delay.

Petrioli et al. (2014) propose Rainbow mechanism to solve the problem of routing around a dead end, the advantages of which are the resilience of localization errors and channel propagation impairments, as well as independent of network topology. The work in Gupta et al. (2015) demonstrates that the geometry and location of the obstacles significantly affect routing performance.

4.4. Congestion avoidance

Congestion is one of the major issues affecting the WMSN performance in terms of energy utilization and monitoring reliability. In this section, congestion avoidance routing techniques, aimed at preventing congestion from happening, are further classified into three categories: Potential-field-based routing, Load balancing multimedia routing and Interference-aware multipath routing.

4.4.1. Potential-field-based routing

A number of routing mechanisms utilize the concept of potential field from the discipline of physics to congestion control. This method delivers data along the gradient of the potential field constructed over a network. We survey the existing works depending on the application scenarios supported by them, i.e., single-sink and multi-sink environments.

(1) *Single-sink routing*: Xu et al. propose Potential-based Real-Time Routing (PRTR) (Xu et al., 2013). Through flow differentiation with queue management, PRTR divides data packets into real-time and non-real-time ones, and assign higher transmission priorities to real-time packets so they can pass through congestion areas first. As shown in Fig. 9, non-delay-sensitive traffic from v_B and v_C are scattered to path $v_5 \to v_6 \to v_7 \to$ sink or $v_3 \to v_4 \to$ sink to bypass the hot spot v_2 such that the delay of real-time traffic is reduced and congestion is alleviated. Through priority queue, PRTR can further decrease delay, especially when the front of the buffering queue in v_C consists of more real-time packets.

Gradient-based Multipath Routing Protocol (GMRP) (Hao et al., 2014) achieves low-latency and high-efficiency data delivery in low duty-cycled WSNs. GMRP assigns each path segment with a weight to achieve a desirable trade-off between latency and delivery efficiency, so that a path of long length but sufficient delay gain would be chosen. However, both PRTR and GMRP still remain at a best-effort level, and cannot provide QoS assurance with fine granularity.

(2) *Multi-sink routing*:

Controlled Potential-Based Routing (CPBR) (Kominami et al., 2013) consists of a controlled self-organization scheme for traffic load and energy balancing. The calculation of local potential considers both path length and residual energy, while a control node manages sink potentials by centralized manner. On this basis, Toyonaga et al. (2013) propose a Potential-Based Any-to-any Routing (PBAR) protocol that merges potential-based upstream and downstream routing. Even if multiple sensors fail or a sink fails, the data delivery ratio can recover immediately.

A dynamic traffic-balancing multi-sink routing algorithm is proposed in Tan and Kim (2014), where each node has a gradient to make path decisions. The gradient metric contains the distance cost to a respective sink and traffic condition from neighbors, providing a balance between optimal paths and possible congestion toward multiple sinks. However, it lacks an analytical model to find the optimal weighted factors and the effect of update time on network performance.

Zhang et al. (2015) propose IDDR, a multipath dynamic routing algorithm for data integrity and delay diffserv. This algorithm introduces a virtual hybrid potential field based on the depth and queue length. Packets are separated according to different QoS requirements and their weights, and transmitted towards the sink through different paths depending on the potential field. However, IDDR cannot meet application-specified delay requirement.

A hop-by-hop gradient-based routing scheme is proposed in Gholipour et al. (2015) to effectively distribute traffic from the source to the sinks. Congestion is controlled by dynamically adjusting transmission rate. In particular, a hybrid virtual gradient field is constructed based on depth and normalized traffic load, providing a balance between optimal paths and possible congestion. However, it lacks an analytical model to find the optimal combination of these weighted factors.

4.4.2. Load balancing multimedia routing

Routing dynamics can lead to congestion on specific paths. Load balancing routing helps to mitigate the effect of congestion. The existing works in WMSNs are categorized into two classes: Single-sink routing, Multi-sink routing.

(1) *Single-sink routing*: Isik et al. (2011) propose Load Balanced Reliable Forwarding (LBRF) and Directional Load Balanced Spreading (DLBS) schemes for WMSNs. The former dynamically chooses the next-hop by balancing buffer occupancy levels at the time of delivery. The latter combines local and directional load balancing for more reliable and faster video delivery. However, their performance is limited when the number of contenders increases and when load increases.

A cluster-based Route Optimization and Load-balancing (ROL) (Hammoudeh and Newman, 2015) protocol is proposed that introduces various QoS metrics to meet application requirements. This protocol groups nodes into clusters and build paths based on localized metrics that can be adjusted according to priorities, therefore to improve energy and computation efficiency. An optimization tool is developed for balancing network resources. However, it fails to consider optimized delivery of multimedia data.

(2) *Multi-sink routing*: Multi-Sink Load Balanced Reliable Forwarding (MLBRF) (Isik et al., 2012) scheme provides reliable and energy-efficient video delivery with load balancing over multi-sink WMSNs for target tracking. While a fuzzy logic based sink selection mechanism is designed to facilitate video frame forwarding, a fuzzy inference system is used to evaluate the traffic density to a sink. However, it fails to analyze the cross-layer effects of physical and MAC layers on routing.

4.4.3. Interference-aware multipath routing

Multipath routing is a promising solution to improve resource utilization, alleviate congestion and balance load, which are discussed in this section.

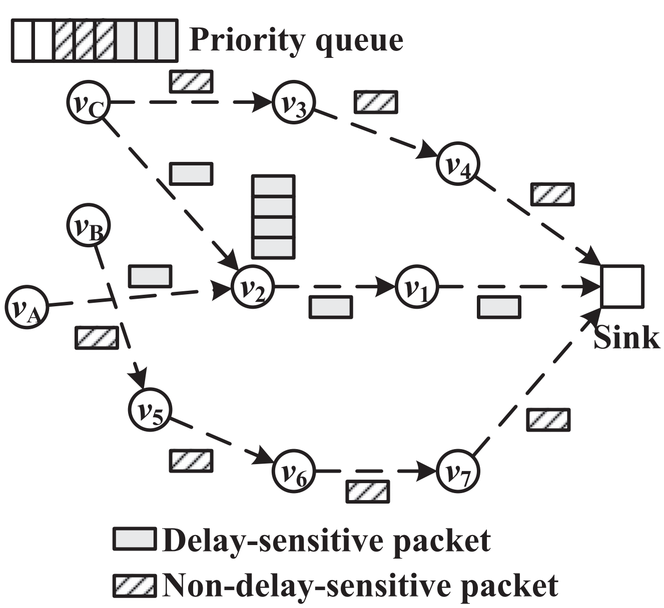

Fig. 9. Routing policy of PRTR (redrawn from Xu et al. (2013)).

A maximally radio-disjoint multipath routing (MR2) (Maimour, 2008) protocol is proposed to satisfy multimedia bandwidth requirements while saving energy in WMSNs. An adaptive incremental approach is designed to provide non-interfering adjacent paths, but may result in degradation in energy efficiency and QoS satisfaction.

Interference-Minimized Multipath Routing (I2MR) (Teo et al., 2008) protocol improves throughput by multipath transmission while reducing localization support and incurring low overheads. To support high-rate streaming, I2MR marks one-hop and two-hop neighbors along the first shortest path as the interference zone of the primary path and constructs interference minimized backup paths.

Low-Interference Energy-efficient Multipath ROuting (LIEMRO) (Radi et al., 2011) protocol improves the QoS of event-driven applications. The set of node-disjoint interference-minimized paths is computed by a cost function that considers residual energy, link quality, and interference level. However, the intense channel competition significantly affects the protocol performance.

Geographic Energy-Aware non-interfering Multipath routing (GEAM) (Li and Chuang, 2013) scheme divides the network topology into many districts and simultaneously forwards data in an interference-free mode, thus improving multimedia transmission in WMSNs. GEAM offers a hole avoidance ability, and can maintain stable performance against topology changes. The main drawback is its incapability to guarantee all the generated paths to meet QoS constraints.

An interference-aware multipath routing protocol is proposed in Bidai and Maimour (2014) for MPEG-4 video delivery over a low data rate WMSN. The broadcast nature of the wireless medium is considered to construct multiple node-disjoint paths with reduced effect of interference, thus satisfying bandwidth requirements. However, it cannot provide QoS guarantees for video transmission.

4.5. Bandwidth optimization

Multimedia contents, especially video streams, require high transmission bandwidth. Cognitive radio (Liang et al., 2011), cooperative communication (Hong et al., 2007), and network coding (Bassoli et al., 2013) techniques have been considered as promising approaches to increase the bandwidth-efficiency. A natural step is to integrate them into routing to improve network performance.

4.5.1. Spectrum-efficient multimedia routing

WMSNs mostly use the public frequencies of 68 MHz, 916 MHz, or 2.4 GHz. Frequency overlap across the networks with different radio technologies can cause severe interference and reduce reliability (Liang et al., 2010). Furthermore, since multimedia transmission requires greater bandwidth and channel occupancy, the collision in public frequencies exhibits a higher probability. WMSNs with cognitive radio (CR) capabilities (i.e. cognitive radio multimedia sensor networks (CRMSNs)) can help to address these challenges by introducing a new class of unlicensed or secondary users (SUs) who can share the spectrum opportunistically without interfering with the primary users (PUs). We present one example to illustrate the spectrum-efficient routing approach. In Fig. 10, there are three available frequencies, F_1, F_2, F_3, with different communication ranges. When v_2 selects F_1 for transmission, it connects to v_5 directly, or via v_3 or v_4. However, when F_2 is chosen, it can only connect to v_5 via v_3 or v_4. If it selects F_3, it only connects to v_5 via v_4. Another relay v_3 cannot be used since F_3 is occupied by the PU. In fact, factors that influence QoS should be further considered in the design of CRMSN routing, which are the focus of this section.

Shah et al. (2014) propose SCEEM, a Spectrum-aware Cluster-based Energy-Efficient Multimedia routing that achieves a suboptimal solution for end-to-end QoS support in CRMSNs. Dynamic spectrum access and routing are based on clustering. It utilizes TDMA based intra-cluster communication and CSMA based inter-cluster communication. A node with higher residual energy and spectrum rank will be elected as a CH. The optimal number of clusters is analyzed for distortion optimization of multimedia sources. However, the uses of hybrid protocol and cross-layer design increase the complexity of protocol deployment.

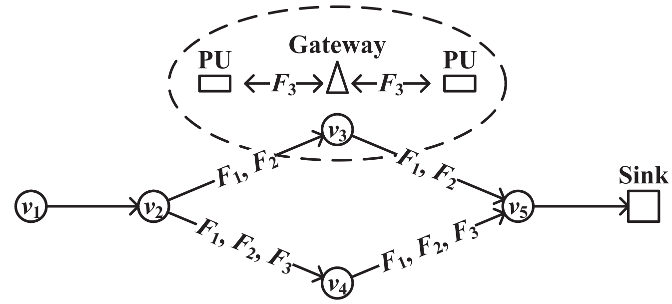

Fig. 10. An example of spectrum-aware routing selection (redrawn from Akan et al. (2009)).

An energy-efficient mechanism (EMCOS) is proposed in Bradai et al. (2015) for multimedia streaming over CRMSNs, where the clustering is based on spectrum availability and spectrum forecast, and the routing/channel selection is based on PU activity forecasts. EMCOS can prevent frequent channel switching so as to improve communication, but cannot provide QoS guarantee for multimedia.

Shiang and Van der Schaar (2009) study a distributed resource management strategy for video routing in multi-hop cognitive radio networks, with objective of minimizing the end-to-end delay given the characteristics of different types of traffic flows. This strategy considers the trade-off between accuracy and cost while using a multi-agent learning algorithm to model node behavior. However, it does not consider any energy metric for video transmissions.

4.5.2. Cooperative multimedia routing

The basic idea behind cooperative communication (CC) is to exploit the spatial diversity gains inherent in multi-user wireless systems without multiple antennas at each node (Mansourkiaie and Ahmed, 2015). In general, a cooperative route consists of cooperative and direct links. As shown in Fig. 11, in CC block, in addition to the direct link $\langle v_2, v_4 \rangle$, the v_3 is used to relay the signal from the transmitter v_2 to the receiver v_4. Through independent fading channels, multiple copies of a packet are delivered to the receiver. Through multi-node cooperative resource allocation, this communication paradigm can effectively reduce energy consumption, and has been applied to routing (Habibi et al., 2013), but there is little literature on QoS.

QoS-aware Distributed Adaptive Cooperative Routing (DACR) (Razzaque et al., 2014) exploits CC to achieve energy-efficient data delivery subject to delay and reliability constraints. A lightweight reinforcement learning method is employed to update the routing nodes and to determine the optimal relay. However, it may not be compatible with non-critical applications.

The work in Xu et al. (2012) investigates the Bandwidth-Power aware Cooperative MultiPath Routing (BPCMPR) problem in WMSNs, focusing on minimizing energy consumption while satisfying bandwidth requirement. It utilizes non-linear program to formalize the optimal problem. Then a polynomial-time heuristic algorithm is designed that reaches the approximation factors 2 and $\frac{4}{3}$ to the optimal solution. Despite a decrease in energy consumption, the delay is relatively large.

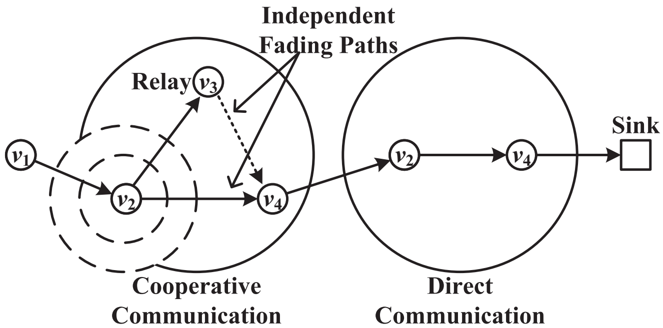

Fig. 11. An example of cooperative route (redrawn from Mansourkiaie and Ahmed (2015)).

4.5.3. Network-coding-based routing

Network coding (NC) enables sensors to have both routing and coding functions and has been proved to be an effective method to reach the theoretical transmission limit of network capacity. Traditional NC mechanisms are limited to the transmission path determined by the routing protocol, and have to adopt a waiting method to obtain coding opportunities, thus degrading throughput. One possibility is to unify NC to the end-to-end level, in combination with routing, expanding the control scope of NC and identify potential coding opportunities. We categorize the related works into two classes: Multi-source routing and Multi-sink routing.

(1) *Multi-source routing*: The work in Al-Kofahi and Kamal (2013) investigates a distributed deterministic binary NC scheme to enhance the resiliency of multi-hop transmission against packet loss by combining the data units from sensors to produce combinations. A simple routing protocol working together with NC is designed that guarantees maximally disjoint paths from the sensors to the sink. However, it does not consider the impact of redundancy on delay.

(2) *Multi-sink routing*: Tong et al. (2015) propose CodeMesh, a coding-aware cross-path anycast routing protocol with inter-flow NC to maximize the lifetime of time-driven multi-sink networks. CodeMesh combines proactive and reactive protocol features while taking advantages of the benefits from multiple sinks. Its route establishment does not rely on clock synchronization. However, it lacks a scheduling mechanism to improve real-time performance.

Adaptive Opportunistic Forwarding (AONC) (Shen et al., 2012) strategy is, based on NC, aimed at improving the transmission quality of video in WMSNs. Through dynamic priority assignment, this strategy can ensure that packets have a better chance to be coded and transmitted, thus achieving much higher throughput.

The work in Cui et al. (2012) investigate the lossy data compression problem in a WSN that has multiple correlated sources and multiple sinks. A distributed resource allocation scheme is introduced to improve routing and NC performance, which allows the sinks to adjust the source rates. The purpose is to maximize an aggregate utility in distortion levels of the sources.

5. Analysis and comparison

Table 1 outlines main routing approaches, highlighting the advantages and disadvantages. Between these two aspects, there are interactions of mutual restraint and mutual influence. In many cases, the disadvantages of one technique can be as significant as the advantages. Therefore, designers need to select a particular proposal based on its merits over the others, thus achieving the full gains of network performance and meanwhile to ensure that design does not cause degradation of network performance.

We compare and summarize the characteristics of the surveyed routing solutions with respect to various parameters in Table 2, which is sorted by publication date. We choose various parameters depending upon applications for discussion, including architecture (flat or hierarchical), QoS guarantees, DiffServ, energy efficiency, multimedia awareness (i.e., whether to provide optimization for multimedia), multipath capability, congestion avoidance, bandwidth optimization, in-network processing, hole bypassing, multi-sink awareness (i.e., whether to take advantage of multi-sink to improve network performance).

6. Future challenges and trends

Emerging multimedia applications and rapid development of WMSNs make routing confront a series of challenges. Section 6.1 summarizes the open issues in routing metrics and protocols. In Section 6.2, we discuss the routing development trends and problems to be solved in emerging WMSN application scenarios.

6.1. Open research issues

6.1.1. Link-correlation-aware routing

Recent studies show that there is a strong correlation between inter-receiving data of adjacent wireless links, (i.e. link correlation, Srinivasan et al., 2010) and validate the important influence of this characteristic on routing performance. However, the existing typical routing solutions often assume a link-independent wireless

Table 1
Overview of routing approaches.

Routing approach	Disadvantages	Advantages
Differential-coding-based routing	Increased control and processing overhead	Improved energy efficiency, reduced network traffic
Cluster-based routing	CH may become network bottlenecks	Be able to distribute management tasks around the network
Context-aware routing	Increased schedule complexity and processing overhead	Improved QoS support capabilities
Potential-field-based routing	Increased difficulty in delay guarantee	Less overhead, better scalability
Opportunistic routing	Duplicate transmissions, extra coordination overhead	Higher throughput, better reliability
Spectrum-efficient routing	Increased end-to-end latency and energy consumption imposed by spectrum sensing	More bandwidth, lower error rate
Cooperative routing	Extra relay traffic and interference, more sophisticated schedule	Reduced transmission power, better transmission reliability and coverage
Network-coding-based routing	Packet latency, extra control and computation overhead, restricted and affected by network topology	Improved bandwidth capability, reduced transmission counts
Energy harvesting aware routing	Mostly used in outdoor scenarios, increased deployment cost	Improved energy conversion, longer lifetime
Duty-cycle routing	Extra sleep/wakeup schedule among nodes	Increased interval of battery replacements
Interference-aware multipath routing	Increased complexity in route maintenance and discovery	Better load balancing

Table 2
Comparison of routing solutions.

Routing solution	Pub. year	Arch.	QoS guara.	Diff. Serv.	Loca. awa.	Energy eff.	Multim. awa.	Multip. cap.	Cong. avoid.	Band. opt.	In-net proc.	Hole avoid.	Multi-sink sup.
CUDAR (Hamid et al., 2015)	OA[a]	Flat	D[b]			√	√		√				
GMRP (Hao et al., 2014)	OA	Flat			√	√		√					
SHE (Chen, 2016)	2016	Hier.[c]	D	√	√	√					√		
DASF (Dao et al., 2016)	2016	Flat	D		√	√							
DASF (Spachos et al., 2015)	2015	Flat	D		√	√							
OCRP (Nefzi et al., 2015)	2015	Flat	D&R[d]		√	√							
PWDGR (Wang et al., 2015)	2015	Flat	R		√	√		√				√	
L2OR (Shen et al., 2015)	2015	Flat			√	√		√					
Gupta et al., 2015	2015	Hier.			√	√						√	
IDDR (Zhang et al., 2015)	2015	Flat	D	√	√	√		√	√				√
Gholipour et al., 2015	2015	Flat			√	√			√	√			√
ROL (Hammoudeh and Newman, 2015)	2015	Hier.	D&R	√	√	√			√		√		
EMCOS (Bradai et al., 2015)	2015	Hier.			√	√	√			√			
CodeMesh (Tong et al., 2015)	2015	Flat						√		√			
PECQEA (Zhou et al., 2014)	2014	Flat	D&R&J[e]&B[f]		√	√							
QMOR (Shen et al., 2014)	2014	Flat	D&R		√	√	√	√		√	√		√
IQAR (Sarisaray et al., 2014)	2014	Flat	D	√	√	√	√						
Varalakshmi et al., 2014	2014	Hier.			√	√	√						
Huang et al., 2014	2014	Hier.	D&R&B	√		√	√	√					
EQGOR (Cheng et al., 2014)	2014	Flat	D&R		√	√		√					
CROR (Spachos et al., 2014)	2014	Flat		√	√	√	√	√					
TCOR (Coutinho et al., 2014)	2014	Flat	R		√	√		√					
ALBA-R (Petrioli et al., 2014)	2014	Flat			√	√			√			√	
Yilmaz et al., 2014	2014	Hier.				√						√	
Tan and Kim, 2014	2014	Flat			√	√			√				√
Bidai and Maimour, 2014	2014	Flat					√	√					
SCEEM (Shah et al., 2014)	2014	Hier.	D&J			√	√			√			
DACR (Razzaque et al., 2014)	2014	Flat	D&R			√				√			
ProHet (Chen et al., 2013)	2013	Flat	IQ			√							
Chen et al., 2013	2013	Flat	IQ		√	√							
DCR (Hao et al., 2013)	2013	Flat	D		√	√							
PRTR (Xu et al., 2013)	2013	Flat	D	√	√				√				
CPBR (Kominami et al., 2013)	2013	Flat			√	√			√				√
PBAR (Toyonaga et al., 2013)	2013	Flat	R		√	√			√				√
GEAM (Li and Chuang, 2013)	2013	Flat			√	√		√	√	√		√	
Al-Kofahi and Kamal, 2013	2013	Flat	R					√		√			
ILSR (Li et al., 2012)	2012	Flat	IQ		√	√							
QoS-PSO (Liu et al., 2012)	2012	Flat	D&R&J&B			√							
CAQR (Dai et al., 2012)	2012	Flat	D&R		√	√	√		√		√		
Shah et al., 2012	2012	Flat	D&E&B	√	√	√	√	√	√				
Zuo et al., 2012	2012	Hier.			√	√	√					√	
Almalkawi et al., 2012	2012	Hier.		√	√	√	√						
MEVI (Rosário et al., 2012)	2012	Hier.	D&B			√	√						
ERB-GR (Noh and Hur, 2012)	2012	Hier.	R		√	√							
MLBRF (Isik et al., 2012)	2012	Flat			√	√			√				√
BPCMPR (Xu et al., 2012)	2012	Flat	B			√		√		√			
AONC (Shen et al., 2012)	2012	Flat		√			√	√		√			
Cui et al., 2012	2012	Flat	IQ					√		√			
LOCALMOR (Djenouri and Balasingham, 2011)	2011	Flat	D&R	√	√	√							√
EEQAR (Lin et al., 2011)	2011	Hier.	D		√	√							
PEMuR (Kandris et al., 2011)	2011	Hier.			√	√	√						

Table 2 (*continued*)

Routing solution	**Pub. year**	**Arch.**	**QoS guara.**	**Diff. Serv.**	**Loca. awa.**	**Energy eff.**	**Multim. awa.**	**Multip. cap.**	**Cong. avoid.**	**Band. opt.**	**In-net proc.**	**Hole avoid.**	**Multi-sink sup.**
CUDAR (Hamid et al., 2015)	OA[a]	Flat	D[b]			√	√		√				
Costa, 2011	2011	Flat	D&C			√		√	√				
SDRCS (Xue et al., 2011)	2011	Flat	D	√		√			√			√	
HBF (Li et al., 2011)	2011	Flat			√	√			√			√	√
TADR (Ren et al., 2011)	2011	Flat			√				√				
Isik et al., 2011	2011	Flat			√	√	√		√				
LIEMRO (Radi et al., 2011)	2011	Flat				√		√	√	√			
EQSR (Ben-Othman and Yahya, 2010)	2010	Flat	D&R	√		√		√					
IQAR (Tan et al., 2010)	2010	Flat	IQ		√	√					√		
DGRAM (Shanti and Sahoo, 2010)	2010	Flat	D		√	√							
Lari and Akbari, 2010	2010	Flat	D&B	√			√	√					
Fonoage et al., 2010	2010	Flat		√	√	√		√	√				
TPGF (Shu et al., 2010)	2010	Flat	D&R		√	√	√	√				√	
THVR (Li et al., 2009)	2009	Flat	D	√	√				√				
DHGR (Chen et al., 2009)	2009	Flat	D		√	√							
EARQ (Heo et al., 2009)	2009	Flat	D&R		√	√							
ORTR (Kim and Ravindran, 2009)	2009	Flat	D	√	√	√		√	√				
He et al., 2009	2009	Flat	D&R			√	√						√
Shiang and Van der Schaar, 2009	2009	Flat		√	√					√			
DARA (Razzaque et al., 2008)	2008	Flat	D&R	√	√	√		√					√
Huang and Fang, 2008	2008	Flat	D&R		√	√		√					
Chen et al., 2008	2008	Flat	D	√	√	√	√	√		√			
MPMPS (Zhang et al., 2008)	2008	Flat		√	√			√					
Noh et al., 2008	2008	Flat			√	√							
MR2 (Maimour, 2008)	2008	Flat	B			√		√	√	√			
I2MR (Teo et al., 2008)	2008	Flat	B					√	√	√			
Ergen and Varaiya, 2007	2007	Flat	D			√							
DGR (Chen et al., 2007)	2007	Flat	R		√	√	√	√		√			
Kwon et al., 2007	2007	Flat		√	√								
Noh et al., 2007	2007	Flat	D&R		√	√							
MMSPEED (Felemban et al., 2006)	2006	Flat	D&R		√			√					
RPAR (Chipara et al., 2006)	2006	Flat	D		√	√							
SPEED (He et al., 2005)	2005	Flat	D		√				√			√	
Savidge et al., 2005	2005	Flat	D	√	√	√	√						
EAQoS (Akkaya and Younis, 2003)	2003	Hier.	D	√		√							

[a] Online available.
[b] Delay.
[c] Hierarchical.
[d] Reliability.
[e] Jitter.
[f] Bandwidth.

network environment in the calculation of the key metrics, leading to extra communication and scheduling overheads. Therefore, during routing decision-making, targeted use of link correlation could improve transmission performance.

Before applying link correlation into routing for high throughput and low delay, a natural task is to analyze the impact of link correlation on data transmission. A link-correlation-aware OR scheme that captures the diverse low correlated forwarding links is presented in Wang et al. (2015). Kim et al. (2015a) propose to utilize signal-to-interference-plus-noise ratio (SINR) to detect link correlation, and to model the correlation. When applied to routing, higher energy efficiency can be achieved. The authors further propose cETX (Kim et al., 2015b), a unified metric incorporating spatiotemporal correlation, to compensate for estimation errors caused by the widely used metric. The study in Zhao et al. (2015) shows that, apart from physical-layer parameters, the network-layer parameters significantly impacts link correlation.

6.1.2. Opportunistic cognitive routing

With the wide application of IoMT, many different types of WMSNs may be deployed in one area. One of the major challenges is the scarcity of spectrum combined with high radio interference. Distributed opportunistic cognitive routing, combining the advantages of both OR and opportunistic spectrum access, is more suitable for CRMSNs especially in flexibility. One main feature makes it much different from traditional OR with multi-channel or single-channel, i.e. spectrum-aware metric on each link to capture the characteristics of the available spectrum holes. With opportunistic cognitive routing, packets may transverse the network over different paths and even over different channels for the same link, leading to two problems that need to be solved: (1) how to choose an appropriate spectrum band in real-time, (2) how to determine a suitable forwarder list with low cost. It is challenging because of high spectrum diversity and stringent QoS requirements in CRMSNs. Chiarotto et al. (2011) propose to apply OR to exploit spectrum leasing. SUs serve as extra next-hop relays for the primary network in exchange for spectrum leasing. Opportunistic Cognitive Routing (OCR) (Liu et al., 2012) protocol consists of a heuristic relay selection algorithm that can approach optimal solution. However, these methods are not directly tailored for CRMSNs.

6.1.3. Topology-aware multimedia routing with network coding

Despite increased reliability for multimedia routing in some scenarios, there are many limitations when applying NC in realistic WMSNs. First, Coding operation leads to additional processing expenses, which may offset its benefits. Second, the many-to-one communication paradigm makes it difficult for the nodes to capture inter-flow coding opportunities. Third, the introduction of NC often leads to strongly increased delay (Voigt et al., 2012), increasing the difficulty of real-time assurance. Last but not least, traditional NC solutions and topology-aware mechanisms (Xie and Wang, 2014) do not take into account the inherent characteristics of multimedia communication, and therefore, cannot support multimedia applications with high efficiency.

As discussed above, NC-based routing solutions are highly dependent on specific application scenarios and data flow characteristics. In particular, NC can take advantages of the benefits from a multi-sink scenario and from a multi-source scenario. Thus, it is essential to design a topology-aware multimedia routing, in consideration of the trade-off between coding gain and QoS.

6.1.4. Trust-aware multimedia routing

Most of existing research on routing in WMSNs considers security and video quality separately, while such networks are facing challenges of severe safety. Providing, secure and reliable multimedia services have become the trend of research. Trust-aware multimedia routing is the design concept of adding credible behaviors to the traditional secure routing to strengthen multimedia task processing, achieving adaptive security and QoS control.

Little work has been done on the study of trust-aware routing for WMSNs. Security and Quality Aware Routing (SQAR) (Rashwan et al., 2015) protocol utilizes secret sharing on a data packet to achieve secure delivery of data through multiple disjoint paths. The sharing mechanism is only applied on the I-frames of the video codec H.264 in order to reduce transmission overhead. The main advantage is the capacity to achieve better trade-off between the security and video quality.

6.1.5. Green multimedia routing

Research on green routing in WMSNs needs to comprehensively consider energy efficiency and QoS, and the problem of how to achieve a dynamic equilibrium between them needs to be solved. In general, the trade-off mechanisms are in gradual progress from simple weighted sum to the multi-objective optimization, especially the widely used artificial intelligence methods, providing a theoretical basis for better performance trade-off (Gao et al., 2016). However, there are many challenges we have to address. The trade-off is usually performed during route selection and update, which means that there are multiple QoS variables that need to be identified in real-time. Another challenge is that varying QoS demands may result in an increase of complexity in energy management. It is still an open issue on how to design a flexible trade-off mechanism in routing for green WMSNs.

6.1.6. QoS-aware three-dimensional geographical routing

The global topology of a real-world WMSN is complex and irregular. Sensors are often deployed in three-dimensional (3D) environments such as mountains or underwater. The assumption of two-dimensional (2D) field may lead to inaccurate path estimation in irregular and concave areas (Tan et al., 2013). Therefore, a number of approaches have been proposed to extend 2D geographic routing to 3D. Xia et al. (2011) propose a deterministic 3D greedy routing with volumetric harmonic mapping for deterministic and guaranteed delivery. A trace-routing with guaranteed delivery is presented in Xia et al. (2014) to construct a virtual cutting plane to intersect boundary surface. A scalable and distributed routing (SINUS) (Yu et al., 2013) is proposed to provide guaranteed delivery and balanced load for high genus 3D settings.

Currently, little work has been done to study 3D real-time routing. As one of the most important works, 3D Real-Time Geographical Protocol (3DRTGP) (Rubeaai et al., 2016), introduces a unique packet forwarding region to limit redundant transmissions, and to reduce collisions and congestion. 3DRTGP uses local parameters to make a forwarding decision meeting delay requirement.

6.2. Potential research areas

6.2.1. Routing in multimedia crowd sensing networks

Due to the wide diffusion of mobile devices with sensing abilities, such as smartphones and tablets, their use to obtain large scale information from the environment (crowd sensing) has recently drawn considerable interest from both academia and industry (Ma et al., 2014). In such a scenario, opportunistic networking, as the store-carry and forward paradigm, is a popular way to create and share knowledge through dissemination routing protocols. Recent advances in mobile multimedia sensor devices have led to the development of Multimedia Crowd Sensing Networks (MCSNs). These mobile sensor devices are used to distribute sensing tasks and collect multimedia data by coordinating with mobile internet and thus to accomplish complex and large-scale social sensing tasks. MCSNs face many challenges in basic theory, key technologies, practical applications which WMSNs have never encountered. Currently, little published work has focused on routing in MCSNs. Jung and Baek (2015) propose a multi-hop data forwarding protocol for crowd sensing, where opportunistic users and static sensors use a non-unique abbreviated address instead of the IPv4 or IPv6 addresses thus reducing the header overheads. However, it cannot meet the requirements of MCSN applications. There are many unsolved problems in MCSN routing.

6.2.2. Routing in Internet of Multimedia Things

WMSNs constitute an integral part of the IoMT paradigm, providing the majority of hardware infrastructure support. The routing protocol for low-power and lossy networks (RPL) (Gaddour and Koubâa., 2012) is recently standardized as a routing protocol for the IoT. While RPL greatly meets the requirements of low-power and lossy networks (LLNs), several issues are open for improvement and specification in IoMT. Gaddour et al. (2015) attempt to overcome the limitations of the standardized objective functions of RPL to provide QoS supports for LLNs. A cross-layer-based beaconless OR is proposed in Rosário et al. (2014) for video dissemination in mobile IoMT, taking into account the importance of different types of video frames.

Some issues on routing in a heterogeneous IoMT environment are still open. An IoMT communication terminal includes many types of access networks such as WMSNs, WiFi/WiMAX, WPAN. Thus, an end-to-end QoS conversation generally crosses various types of wireless access networks. Because of the differences in terms of architecture, bandwidth, coverage ability and service cost, these accessed QoS support abilities are substantially different. This requires a routing protocol with cross platform capability.

6.2.3. Routing in underwater multimedia sensor networks

An Underwater Multimedia Sensor Network (UMSN) consists of multimedia sensors deployed to perform environmental monitoring over a body of water, enabling a wide range of aquatic applications such as multimedia coastal and tactical surveillance, undersea picture and video collection, and disaster detection. These applications require the routing mechanism to be redesigned for delivering multimedia content with a certain level of QoS (Pompili and Akyildiz, 2010).

Relatively little literature has focused on QoS routing in UMSNs. In Pompili et al. (2010) two distributed geographical routing algorithms are proposed for delay-insensitive and delay-sensitive applications in underwater networks. Location-Aware Routing Protocol (LARP) (Shen et al., 2015) improves reliability of message transmission while reducing delivery delay. Multipath power-control transmission (MPT) (Zhou et al., 2011) protocol combines with power control at the physical layer and packet combining at the destination, providing packet error rate guarantee while reducing energy consumption and delay in underwater networks.

6.2.4. Routing in flying multimedia sensor networks

With rapid technological advances on long range and low-power micro radio devices, cheap airframes, powerful imaging devices and micro-processors, there has been an increasing interest of unmanned aerial vehicle (UAV) equipped with multimedia sensors in both military and civilian applications (Meng et al., 2015). As a special class of an video surveillance networks, Flying Multimedia Sensor Network (FMSN) is an emerging technology that provides an unprecedented aerial perspective for aerial and ground monitoring in real-time. However, the requirements of FMSNs vary largely from traditional networking model of Mobile Ad-Hoc Networks (MANETs) and Vehicular Ad-Hoc Networks (VANETs), the unique attributes of which includes intermittent links and fluid topology, limited spectrum, mechanical and aerodynamic constraint, and so on.

Few practical studies have focused on QoS routing for FMSNs. To achieve robust multimedia transmission in such networks, a connectivity enhancement mechanism for geographic routing, called ECORA, is proposed in Costa (2014). ECORA consists of position prediction and link-lifetime estimation modules, but requires continuous support from node status information.

6.2.5. Routing in cloud/fog-assisted multimedia sensor networks

Cloud Computing (Armbrust et al., 2010), due to its scalable environment, may contribute to the offloading of jobs that take place from the resource constrained sensor to the cloud, thus to save energy. While this technique suffers from limitations in real-time performance, Fog Computing (Vaquero and Rodero-Merino, 2014) provides computation, storage, and networking services between sensors and Cloud Computing data centers. The characteristics of the Fog (e.g., proximity and location awareness, geo-distribution) make it the suitable platform to support WMSN applications (Bonomi et al., 2012).

The integration with Cloud/Fog, while enabling a new breed of WMSN applications and services, also raises challenges and open issues in routing, including: (1) routing to access to the heterogeneous sensor cloud/fog, (2) visualization and recommendation for routing decision making, and (3) resource-efficient routing to balance various requirements on the resource-usage matching and collaborations. In addition to these, considering data privacy and security, sensor data owners usually need to encrypt data before uploading onto the cloud (Fu et al., 2015, 2015), and therefore it is important to achieve adaptive security control in multimedia routing.

6.2.6. Routing in software-defined multimedia sensor networks

In the IoMT environment, for each deployed WMSNs, the control of transmission path is given to individual sensor making decisions according to a specific distributed routing protocol. Because of operational independence among network systems, routing packets cannot be unified management, resulting in unequal traffic distribution and lower resource utilization. One possible solution is to achieve the separation of control and data plane. Using software-defined networking (SDN) (Casado et al., 2014), routing operation is removed from the forwarding elements and is handled by a central controller, and network devices responsible for forwarding can be programmed using an open interface, thus improving flexibility in network control and management. Nevertheless, there is still a lack of clear understanding of what are the advantages of SDN in WMSN scenarios and how the routing should be designed for software-defined WMSNs.

7. Conclusion

WMSNs have promoted a number of creative applications, while facing new and unique challenges. The objective of this survey is to highlight important topics in WMSNs, i.e., the challenges and current trends in routing. The main issues when designing the routing protocol are explored to provide stable and resource-efficient path with QoS/QoE support. However, it is difficult to achieve because of the restrictions imposed by the WMSN features, which distinguish it from traditional WSNs. This paper extracts the particularities and challenges in the design of routing for WMSNs, and then provides an exhaustive survey of recent research progress in this area. Moreover, we have pointed out the open research issues and potential research areas that need to be solved in future WMSN/IoMT systems. We hope that this survey will help to improve the understanding of the issues and challenges in WMSNs and the examination of the routing issues.

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