A Survey on Multipath Routing Protocols for QoS Assurances in Real-Time Wireless Multimedia Sensor Networks

Mohammed Zaki Hasan, Hussain Al-Rizzo, and Fadi Al-Turjman

***Abstract*—The vision of wireless multimedia sensor networks (WMSNs) is to provide real-time multimedia applications using wireless sensors deployed for long-term usage. Quality of service assurances for both best effort data and real-time multimedia applications introduced new challenges in prioritizing multipath routing protocols in WMSNs. Multipath routing approaches with multiple constraints have received considerable research interest. In this paper, a comprehensive survey of both best effort data and real-time multipath routing protocols for WMSNs is presented. Results of a preliminary investigation into design issues affecting the development of strategic multipath routing protocols that support multimedia data in WMSNs are also presented and discussed from the network application perspective.**

***Index Terms*—Wireless sensor networks, quality of service, real-time, wireless multimedia sensor networks, multipath routing.**

I. INTRODUCTION

THE DEMAND for a wide variety of network services and various multimedia applications have been the major driving force behind the innovation and development of various networking technologies such as IEEE 802.11n, 4G/5G Long-Term Evolution-Advanced (LTE-A) and Wireless Sensor Networks (WSNs) [1]. Integration of these applications in modern networking poses a new set of constraints on QoS and often require suitable routing strategies. Routing strategies are key for meeting the different demands for network capacity provisioning and QoS guarantees in such networks. Wireless Multimedia Sensor Networks (WMSNs) have been used in numerous applications in the era of Internet of Things (IoT) that require ubiquitous access to both real and non-real time applications as depicted in Fig. 1 [2]. WMSNs utilize the multimedia sensing technology to monitor changes in the surrounding environment and route the collected information via routing protocols to remote controlling units [3]. WMSNs are expected to be among the pillars in realizing the IoT paradigm by fostering applications such as smart cities, smart agriculture, smart security and emergency systems [4]. Certain applications of WMSNs may operate for several months or even years [5]. The deployment of multimedia devices depends on the application and the environment [5]. This means that each sensor node shall be modified distinctively according to the application scenarios [6]. For example, in security and emergency applications, a low-cost maintenance is required, whereas urban applications are more apt to risk of environmental interference [5]. Therefore, the network designer may encounter several conflicting design aspects, challenges and factors that influence the design of WMSNs in these environments. These characteristics, challenges and factors depend on the nature of real-time multimedia traffic data flow, such as the application specifics of QoS requirements, high bandwidth, tolerable end-to-end delay, resource constraints, multimedia source coding techniques, cross-layer coupling of functionality, and multimedia in-network processing [7].

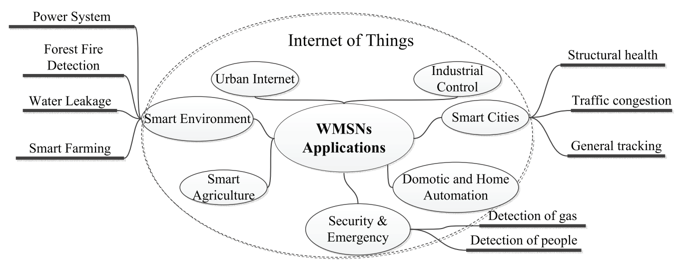

Fig. 1. Applications of WMSNs in different environments.

These characteristics are handled either by modifying existing protocols in WSNs or by proposing new methodologies such as multi-radio multi-channel systems, switching between multiple channels, multipath routing, or mixtures of these methods [8]. In Table I, we provide some popular applications of WMSNs, proposed multipath routing protocols, and the optimal solutions proposed for different application scenarios and environments. Generally, routing protocols for real-time applications impose severe demands on different QoS metrics such as low delay, high throughput, and high reliability [9]. Therefore, these characteristics along with other research design issues such as security, connectivity and coverage have received considerable attention and are most likely

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TABLE I
APPLICATIONS OF WMSNs

Applications	Applications Scenario	Routing Protocol	Propose Solution
Smart Environment	Power system, smart farming, water leakage and forest fire detection	RTLD [92], Task allocation for real-time applications [101], RPAR [97], SONS [99]	Multipath multi-QoS constraints
		EQSR [124], RTRR [127], ICPSOA [130].	Multipath reliability constraints
		EADD [138]	Data-centric protocol
		SHRP [152]	On-demand fashion
Smart Cities	General geographical tracking applications	SAR [85], SPEED [86], [87], EE-SPEED [88], REAR [91], QuESt [95], THVR [98], Disjointed multipath routing [102], AMPMCR [109], IAMVD [111]	Multipath multi-QoS constraint
		MMSPEED [113], ReInForM [114], NC-RMR [115], EERMR [116], DMRF [117], QoSMRP [119], MCMP [121], ECMP [122], PMR [9], QoSNet [123]	Multipath reliability constraints
		DD [137]	Data-centric protocol
		RM-DSR [144], TinyONDMR [147], RMRP [150]	On-demand Fashion
Security and Emergency	Detection of gas, detection of people	Routing of high-priority packets in WSNs [96]	Multipath multi-QoS constraint

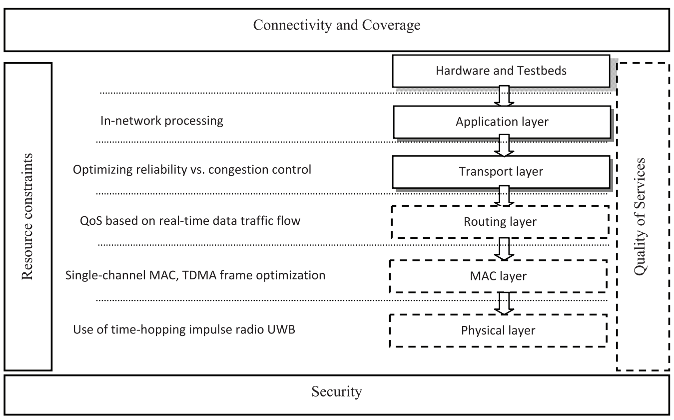


Fig. 2. Research challenges at the various WMSNs layers of the communication protocol stack [2].

to be considered in the different layers of the communication network protocol stack as shown in Fig. 2 [10].

Energy efficiency is a common challenge for WMSNs given the various energy-efficient mechanisms developed at the different layers of the network protocol stack [11]. For example, energy-aware routing protocols in which the available energy in each node can be used to select the optimal path while satisfying the QoS requirements has been proposed [11].

Multipath routing strategy has emerged as the technology of choice in WSNs, which can fulfill QoS metrics and networks constraints in most real-time applications [12]. The demands of multipath routing strategy combined with various performance demands dictated by different applications have led to the proposal of a number of new routing protocols to efficiently utilize the limited available resources in addition to the features of multimedia data [13]. Moreover, the performance of traditional sensor nodes should be enhanced to keep with the fast-changing and realistic events in the real world [9].

Multipath routing operation is relevant for providing adequate network resources in various traffic conditions in order to fulfill these requirements [14]. Multipath routing techniques have been extensively used for improving the delivery of multimedia content, providing fault-tolerance routing and supporting QoS in networks from multihop Local Area Networks (LANs), Wireless Area Networks (WANs) and the Internet, and finally in Ad-hoc networks and WSNs [15]. Furthermore, the effectiveness of multipath routing strategies is essential to achieve high-quality network services and guaranteed QoS at high data rates. Consequently, the objective is to assign more loads to under-utilized multiple paths and less load to over-committed paths so that uniform resource utilization of all available paths can be ensured to distribute network traffic [16], [17]. Multipath routing protocol is cost effective for heavy load balancing structures without dynamic traffic engineering [1], [18]. To exploit multipath routing strategy, it is necessary to determine the number of available paths. Clearly, the number and quality of the selected paths dictate the performance of the multipath routing protocol. Thus, designing a multipath-routing algorithm for multimedia applications is very challenging because of several characteristics and features of WMSNs. The breakdown of multipath routing schemes at different taxonomic levels and their features present a complete set of network routing protocols and highlights the key challenges of a communication routing protocol. With this broad picture in mind, we aim at assisting the reader in understanding what is essential and critical to QoS assurances with the current multipath strategies in WMSNs. In order to assist the readers, we provide in Table II a list of abbreviation along with brief definitions as used throughout the paper.

The rest of the paper is organized as follows. Section II presents a review of related work. In Section III, we present the system architecture and design issues of the routing algorithm, whereas in Section IV, we present the proposed high-level WSN multipath-routing protocol taxonomy. In Sections VI and VII, state-of-the-art multipath routing techniques are presented. Section VIII provides a comprehensive analysis of major multipath routing approaches for WMSNs. In Section IX, some open issues and research directions are identified. Finally, conclusions are provided in Section X.

II. COMPARISON WITH RELATED SURVEY ARTICLES

Most of existing surveys of QoS-enabled WSN routing protocols deal with application and architecture

TABLE II
ABBREVIATION

Abbreviated	Name	Abbreviated	Name
ADC	Analog-to-Digital	MDP	MArkov Decision Process
AE	Available Energy	MIP	Mixed Integer Programming
AMPMCR	Adaptive Multi-Constraint Multipath Routing	MOGA	Multi-Objective Genetic Algorithm
AODV	Ad-hoc On Demand Vector	MP-DSR	Multipath Dynamic Source Routing
AOMDV	Ad-hoc Multipath Demand Vector	NC-RMR	Network Coding-Reliable Multipath Routing
ARRCH	Adaptive Reliable based on Clustering Hierarchy	NSGA-II	Non-dominated Sorting Genetic Algorithm
BE	Best-Effort	OS	Operating System
BF	Broadcasting Flooding	PARSEC	Parallel Simulation Environment for a Complex System
BFS	Breadth First Search	PMR	Partitioning Multipath Routing
CC	Cell Controller	PPP	Packet Reception Rate
CMOS	Complementary Metal-Oxide Semiconductor	QoS	Quality of Service
CMVT	Cross-layer Multipath Video Transmission	QoSMR	Quality of Services Multipath Routing
CPU	Central Processing Unit	QoSNet	Quality of Service Network
CR	Cognitive Radio	QuESt	QoS-Based Energy Efficient Routing
CRSNs	Cognitive Radio Sensor Networks	REAR	Real-time and Energy Aware QoS Routing
CSMA/CA	Channel Sense Multi-Access/Collision Avoidance	Re-InForM	Reliable Information Forwarding Multiple Paths
DD	Directed Diffusion	RMA	Rate Monotonic Algorithm
DFM	Duplication of Forwarding Messages	RMDSR	Robust Multipath Dynamic Source Routing
DMRF	Dynamical Jumping Real-time Fault-Tolerant	RMRP	Resilient Multipath Routing Protocol
DPS	Dynamic Packet State	RPAR	Real-time Power-Aware Routing
DSA	Dynamic Spectrum Access	RRP	Rumor Routing Protocol
DSR	Dynamic Source Routing	RSSI	Received Signal Strength Indicator
EADD	Energy Aware Directed Diffusion	RTLD	Real-time with Load Disturbed Routing
EBMR	Energy Balancing Multipath Routing	RTRR	Real-time Robust Routing
ECCs	Error Correction Codes	SAR	Sequential Assignment Routing
ECMP	Energy Constrained MultiPath	SEER	Secure and Energy-Efficient Multipath Routing
EDF	Earliest Deadline First	SNR	Signal-to-Noise Ratio
EEPBC	End-to-End Path Battery Cost	soft-E2E	soft-End-two-End
EERMR	Energy Efficient Reliable Multipath Routing	SONS	Self Organizing Network Survivability
EH-WSN	Energy-Harvesting Wireless Sensor Network	SPEED	A Stateless Protocol for Real-Time Communication in Sensor Networks
EXT	Expected Transmission Count	SPEED-EE	SPEED-Energy Efficient
EYES	European Eduction Youth Environment Substantiality	SPIN	Sensor protocols for Information via Negotiation
FECC	Forward Error Correcting Codes	SPIN-BC	SPIN-Broadcast
FIFO	First-In-First-Out	SPIN-EC	SPIN-Energy Consumption
GBR	Gadient-Based Routing	SPIN-PP	SPIN-Point-to-Point
GPS	Global Position System	SPIN-RL	SPIN-Reliability
HRT	Hard Real-time	SRT	Soft Real-time
IAMVD	Interfernce-Aware Multipath Video Delivery	TCP/IP	Transmission Control Protocol/Internet Protocol
ICPSOA	Immune Cooperative Particle Swarm Optimization Algorithm	THVR	Two-Hop Velocity-based Routing
IFS	Iterated Function system	TinyONDMR	Tiny Optimal Node-Disjoint Multipath Routing
IoT	Internet of Things	WAN	Wireless Area Networks
ISP	Internet Service Provider	WFQ	Weighted Fair Queuing
LANs	Local Area Networks	WLAN	Wireless Local Area Network
LQI	Link Quality Indicator	MDC	Multiple Description Coding
LTE-A	Long-Term Evolution-Advanced	WMSNs	Wireless Multimedia Sensor Networks
MAC	Medium Access Control	WSNs	Wireless Sensor Networks
MCMP	Multiple Constraint MultiPath	XOR	Exclusive OR

requirements along with their respective routing strategies [8], [13], [14], [16]. However, there are additional criteria that should be emphasized when designing routing protocols for WMSNs. The most important of these are the lifetime of the multimedia sensor network, and the overall QoS requirements of the respective real-time applications. We will review existing survey articles and highlight the gaps in those surveys as compared to the focus of this paper.

Early surveys focused on general architectural issues and open research problems in the field of WSNs [8], [19]–[27]. These surveys were based on the requirements of real-time applications and only cover certain aspects of QoS in WSNs, such as reliability, scalability, and ability to support real-time activities, which are not directly applicable to the more recent WMSNs. An introductory survey was presented in [25] to discuss constraints and solutions related to each layer of the WSN stack, including sensor node hardware requirements. Open research challenges were presented for each layer. General research challenges in terms of operating systems, networking and middleware protocol requirements to support various WSN requirements were presented in [22]. In [8], routing protocols for WSNs were discussed and classified into two main categories: network structure and protocol operations. The authors outlined the design tradeoffs between energy efficiency and communication overheads in the context of various routing paradigms. Akkaya and Younis [26] surveyed 27 WSN routing protocols that were current as of 2004 and presented a protocol classification based on multipath, query-based, negotiation-based, and QoS-based approaches. In addition, design issues such as network flow considerations and quality modeling were highlighted. A taxonomy for WSN routing protocol classification was developed in [19], where the system, network, operational and objective models were used to classify various WSN routing protocols.

Subsequent surveys considered additional issues such as energy efficiency [8], geographic location [28], network scalability [29], and cross-layer approaches [21]. In [25], the advantages and performances of various approaches for real-time routing protocols and algorithms for WSNs were highlighted, and cross-layer design was introduced as a viable design approach. In [21], a survey of various MAC and routing protocols for supporting real-time QoS for WSN in terms of reliability, data aggregation, and cross-layer protocol solutions were presented. In addition, trade-offs among different constraints in real-time applications, such as energy efficiency and delay performance, were highlighted. Energy-constrained routing protocols were studied in [30], where the taxonomy presented in [8] was expanded to consider energy efficiency. Existing routing strategies were classified based on four main criteria, namely, network structure, communication model, topology and reliable routing approaches.

In [28], position-based routing protocols were surveyed for WSNs. Flooding-based routing, curve-based routing, grid-based routing, and behavior-based routing were discussed. Metrics such as energy consumption, negotiation overheads, complexity, reliability, scalability, and multipath strategies were used for comparison. Scalability issues were also considered in [31]. Hierarchical routing strategies for large-scale WSNs were classified based on control overheads and energy consumption. Details of various protocols, as well as advantages and disadvantages in terms of the message complexity, memory requirements, localization, data aggregation, clustering algorithm, intra-cluster topology, cluster head selection and multipath routing strategy were presented in [31].

Another emerging trend in recent surveys is the focus on real-time multimedia data transmission in WSNs. Gürses and Akan [32] surveyed issues related to supporting multimedia communication over WSNs. The design constraints and factors that influence multimedia delivery over WSNs, solutions appropriate for respective layers of the networking stack, along with their shortcomings and other major open research issues were highlighted. Cross-layer designs for multimedia streaming were investigated in [33]. The paper discussed mechanisms for cross-layer optimization, and outlined future research directions for each layer of the network stack. In [10], architectures, algorithms and protocols were proposed for the various layers of the networking protocol stack, as well as cross-layer designs for WMSNs along with an evaluation of the performance of existing hardware and test-beds. Multipath routing techniques were introduced to address QoS requirements for WMSNs.

Energy efficiency and multipath routing approaches are the main focus of current research efforts in WMSNs. In [14], energy-efficient routing strategies were introduced for WMSNs, along with discussion of performance issues of each routing strategy and energy-efficient routing challenges for WMSNs, as well as limitations of current non-multimedia routing strategies. The benefits of various multipath routing protocols for WSNs and their benefits were presented in [33] and [34]. The authors addressed the main characteristics of the multipath routing schemes and classified them according to their attributes. In [13], multipath routing protocols were classified based on three main criteria: alternative path routing, reliable data transmission, and efficient resource utilization. The multipath routing protocol taxonomy in [17] used path selection techniques and traffic distribution mechanisms to classify the surveyed protocols. The paper also discussed the suitability of the selected multipath routing protocols for meeting the performance requirements of various applications. Other considerations such as swarm intelligence based routing, geographic awareness routing, and redundant traffic reduction based on similarity of multimedia data sources from nearby locations were studied in [7]. However, Abazeed *et al.* [7] classified the WMSNs routing protocols according to the direction of sensor nodes equipped with multimedia devices. The classification depends on the routing system architecture and design issues for WMSNs.

Radi *et al.* [13] classified a multipath routing taxonomy for WSNs into three categories with emphasis on their advantages and disadvantages. Singh *et al.* [35] surveyed multipath routing and provisioning in the Internet, end-user's and Internet Service Provider's (ISP) perspective. However, our survey and the survey presented in [13] have several major differences. First, our survey is more up-dated and covers most existing multipath routing protocols of WMSNs, some of which are not covered in the previous work. Second, our survey focuses on the importance of particular multipath routing strategies for QoS assurances of real-time applications. Furthermore, we exploit mechanisms for the multipath routing strategy that aim not only at circumventing single point failure but also to facilitate network provisioning. This investigation provides a comprehensive survey on both traditional data and more recent real-time multipath routing protocols.

Our survey presents an overall picture of QoS assurances in WMSNs via investigating and comparing advantages and disadvantages of existing multipath routing protocols. It should be pointed out that this paper also provides an analysis of the classification of multipath routing protocols in terms of the exploitation and design issues for multipath strategies aimed not only at circumventing the multipath configuration but also on the effectiveness of network provision to network services and guarantees of QoS parameters. Table III provides a comparison between our survey and related survey articles available in the literature. To this end, a new classification is proposed that classifies existing protocols according to the exploitation and selection of multiple paths. Moreover, a complete description with comparisons among different WMSNs applications are presented in our survey.

III. Routing System Architecture and Design Issues

The extension of WMSNs has stretched the horizon of traditional WSN. WMSNs allow monitoring and control of real-time information with low cost and miniaturized sensor nodes. This brings different architectures, design goals and constraints.

How can WMSNs reach to the derived reliable scalable architectural frame model to achieve QoS parameters with lower algorithmic complexity? Particularly, a routing strategy can be embedded into low-cost microprocessors to extend the lifetime of the sensor network without jeopardizing reliable and efficient communications. Generally, the architecture and design issues for routing protocols in WMSNs give rise to new challenges. The most dominant and challenging factors

TABLE III
A COMPARISON AMONG RELATED SURVEY ARTICLES

References	Considered performance metrics Routing strategies	Energy	Reliability	Scalability	Complexity	Topology	Security	Description
References[19]†								Used system, network, operational and objective model metrics to classify various routing protocols.
References[21]†	✓	✓	✓	✓		✓		Surveyed MAC and routing that support real-time QoS for WSNs.
References[22]†	✓	✓	✓				✓	Surveyed general research challenges for supporting various WSN requirements.
Reference [25]†	✓	✓	✓	✓	✓	✓		Discussed node hardware requirements at each WSN stack layer.
Reference [26]†	✓	✓	✓	✓	✓	✓		Discussed routing design issues such as network flow and quality modeling.
Reference [27]†	✓	✓	✓	✓	✓	✓	✓	Discussed tradeoffs between energy efficiency and communication overhead.
Reference [29]†	✓	✓	✓	✓	✓	✓		Surveyed position-based routing protocols.
Reference [30]†	✓	✓	✓	✓				Surveyed routing protocols considering scalability issue.
Reference [31]†	✓	✓	✓	✓	✓	✓		Expanded taxonomy in [27] to consider energy efficiency.
Reference [32]†	✓	✓	✓	✓	✓	✓		Surveyed hierarchical routing strategies for large-scale WSNs.
Reference [33]‡		✓	✓					Surveyed issues related to supporting real-time multimedia streaming traffic, without providing analysis of multipath mechanism.
Reference [34]‡		✓	✓					Discussed mechanism for cross-layer design optimization, but does not provide analysis of multipath mechanism in term of exploitation and design.
Reference [10]‡	✓	✓	✓	✓	✓	✓		Surveyed most routing protocols in WMSNs along with introducing multipath routing mechanism, but does not provide any analysis of multipath mechanism in term of exploitation and design.
Reference [14]‡	✓	✓	✓	✓	✓	✓		Introduced energy-efficient routing strategies.
References [34],[35]‡	✓	✓	✓	✓	✓	✓		Discussed the main characteristics of multipath routing schemes and provided classification according to their attributes.
Reference [13]‡	✓	✓	✓	✓				Provided classification based on main criteria, but does not focus on the importance of particular multipath routing strategies.
Reference [14]‡	✓	✓	✓	✓	✓	✓		Introduced energy-efficient routing strategies.
Reference [17]‡	✓	✓	✓	✓	✓			Used path selection techniques and traffic distribution mechanisms to classify the various surveyed protocols.
Reference [7]‡	✓	✓	✓	✓	✓	✓		Provided classification for WMSNs routing protocols according to the direction of sensor nodes equipped with multimedia devices.
Reference [36]‡	✓		✓	✓	✓	✓		Surveyed multipath routing and provisioning in the Internet, end-user and Internet Service Providers (ISP).
Our	✓	✓	✓	✓	✓	✓		Provided an analysis of the classification of multipath routing protocols in terms of the exploitation and design issues for multipath strategies.

†: Surveys based on the requirements of real-time applications and only cover certain aspects of QoS in WSNs. However, they can not be directly applied to WMSNs.
‡: Surveys based on classification of routing protocols. However, they did not cover the importance of particular multipath routing strategies for QoS assurances of real-time applications in WMSNs.

to achieve efficient communication in WMSNs are addressed in the following subsections.

A. *Hard and Soft Real-Time Operation and Best-Effort for Resource Constraints*

Real-time WMSNs consist of three types: hard and soft real-time systems and best-effort systems.

1) Hard Real-Time (HRT): HRT applications involve a mechanism that operates on a preemptive and context-switching Operating System (OS) with switching tasks in and out of execution modes based on the scheduled time slots to maintain real-time characteristics [23]. These applications might require an OS to deterministically delay different tasks. Traditional schedulers, for example, Rate Monotonic Algorithm (RMA) and Earliest Deadline First (EDF), might be suitable for such applications [23], [24].

2) Soft Real-Time (SRT): SRT applications involve a system that attempts to meet time constraints related to tasks, operations and applications by applying system resources, including a high clock rate, fast processors, cache and buses [23].

3) Best-Effort (BE): BE applications are necessary to guarantee the best achievable performance, however they may not be relatively focused on static measures, such as Central Processing Unit (CPU) allocation.

Designing routing protocols for WMSNs is influenced by many factors such as the cost of hardware, network topology, power consumption, etc. which all affect either probabilistic or deterministic end-to-end QoS metrics. When considering real-time support in WMSNs, energy efficiency should not be ignored, as energy consumption is the main constraint in WSNs. Therefore, there is often a tradeoff among these constraints [36], [37].

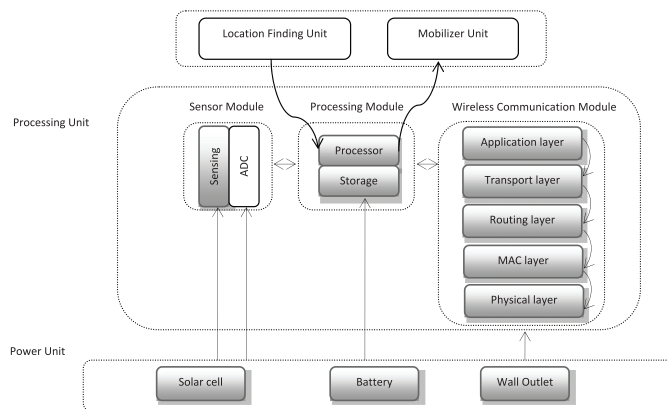


Fig. 3. Basic components of WMSNs.

B. *Energy Efficiency Model*

WMSNs can be used in various applications spanning over an extended physical area. Therefore, for easier installation, the integration with a deployed wireless communication network module is a viable option. A large number of nodes are required for adequate coverage and collection of multimedia information for a prolonged duration. Typically, generating higher volumes of data traffic not only require extensive processing but also higher transmission rates [14].

Basic components of a typical wireless multimedia node are illustrated in Fig. 3 [38] including the sensor module responsible for capturing sensory information fed to a processing module. A sensor module consists of two sub-components: sensory devices for capturing a signal and an Analog-to-Digital Converter (ADC). The main role of the processing module is to process the sensory data, encapsulation and forwarding to other nodes or to a sink via a wireless module. Multimedia sensors provide audio and video sensing capabilities to make the sensor node operational in the WMSN environment. These multimedia extensions come with depicting costs in the shaded unit in Fig. 3. Because audio and video units are required, higher energy consumption is required, a larger space for random memory is expected and a higher amount of bandwidth may be required due to the excessive multimedia content [38].

A major component in a sensor node is the power supply unit which has a limited power resources. Basically, the power unit consists of power managements (solar cell, battery, wall outlet, and/or capacitor) and energy sink [39]. A special kind of sensor network, called Energy Harvesting-Wireless Sensor Network (EH-WSN) is reported [40]–[42], whereas each node is equipped with rechargeable power supply instead of a traditional battery. Though unlimited power can be provided by vibration, light, and heat, the residual energy is not more any useful quantity to preserve [40]. Moreover, a battery is periodically recharged to keep the node continuously working rather than minimizing energy consumption. The node lifetime is defined by the time during which the energy level of the node is above a certain threshold that allows it to perform its operation such as transmitting, receiving, or processing data [41]. Therefore, once the energy level drops below this threshold, the node should go to sleep to charge up, otherwise the battery is considered dead and unable to continue the operations [41]. This means that is desirable to know that different nodes harvest different amount of energy. But this will be somehow a tiresome task or might be even impossible since most WMSNs depend on deployment and environmental conditions which need to recharge the battery in order to get as much as autonomy as possible [11]. Reducing or eliminating the problem of the limited lifetime will enable the network designers to develop the functionality of node by adding extra features and components [40].

A combination of energy-efficient mechanisms at the different layers in the protocol stack of WMSNs is used to minimize energy consumption and maximize the lifetime of network. Thus, how could these routing protocols maximize the workload in the energy harvesting network as well as the lifetime of the networks? The answer to this question is to develop an energy-efficient routing protocol that is able to balance and optimally allocate available energy among active nodes. To improve energy saving performance, each sensor node can be used to select the optimal paths based on the variation of environmental conditions [42].

Single-path and multipath routing mechanisms consider the most recent energy-efficient routing mechanisms according to the energy level of a particular node. Single-path approaches vary among different selected paths thereby balancing the energy depletion among the nodes and extending the network lifetime. Multipath routing can achieve better balancing than single-path since multipath approaches can achieve load balancing, and prevent congestion in the network by distributing the energy consumption among optimally selected paths [42].

C. QoS Modeling Requirements

End-to-end QoS requirements using a large number of mechanisms and algorithms have been pursued in different network stack layers to satisfy QoS parameters [8], [25]–[27], [37], [38]. At the same time, different wireless network communications may impose specific constraints on supporting the QoS requirements depending on their particular characteristics, challenges, and design requirements.

QoS support can be met by a plethora of approaches; for example, data centric, protocol centric, cross-layer optimization, cooperative and distributed algorithms [14], [43]–[45]. Our survey focuses on QoS requirements imposed by the applications on the network because of the proliferation of applications requiring some guarantee of services from the network and the performance of applications depend largely on the QoS assurances in WMSNs [45].

More particularly, how can the underlying network routes the QoS constrained data while efficiently utilizing network resources? The QoS requirements of WMSNs may be very different from those of WSNs in terms delay, jitter, bandwidth, and energy consumption.

As a result, some WMSN applications rely on new QoS parameters that prefer measurement of the transmission of the sensor data in an efficient and effective manner [46]. Furthermore, network designers should be able to investigate which system architecture or mechanism can be exploited to provide better services than the best effort services such as differentiated services (soft-QoS) and guaranteed services (hard-QoS) for the WMSNs applications. Some QoS requirements are briefly described in the following sub-sections.

1) Latencies: Ensuring stringent timeliness is essential for real-time video applications. Timeliness can be provided either on a guaranteed or best-effort basis according to the tolerance level of the multimedia application [14]. In addition to timeliness, there are several other factors that cause latencies in WMSNs, including in-network processing, transmission and queuing delays [2], [10], [14]. Thus, reducing delays is a crucial task for real-time WMSNs applications. Generally, end-to-end latency can be classified into two classes: soft-latency bounded systems (deterministic constraint) and hard-latency bounded systems (predictive constraint) [14]. In hard-latency systems, the service cannot ensure meeting its deadline. Therefore, failure to do so is considered as a failure of the whole system, whereas the delay of a fraction of data traffic can be probabilistically guaranteed in soft-latency systems [14].

2) Bandwidth: Multimedia content, especially video streams, requires a high amount of bandwidth for transmission. In addition to multimedia transmission, some intermediate sensor nodes act only as relay nodes in a dynamic topology because of low transmission range and multihop communication. Therefore, use of single-path routing strategy for transmission of multimedia may exhaust the energy of the path, resulting in network failure. Thus, a bandwidth constraint based on low-power transmission consumption must be handled by the multipath routing strategy [14].

Generally, QoS support becomes increasingly challenging because of the increasing desirability of connectivity and

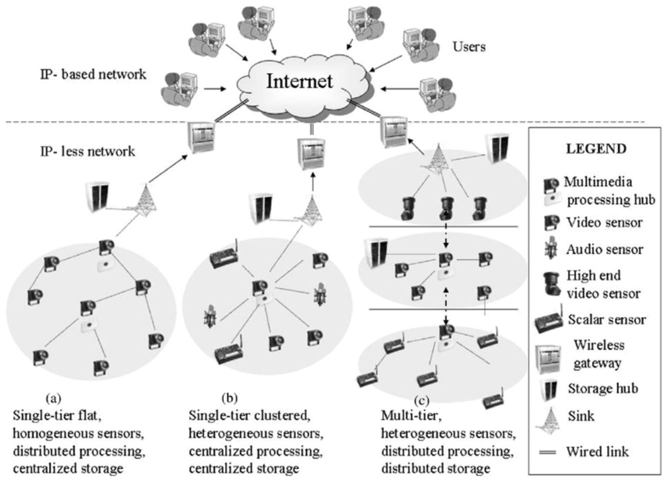


Fig. 4. Architecture of a WMSNs [14].

exchange of best-quality media information at any time, at any location and in any manner. Therefore, designing effective routing strategies in WMSNs should be performed for QoS requirements for different classes of traffic patterns. This remains an open research area and a major challenge in the WMSNs field [47], [48].

D. Sensor Network

Modeling large-scale sensor node deployment such as for nodes communicating over wireless networks with lossy links and without infrastructure, is considered another challenge in WMSNs research [2], [10], [14]. The models can be classified either as deterministic or self-organizing (randomized). In the deterministic model, the sensor node is deployed, and packets are routed through predetermined paths. In the self-organizing model, sensor nodes are scattered randomly by creating an infrastructure in an ad-hoc topology [49]. In terms of infrastructure distribution, position of the sink, cluster head, and scope of the monitored area are crucial in terms of energy efficiency, performance, and real-time routing protocols. The architecture of WMSNs consists of three classes: single layered, flat layered, and homogeneous, as shown in Fig. 4 [14].

WMSN architectures not only support heterogeneous nodes, but also independent applications with different requirements. Thus, it is necessary to develop a flexible and hierarchical architecture that can accommodate requirements of all applications in the same infrastructure [2], [50]. Typically, heterogeneous sensory data are reported at different rates to some multimedia applications that may require a diverse mixture of more additional QoS constraints [51].

E. Data Delivery Model

Data sensing and reporting models depend on the applications for both WSNs and WMSNs and the time criticality of data reporting. Because of various applications have common requirements, it is sufficient to analyze each application by the classification of the data delivery model. Such models are concerned with reporting data toward the sink along with their corresponding requirements. Generally, data sensing and reporting can be categorized into four basic traffic data delivery models or services: time-driven (continuous), event-driven, query-driven and hybrid [47], [49].

1) Continuous Time-Driven Delivery Model: This model is suitable for applications that require periodic dispatch of real-time data for monitoring, such as surveillance or reconnaissance, where the sensor node constantly switches between the sensors and transmitters to sense the environment and transfer data in a periodic order.

2) Event-Driven and Query-Driven Models: These models consider the most commonly used applications in WMSNs. When a certain event occurs, the sensor nodes react immediately to the changes in the sensed attribute, or a query is generated by the base station [52].

3) Hybrid Model: This model is used in some networks that use a combination of continuous, event-driven and query-driven data delivery based on the conditions of patterns carried out by the traffic and the classification of traffic requirements, for example, a surveillance application that periodically sends both event-triggered video and temperature. The design of the routing protocol is highly influenced by the data delivery model, especially when the design involves minimization of energy consumption and route stability [45].

F. Dynamic Network

Component-based architecture in the WSNs consists of three main components: the sensor node, sink and monitored event [53]. Most researchers consider a stationary state of sensor nodes while designing the network architecture, whereas others considered the mobility status of sensor nodes and even the sink node to improve network conditions. In addition to energy consumption, real-time routing stability becomes another issue in routing the message to or from the mobile nodes and other QoS metrics [54]. The sensing/reporting can be either for dynamic or static events; for example, dynamic events are target detection/tracking applications and forest monitoring for early fire prevention is a static event. Monitoring a static event allows networks to work in a reactive mode, simply generating traffic when reporting [26].

G. Reliability and Fault Tolerance

The concept of reliability concerns the ability to deliver multimedia data to the sink with minimum packet loss [14]. A different reliability constraint arises and needs to be imposed depending on the application demands that may require delivering the packets in a reliable transmission manner to the sink with timeliness and without loss of packets.

Similar to WSNs, the primary path in WMSNs may not often be able to support the sensed data because of broken links, among other reasons. Therefore, establishing the reliability of single and multipath routing protocols is challenging since multimedia applications generate high asymmetric traffic patterns, requiring high transmission rates and extensive processing. This challenge arises mainly because of the func-

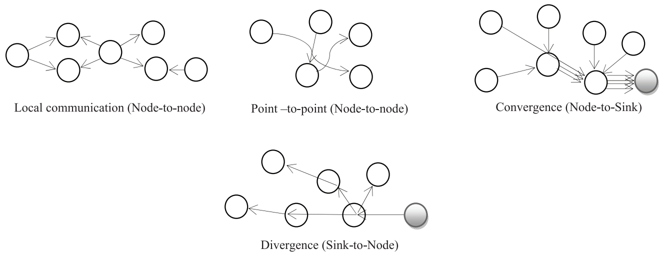


Fig. 5. The pattern of data traffic in WMSNs [30].

tional model of operational characteristics of routing protocols for data to reach to the sink. As long as WMSNs are used in various multimedia applications, this may generate a wide range of traffic patterns. The pattern of data traffic can be either single-hop or multihop [14], [55]. The pattern can be divided according to the node density of the network or whether the network supports in-network processing, i.e., the number of transmissions and reception of data packets processes in sensor nodes and/or whether any processing procedure is applied in the network, into the following as depicted in Fig. 5 [30].

1) Local Communication (Node-to-Node): This type of communication has been proposed for Ad-hoc networks where a node broadcasts its status to the nearest neighbor [47].

2) Point-to-Point (Node-Node): This pattern is used to send an arbitrary node data packet to arbitrarily directed node. This pattern is primarily used in WLAN environments. Point-to-point routing is not widely used for WSNs because building a routing tree does not scale well for sensor nodes that have only small data memory [56].

3) Convergence (Node-to-Sink): This pattern needs to be supported to route responses back to the sink. Typically, this communication is defined as many-to-one (reverse multicast), in which multiple nodes or a single node respond for collection directly or indirectly to the sensed data packet and transmits to the sink. This pattern is commonly used for data collection in WSNs and can also be unicast [56].

4) Divergence (Sink-to-Node): This pattern needs support routing requests originated from the sink to multiple nodes. This is a general paradigm including other group-based routing concepts such as anycast (one-to-many), multicast and many-cast routing, implying that any node that has the requested data can respond to the query [37]. Particularly, divergence traffic pattern is used when a sink node or base station sends control messages or queries to sensor nodes. Several techniques have been proposed to understand how different routing approaches respond when handling various requests in different network environments [8], [57]–[64].

One of these techniques adopts multipath routing strategy for performing fault-tolerant routing. The idea is to provide alternative or resilient routes for guaranteeing reliable flow of transmission of data packets over multiple hops [65], for example, sending copies of the same packets over multipaths to increase the probability that at least one of the copies reaches the sink with timelines.

H. Summary

Designing a routing scheme for real-time WMSNs is influenced by several factors, such as cost, transmission medium, network topology, power consumption, etc., which all affect either probabilistic or deterministic end-to-end QoS metrics guarantees, such as delay, jitter, and throughput. Moreover, WMSNs have specific requirements that are difficult to fulfill such as traffic flow of large burst of data at a high bit-rate. These characteristics need to be addressed taking into account hardware, bandwidth and power limitations of the sensor nodes. Therefore, designing effective routing strategies that achieve all of QoS requirements for different classes of multimedia data traffic remains a major challenge in WMSNs.

IV. Routing Techniques in WMSNs-Classification

A routing strategy is a key building block in a network protocol stack. It is a sub-component of the network layer in the sensor network stack layer model and is central to the proper functioning of any multihop communication system [30].

Routing strategy is defined in terms of the process of discovering and selecting paths in wireless networks from the target area that sends network traffic towards the sink node [8]. Therefore, the prime role of a routing protocol is to establish a path between the sources and sink node while keeping track of the path availability and facilitating successful transmission of data along the selected paths [8]. In the following subsections, we will discuss the main classification of routing techniques of multipath routing protocols in the realm of WMSNs. Different criteria used to classify multipath routing protocols are given. Furthermore, we provide taxonomies for multipath routing protocols in WMSNs. Generally, there are three main phases of multipath routing: path discovery, path selection, and path maintenance. Once the paths are discovered, a routing protocol should decide how to select a path for sending data. Actually, the discovery, selection and maintenance of paths depend on some node-specific and/or network-wide metrics such as QoS requirements, residual-energy budget along the selected path, and more [60]. Discovering and maintaining paths are also impacted by the data traffic, which is a major issue in designing the architecture of sensor nodes for multimedia applications. For example, the available buffer sizes, the limitation of resources (e.g., energy, memory and processing power), QoS constraints, distribution of node density, their connectivity and unexpected changes in node status during the duty cycling (e.g., inefficiency or failure) give rise to frequent and unforeseen topology alterations. Furthermore, these issues are also impacted by the fact that the common wireless channel is broadcast in nature, such as the control and corruption of data packets at the physical layer or collision of MAC protocols [66], [67].

A. Designing Issues for Multipath Routing

Traditional routing approaches have been developed for cellular networks or wireless Ad-hoc networks and thus they are not sufficient for WSNs which are more demanding than other wireless networks [30]. Many new routing strategies have been proposed to solve routing problems in traditional WSNs [60]–[64]. The design of routing protocols for WMSNs, however is still an open research area. In addition to the major issues of designing routing protocols in WSNs, there are new characteristics and constraints due to the nature of multimedia content that must be handled over the network such that routing protocols for WSNs are not applicable to WMSNs.

Most recent work seeks to handle these characteristics and their design challenges to solve the routing problem of streaming real-time multimedia content by modifying previous routing protocols in WSNs, for example, using multiple performance metrics to meet the additional QoS requirements [8], [68]. New solutions are proposed based on various new methodologies; for example, using multi-radio, multichannel, or multiple-input and multiple-output MIMO systems, switching between multiple channels, selecting multipath routing, or a mixture of these methods [2], [8]. Other approaches utilize optimization for cross-layer design between multimedia source coding techniques at the application layer and the routing layer to exploit optimal multipath selection or in-network processing [8]. In addition, cross-layer design between MAC layer and routing allow packet-level service differentiation or priority-based scheduling, and more power efficient routing mechanisms [17].

B. The Taxonomy of Multipath Routing Techniques

A plethora of research on taxonomies for Mobile Ad-hoc NETwoks (MANETs) and WSNs have reported the baseline model of routing protocols [7], [69]. A routing protocol can be classified into one of four main parallel schemes, and each scheme is used to classify the routing protocol according to topology based, communication model, network structure, and reliable routing [26]. Some routing protocols adhere to some requirements and resource-constraints nature of WMSNs to meet QoS in order to handle various types of multimedia and mixed traffic [45]. Designing multipath routing protocols for WMSNs requires additional research that extends the protocols proposed for WSNs [7]. Indeed there are several ways to classify multipath routing protocols depending on different parameters and factors such as reliability, latency, bandwidth, and load balancing [70]. One of these classification is based on number and type of QoS constraints of paths. The classes and sub-classes of classification are not mutually exclusive as many protocols belong to more than one class or subclass [70]. Hence, the main division of taxonomy is based on equal assignment of different functionality to the sensor nodes.

Reliability has emerged as a factor to classify multipath routing protocols, since a reliable monitoring of the environment is very important in a variety of multimedia applications [71]. However, we use the reliability factor to classify the routing protocols according to the QoS requirements of multimedia applications. As depicted in Fig. 6, multipath routing protocols can be classified into two main categories: concurrent multipath unicast forwarding and alternative multipath broadcast flooding. The first approach is based on sending multiple copies of same data packets over multipaths which increases the accuracy of various tracking in a variety of civilian and military applications [71]. The second approach is usually implemented by collecting or distributing information to all nodes in wireless domain by performing a broadcast operation. In our classification, the decision to route data over multipath depends on the mechanism of discovering and selecting a reliable path to meet certain objectives such as congestion minimization, and application constraints (throughput, delay, and bandwidth) as shown in Fig. 7. In particular, emphasizing path selection mechanisms for traffic flow to reduce the overhead, complexity of the multipath routing scheme, and to accommodate constraints on the selected paths [35]. Therefore, the classification of multipath routing protocols is based on the way routing paths are established during the path discovery phase and the way routing paths are selected to distribute the traffic under specific constraints. To successfully achieve the applications requirements, multipath routing protocols may use the characteristics of the two methods of

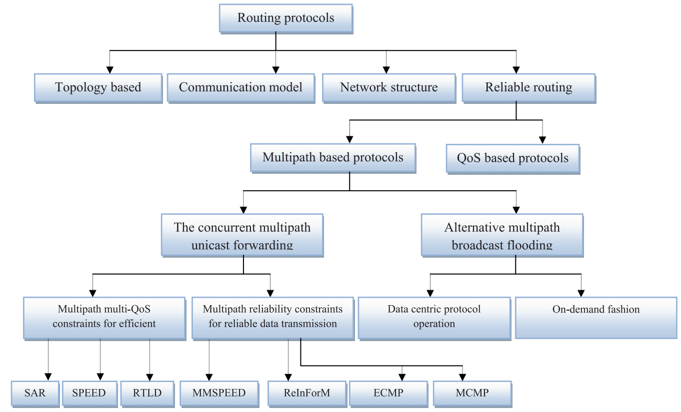


Fig. 6. The taxonomy of multipath routing protocols.

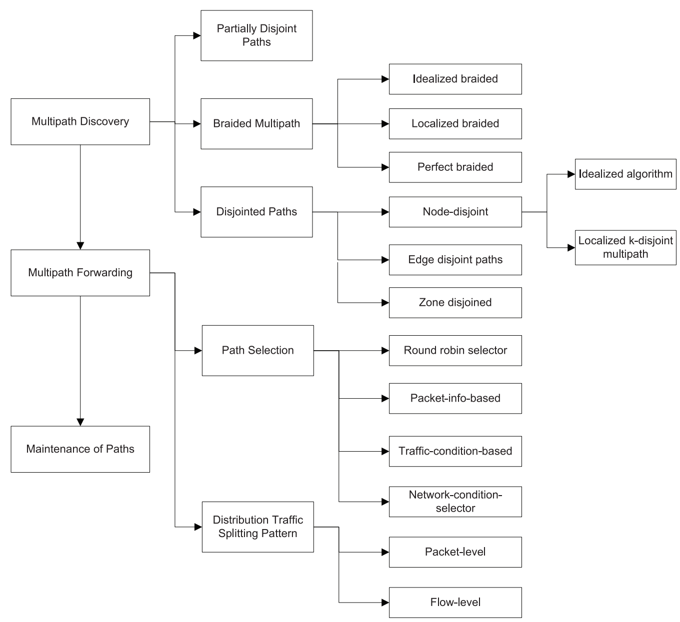


Fig. 7. Taxonomy for the design of a multipath routing protocol.

classification to govern the performance of WMSNs in terms of QoS parameters and energy efficiency.

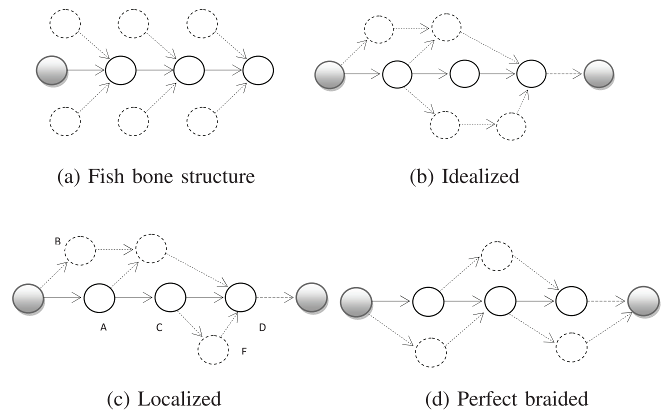
Both taxonomies are complementary and suitable for meeting the requirements of WMSNs. They describe the determination of the availability of multiple paths as well as the distribution of traffic under multi-constraints and reliability. Figure 6 depicts the breakdown of the second-level of the taxonomy of multipath routing protocols that will be enumerated in the subsequent sections.

C. Summary

Routing governs the performance of WMSNs in terms of QoS metrics. The design of a routing algorithm depends on several parameters that must accommodate multiple conflicting objectives and constraints, imposed by strategies on technologies and user requirements. Multipath routing is a promising strategy for achieving QoS metrics such as bandwidth, delay, and throughput as well as demands of the users. Several WMSN routing protocols have been proposed based on classifications that depend on different factors and on the users' requirements. We use the reliability factor to classify such routing protocols and to describe the benefits of multipath routing protocols according to QoS requirements in multimedia applications.

V. MULTIPATH ROUTING PROTOCOLS: CHALLENGES AND ISSUES

Multimedia applications encompass monitoring of real-life events which necessitates that efficient multipath routing mechanism should be developed for the transmission of information while meeting QoS requirements [45]. The QoS requirements are expressed as a combination of QoS parameters of multipath [72]. Thus, different multimedia applications have different QoS requirements and multipath routing protocols in WSNs or WMSNs have their own unique advantages and disadvantages [60]–[62]. Consequently, it is a challenge to find or design an appropriate protocol or a class of protocols that fulfill all QoS requirements of an efficient routing protocol [9]. Furthermore, real-time multimedia applications encounter an additional challenge for energy-efficient multimedia processing [70]. Certainly these challenges include optimal routing to meet the dynamic network constraints and application-specific QoS guarantees. In response to this challenge, particular QoS requirements require information of current status of the network as well as resource constraints since routing decisions are made based on these information [35]. For example, in certain applications a multipath routing algorithm may select a set of node-disjoint paths with relaxation of node-disjointness. This is referred to as a set of partially disjoint paths, or braided multipath, i.e., link disjoint. For each node in the primary path, an optimally selected alternative path may not have any computed node in common. However, these kind of alternative paths could potentially have comparable latency to the primary path, and therefore, expend more or less same amount of energy as the primary [35]. Nevertheless, both link/node-disjoint paths improve the reliability and offer more aggregate bandwidth than non-disjoint due to bottleneck link/node failure for non-disjoint paths which negatively impacts the performance of multipath routing [71].



(a) Fish bone structure (b) Idealized

(c) Localized (d) Perfect braided

Fig. 8. Construction of partially disjoint paths and braided multipath.

Many researchers seek to discover and select reliable paths by finding node-disjoint as well as link-disjoint path. These algorithms do not take into consideration QoS parameters. However, successfully meeting certain objectives like QoS requirements and congestion minimization might require a global view of the network topology as well as it resources [73]. It should be noted that, they are difficult to measure and generally can generate high overhead in networks [60], since resource availability information are periodically exchanged among nodes [35]. Other multipath routing protocols can aid in saving batteries by distributing network traffic uniformly among the sensor nodes; however, they increase the delay per packet transmission along the longer selected paths [74]. Many multipath constructing strategies have been proposed in the literature [60]–[62] to describe the performance of multipath routing protocol by the number and quality of selected paths. These constructions can be broadly classified into multipath discovery, forwarding and maintenance [8]. Figure 7 illustrates the components and issues related to constructing multipath routes under the three categories discussed in this survey.

A. Multipath Discovery

As mentioned in Section III-G, the pattern of data traffic in WSNs can be either single-hop or multihop. Therefore, the main task in multihop communication is to determine a set of intermediate nodes that should be selected [16].

Figure 8 illustrates the construction of partially disjoint paths and braided multipath after the route discovery mechanism to create several paths from the source to the sink.

Obviously, designing a multipath routing protocol is more challenging than single path routing due to the difficulty in finding the number of paths with a desired property in an effective and efficient manner. Furthermore, non-disjoint or single paths are easy to discover due to the absence of constraints on common nodes and links with any loop-free paths. Typically, this construction depends on many parameters to make the right routing decisions. Among these parameters is the extension of the unicast path to the multipath unicast path, which in turn depends on the amount of path disjointedness and is considered the main criterion used to utilize existing routing multipaths [13], [60]–[62]. The performance of multipath discovery mechanisms depends on the number and quality of discovered paths, which in turn depends on the availability of network resources at intermediate paths, characteristics of paths and QoS requirements [35]. There are various multipath routing discovery mechanisms, as illustrated in Fig. 8 and are summarized below.

1) Partially Disjoint Paths: This mechanism is used to improve single-path routing protocols by providing a group of multiple alternative paths that are not simultaneously used in a large dense area [63], [64]. Basically, the discovery mechanism takes advantage of the broadcast nature where nodes overhead packets are transmitted by their neighbors. Once the overheard packet arrive, a unicast route reply message is transmitted by the node's neighbor, and records that neighbor as the next hop to the sink in its alternate route table [63], [64]. Therefore, multipath routing mechanism is able to discover a primary path with an alternate path that looks like a fish bone (see Fig. 8a). The pattern of data traffic selects one of these discovered multiple paths at a time, whereas others are kept as a backup in case the path used becomes broken. However, if all discovered multiple paths are broken, then a new multipath discovery procedure is initiated. Typically, this mechanism is used to improve the reliability of data delivery and helps to reduce the overheard communication and end-to-end delay.

2) Braided Multipath: Also referred to as Meshed-Multipath [73]. This mechanism is slightly different than the partially disjoint paths in that it increases resilience to node failure along with longer alternate node-disjoint paths. Because of some attractive resilience of partially disjoint path properties, more energy can be expended than that expended on the primary path.

Generally, there exists many possible definitions for data dissemination in the braided multipath mechanism. Therefore, a constructive definition for the braided multipath mechanism follows the directed diffusion paradigm that can be divided into three techniques [73]:

(a) Idealized braided: For each node on the primary path, the gradient is computed to determine preferred neighbor to find the best path from the source to sink that does not contain that node. This results in a set of braided paths that either lie on the primary path or geographically close to the primary path as illustrated in Fig. 8b.

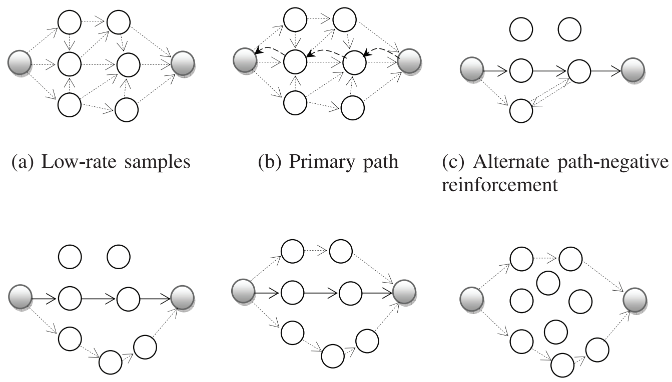
(b) Localized braided: The braided multipath technique relaxes the requirements like the idealized braided algorithm for node disjointedness of the complete multipath [73]. This technique uses two types of path reinforcement messages instead of finding a small number of alternate paths that depend on some localized techniques to construct braids at each node along the primary path. This technique can be briefly described as follows. The procedure initializes the sink to originate a primary path reinforcement message to the next preferred neighbor B as illustrated in Fig. 8c. Once an intermediate node C has received the primary path reinforcement, it will transmit the primary path reinforcement to its next preferred neighbor D. Thus, the constructed path traversed by the primary path reinforcement forms the primary path. In addition, the forwarding operation for each node C lies on the primary path, which also initiates a primary path reinforcement message to the next preferred neighbor E. Once a node is not on the primary path, it will receive alternate path reinforcement, and it forwards to its next preferred neighbor. Otherwise, if a node is on the primary path, it stops the propagation of the alternate path reinforcement. The multipath structure formed by this technique is illustrated in Fig. 8c.

(c) Perfect braided: This technique achieves greater resilience of the primary braided path by generating a combination among the various alternate paths with failures on the primary path. For example, in Fig. 8d, the number of distinct alternate paths is proportional to the n^{th} Fibonacci number, where n is defined as the number of nodes on the primary braid path [73].

3) Disjoint Paths: This method is considered more attractive in many multipath routing applications because of the independence of the paths. Many multipath routing algorithms and protocols have been proposed to find disjoint paths in WSNs [9]. There are three types of disjoint paths: node-disjoint, edge disjoint, and zone-disjoint. Clearly, both node-disjoint and edge disjoint are the same, and improve performance in terms of reliability [73].

(a) Node-disjoint paths: This technique is of particular interest in many applications because of the independence and resilience provided by a number of alternate paths constructed within the primary path and also with each other. These discovered paths are unaffected by failures on the primary path but can potentially be less desirable than the primary path. This technique for constructing multipath-disjoint nodes can be divided depending on the global knowledge of topology and network characteristics into two types:

(1) Idealized algorithm: This algorithm uses two types of reinforcements. It initiates low-rate scenario as seen in Fig. 9a with a flooded network. Then, the sink has enough empirical information to determine a neighbor that can provide QoS metrics to send out primary-path reinforcement as illustrated in Fig. 9b. Once the sink starts receiving data along with the primary path, the sink propagates the alternate path reinforcement to its next most preferred neighbor A. This neighbor A continues the propagation in the same direction of the source to its most preferred neighbor B. If B is already on the primary path between the source and sink, it sends a negative reinforcement to A (Fig. 9c). Then A selects B as the next best preferred neighbor. Otherwise, B propagates



(a) Low-rate samples (b) Primary path (c) Alternate path-negative reinforcement

(d) Alternative path P1 (e) Caveat (f) Zone-disjoint paths

Fig. 9. Illustrating the discovery of multipath mechanism.

the alternate path reinforcement to its most preferred neighbor (Fig. 9d).

(2) Localized k-disjoint multipath: The idealized algorithm mechanism can be extended to construct k-disjoint multipath by sending out separated k-alternate path reinforcements from the sink to each next preferred neighbor. Fig. 9e depicts the localized algorithm and the differences with an idealized algorithm that accounts for some performance for the discovery of the first alternate path.

(b) Edge-disjoint paths: This technique uses more specific, on-demand routing protocols. It is also called diversity injection and is used to find multiple disjoint paths between source and sink [73]. Generally, the procedure of route discovery of an on-demand routing protocols is initialized by broadcast route query messages by every node in the network. Once intermediates receive the messages, they only respond to the first received route query and discard the duplicate queries. Edge-disjoint attempts to reclaim the dropped information contained in the duplicate messages by recording, in a temporary query cache, the accumulated route information contained in all received route query messages. Because of the route query messages are only forwarded at each node, the received route messages at a node traverses various paths. By claiming the path information, a node acquires the reinforced route information back to the source.

(c) Zone-disjoined paths: This technique defines an unselected path that has no shared nodes nor edges with another path. Moreover, it cannot be within the interference range of the discovered paths, as shown in Fig. 9f.

(d) Totally disjoint multipath: The set of distinct paths that are zero-edge connected when concurrent data transmission takes place. Hence, the discovered multipath does not interfere which is referred to as totally disjoint paths [73].

(e) Maximally disjoint multipath: This refers to a set of node-disjoint paths that maximizes a disjoint characteristic among all possible paths, while keeping common nodes at a minimum.

(f) Radio disjoint multipath: The set of available paths with minimum radio interference, or the multiple non-interfering paths that are used to reduce the effect of interference between nodes as far as possible.

Due to QoS constraints, different resource limitations, and multimedia source coding techniques in WMSNs, the amount of disjoined multipaths is considered as a fundamental challenge that should be taken into account when discovering a group of multipaths that may not be constructed of high-capacity paths.

The question is how can forwarding path groups being selected to discover multiple paths without considering energy consumption and satisfying the QoS metrics along with the selected path? To answer such a question, it is necessary to define the problems associated with real-time support and reliability in wireless sensor applications.

Many routing protocols have been proposed [37]. One proposal is to select the number of optimal paths. Others just select the optimal path and maintain backup paths for the fault tolerance problem. Therefore, the operation of the selected paths is considered for better various QoS parameters [8].

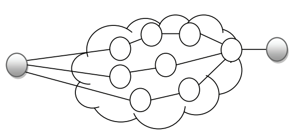
B. Multipath Forwarding Models

A multipath forwarding model consists of two main components that are also important for load distribution: the selection path and distribution traffic splitting pattern, as illustrated in Fig. 10 [1]. Various multipath forwarding models perform load traffic distribution in a different manner because of the difference in their internal functions of path selection and the distribution of traffic splitting pattern, which may exhibit different advantages and shortcomings [1]. The multipath forwarding is among the contribution of this survey and is intended to assist the readers in understanding the different types of path selection mechanisms, and traffic units. Figure 10 illustrates examples of various multipath forwarding mechanisms.

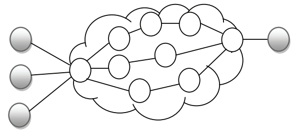
1) Path Selection: The selection of an adequate number of paths is considered a second important issue after the construction of multiple paths for data transmission purposes. Path selection for each multipath routing protocol is independently determined and should be selected to meet the performance demands of WMSNs applications [1], [13]. Most path selection schemes can be categorized into four types according to the purpose of designing a higher performance multipath routing protocol that selects a sufficient number of paths.

(a) Round robin selector: The definition of this scheme is the successive traffic units that are sent across all parallel paths in a round robin manner.

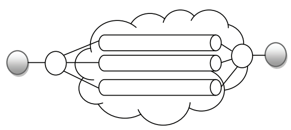
(b) Packet-info-based: The path selection determines the packet identifier that is stored as information in the packet header of the arriving packet. The path



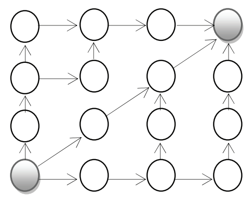
(a) multipath routing at source node with multiple intermediate nodes



(b) multipath routing at multiple sources nodes with multiple intermediate node



(c) multipath routing over multiple pipe streaming links



(d) multipath routing over wireless mesh, ad-hoc or sensor networks

Fig. 10. Various multipath forward configurations.

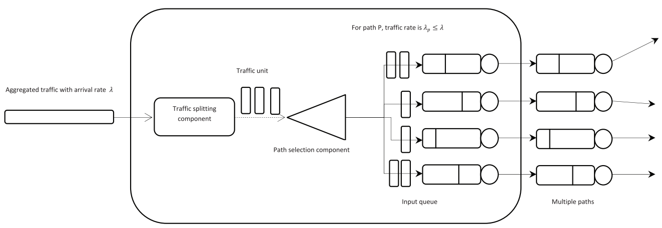


Fig. 11. Multipath forwarding mechanism [75].

selection is determined on the basis of the outcome of function identifier.

(c) Traffic-condition-based selector: The selection of the path depends on the conditions of traffic distribution such as traffic load, traffic rate, traffic volume, and number of data active flows.

(d) Network-condition-selector: The key to this selection is improving network performance such as throughput, delay, lifetime etc. Hence, to improve resources utilization over the selected paths, the injected traffic rates of these selected paths are computed according to the path capacity such as queue length.

2) Distribution Traffics Splitting Pattern: Suppose a group of multiple paths is selected, and then other issues arise such as how a source node should transmit a packet. The source may split a packet into multiple segments, and then transmits these segments by different multiple paths, or it may duplicate copies of packets using different multiple paths. There are two relevant aspects of an allocation strategy: granularity and scheduling [16], [34]. The granularity specifies the smallest unit of information allocated to each path as seen in Fig. 11 [75]:

(a) Per source-destination pair: based on using the same path to forward all traffic belonging to a certain pair of source and destination nodes.

(b) Per-connection: based on allocating all traffic for the same connection to a single path.

(c) Per-packet (packet-level): based on distributing the packets from multiple connections among the existing paths.

(d) Per-segment (flow-level): based on splitting a packet into segments; each segment is forwarded using a different path

C. Maintenance of Paths

In most multipath schemes, the source periodically floods the low-data rate alternate paths. To process, maintenance phase reduces degraded multipath performance due to resource constraints with high dynamics of low-power wireless links of WSN. The main task of paths maintenance in multipath routing protocols is to permit fast recovery from failures on the primary path. Three different situations are involved in this task:

(a) When the primary path has failed.

(b) When all discovered primary paths have failed.

(c) When some of the discovered primary paths have failed.

In the first approach, the frequency of overall low-rate data flooding of paths to recover from failures on the primary path causes latency and a high overhead. Moreover, the discontinuity of a route re-discovery mechanism until failure of all active paths may increases energy consumption and reduce network performance. The third approach is more interesting than the others since it represents a trade-off between energy expenses and the likelihood of total multipath failure [13], [76].

D. Summary

The design of multipath routing protocols for WMSNs is crucial for the provision of QoS. This sparking opportunity has posed new challenges since many tradeoffs need to be considered. Firstly, ensuring reliable and energy efficient end-to-end multipaths to transmit data. Secondly, the large number of available paths combined with multiple paths for each increases the cost of route processing for path selection. It should be noted that the processing and exchanging of information among the different layers of WMSNs impedes the performance of communication.

The challenges associated with design issues for WMSN routing protocols come from all sorts of the functionalities of application areas such as military, health, and other application facilities to meet the QoS requirements. We can group these challenges under two main categories: reliability and timeliness assurance of multipath routing protocols.

VI. CONCURRENT MULTIPATH UNICAST FORWARDING

Unicast path routing protocol covers the construction of a sequence of single efficient quality links from the source to the sink, possibly over multiple hops, eventually providing the significance of the cost of a path. It is the same as the flat routing protocol operation, where each node collaborates with others to perform the task of constructing an optimal path that is called a simple flood operation.

The extension of unicast path to multipath unicast depends on the mechanism of construction, selection and distribution of the optimal n-paths between the source and the sink. This extension is classified into three main operations: discovery, selection and maintenance. In the operation of discovering paths from the source toward the destination, it is common to use dissemination approaches that can be easily adopted in WSNs.

A. Multipath Multi-QoS Constraints for Efficient Resource Allocation

Many researchers have focused on the network layer, as the multipath routing protocol has always played a crucial role in supporting these routing metrics. Many available protocols tackled these constraints, specifically QoS parameters with energy routing metric [77]. The following sub-sections address traditional end-to-end QoS assurances in various specific traffic patterns.

1) Principal Protocols of Multipath Multi-QoS Constraints: Concerning multipath multi-QoS constraints, there are several principal protocols utilized to achieve the multi-QoS constraints for efficient resource allocation.

Sequential Assignment Routing (SAR) was the first routing protocol developed for WSNs [78] in which QoS issues for making a routing decision were considered based on three factors: energy conservation, QoS parameters, and level of packet-priority in the traffic flow. These traffic types were applied through a given flow for each data packet with a constant priority and they remain unchanged until they reach the final destination. SAR uses a table-driven multipath approach that satisfies the QoS parameters, energy consumption, and fault tolerance. The disadvantage of SAR is that the creation mechanism of the multipath causes additional node energy depletion. Thus, it is not suitable for multimedia transmission.

The Stateless Protocol for Real-time Communications in Sensor Networks (SPEED) is considered the first protocol that envisioned soft real-time requirement under specified constraints [79], [80]. Its localization/geographical protocol provides guarantees to support QoS parameters for soft real-time traffic. It supports three types of data unicast, multicast, and anycast. SPEED maintains a desired delivery speed across the network through a novel combination of the non-deterministic QoS-aware of geographic forwarding and feedback control. This combination of MAC (single-hop) layer and network (multihop) layer adopts a cross-layer approach that improves the end-to-end delay transmission time and provides a good response to congestion and voids. However, the disadvantage is in the prolonged lifetime of the sensor node that is achieved by only the reduction of control packets and geographic routing without consideration of other energy metrics during the routing operation.

Energy Efficient SPEED (SPEEDEE) improves the network lifetime of the SPEED protocol by employing an optimization algorithm [81]. The protocol provides a protection for nodes with less energy to avoid their discharge and to provide the nodes with more energy in order to increase the lifetime of the network. The residual energy is calculated based on the algorithm reported in [82] and [83], whereas the delay is computed as in the SPEED protocol [79]. The disadvantage of this protocol is the adaptation of the selected path which may increase the overhead problem between the sensor nodes over a large-scale area.

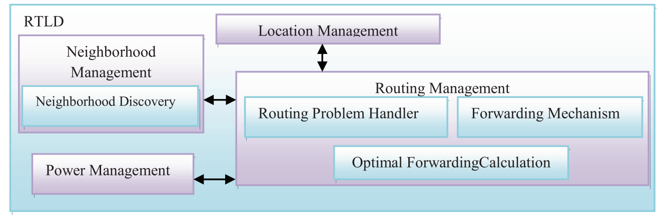


Fig. 12. Block diagram of RTLD routing protocol.

Real-Time and Energy Aware QoS Routing (REAR). This routing protocol has been applied to WMSNs using an advanced Dijkstra algorithm to evaluate the structure of a multipath mechanism and chooses the neighboring distance from node $\imath$ and node $\jmath$ amid all paths to send real data [84]. To reduce queue delay for real-time event packets, a classifier queue model is used for each node to deal with real-time and ordinary data and to balance the network life-cycle. The disadvantage of this protocol is the complexity overhead in creating the multipath algorithm because of the parameters that are associated with each path.

Real-Time with Load Disturbed Routing (RTLD). This routing protocol computes the optimal forwarding hop based on three metrics: link packet reception rate (PRR), residual power of sensor's battery, and packet velocity per single-hop [85], [86]. The routing protocol consists of four functional components: power management, neighborhood management, location management, and routing management. Each component response to the specific management of sensor node is shown in Fig. 12 [69]. The routing management computes the optimal forwarding choice based on three parameters to choose the optimal forwarding: packet speed of moving packet through the hop, PRR and remaining power for every single-hop neighbors, and the delay from the source node to the single-hop neighbor. The disadvantage of this protocol is the elaboration of energy consumption profile for diverse levels of duty cycle of the sensor network, which is used to derive the trade-off between energy conservation and QoS.

Energy-Aware Delay-Constrained Routing: This is an energy-efficient routing scheme for WSNs that ensures low delay for data delivery in the network [87]. Considering transmission power, sensor's energy and the end-to-end delay as constraints, this approach sets up energy-aware multihop data paths. End-to-end delay is achieved by using a Weighted Fair Queuing (WFQ) scheduling technique in each sensor. In addition, leaky-bucket traffic-regulation techniques are utilized to regulate the incoming traffic from the sources and separate the real-time traffic from the non-real-time traffic by applying two different queues in each node. The disadvantage of this protocol is the WFQ which utilizes a highly complex approach for packet scheduling. Moreover, there is a need for tag computation and tag sorting at line speeds. This requirement presents a bottleneck problem that is not suitable for multimedia transmission.

QoS-Based Energy Efficient Routing (QuESt) was proposed in [88] using a multi-objective genetic algorithm that determines a set of nondominated near-optimal paths in a flat network topology (non-clustered). The algorithm satisfies application-specific QoS parameters, end-to-end delay, bandwidth requirements, and energy consumption in WSNs. To satisfy different QoS parameters, constraints for QoS-routing problem were mapped into a constrained Steiner-tree problem. Moreover, the proposed algorithm uses Euclidean distance to present two randomly selected paths from the population. Unfortunately, the Euclidean distance of the Steiner tree problem has proven to be a non-deterministic Polynomial-Hard problem (NP-Hard), with no currently known polynomial time algorithms.

Routing of High-Priority Packets was designed in [89] to suggest a real-time adaptive capability to identify unusual events in the presence of routine data traffic. The classification of the packet depends on whether the data in the packet differs significantly or not from the contents of the previous packet from the same source. The classification setting is either as normal (routine), that is, the same data from previous packets. Otherwise, the packet's content is very different from that of the previous packets, at which point the priority bit will be set to one to indicate an unusual state. The routing function decides the routes for the data packet with high priority. That is, if the incoming rate of the unusual packets is measured by a source node that is higher than a given traffic threshold value θ_U, then the source node chooses to forward all high-priority packets to the destination along the optimal QoS path. Otherwise, the high priority packet rate drops down the traffic measurements window, and the nodes re-route the packets to their destination along shorter paths. The disadvantage of this protocol is unsuitability of the mechanism of re-routing at a large scale given the complexity of the time-slice of the re-routing operation. In addition, the complexity overhead of the shortest-path algorithm during the creation/updating of the routing table at each round robin slice is increased.

Real-time Power-Aware Routing (RPAR) was proposed in [90] to address the main challenges of support for real-time communication. This protocol improves the number of packets delivered before deadlines with low energy cost. The authors assumed that all sensor nodes are stationary and know their location via the Global Position System (GPS). The proposed protocol was designed to work with existing simple Channel Sense Multi-Access/Collision Avoidance (CSMA/CA) asynchronous MAC protocols such as the X-MAC or B-MAC protocols. RPAR consists of four components: a dynamic velocity assignment policy, a delay estimator, forwarding policy and neighborhood manager. The disadvantage of this protocol is that the velocity increases exponentially for each packet as the one-hop distance increases but sharply decreases because of the degradation in link-quality. Unfortunately, increasing power transmission causes more contending nodes and higher collisions when nodes receive two overlapping packets. The location management requires the additional cost of GPS hardware to identify the node's location.

Enhancing Real-time Delivery with Two-Hop Information or Two-Hop Velocity-based Routing (THVR) for a real-time QoS protocol with improved energy utilization, the over one-hop-based protocol SPEED was proposed in [91]. The idea of using the information of two-hop routing is a tradeoff between performance improvement and complexity. The information exchange between two hops starts by sending the message HELLO to two intermediate sensor nodes. Then, each next node sends messages to all of its neighbors informing about the information of their one-hop neighbors. The disadvantage of this protocol is that it is limited only to two-hop information for optimal decision forwarding. The increase in complexity and overhead with an increasing number of hops is high. Moreover, whenever the number of hops has increased, it will give $O(n^4)$ time for improving the performance in energy consumption, where n is the number of nodes in network.

Self Organizing Network Survivability (SONS) routing protocol was proposed in [92] to monitor forest fire. It is an extension of [93] using hierarchical real-time QoS routing to provide survivability and data reliability. Multiple hop spanning trees were used to achieve a large coverage area. The weakness of SONS is the synchronization phase during spanning tree formation needed for dynamic power management which can experience a large number of collisions in areas with high node density.

Tasks Allocation for Real-Time Applications in Hierarchical Heterogeneous Networks has been proposed in [94]. The main objective is to find an optimal allocation that minimizes the overall energy consumption while meeting the application's deadline. The task allocation algorithm exploits the divide-and-conquer algorithm to efficiently solve the scheduling problem for large-scale allocation applications through four methods: task partition, deadlines distribution, scheduling and re-scheduling. A Markov decision process (MDP) is used as the decision modeling tool for solving the optimal scheduling problem. MDP helps to find the optimal policy for all possible states in the Markov diagram. The disadvantage of the protocol is its time complexity in both scheduling and re-scheduling and the computation of optimal policy for task allocation.

Disjointed Multipath Routing for Real-Time Data: A hybrid k-disjointed multipath routing protocol proposed in [95] for WMSNs. This protocol is based on a combination of the strengths of two transmission schemes: the Zigbee and Bluetooth. To effectively transmit multimedia data, the data of the source node are split through Zigbee to be transmitted to several neighboring nodes localized in a Bluetooth scatternet. Then, the protocol minimizes path setting overhead through a competition-based non-overlapping multipath for data transmission. The splitting mechanism has a First-In-First-Out (FIFO) pattern of transmission sequencing on individual paths to combine original multimedia data without sorting in the sink.

Some researchers proposed several multipath routing protocols for traffic load balancing and repartition [62], [96]–[98]. However, most of these protocols did not optimize the traffic load balance and repartition against all selected paths and even according to the resource limitations of WMSN [2].

Therefore, according to the characteristics of WMSNs with the expected network lifetime, Xie and Gu [99] proposed a node disjoint design that emphasizes limited energy to maximize the data gathering performance. The proposed algorithm is composed of two phases. The first phase determines the set of multiple paths and finds the node disjoint path. The second phase selects paths from the set of multiple paths based on load balancing to balance the load in the network. Consequently, the bandwidth is utilized efficiently via a new congestion control message. A gradual increase strategy based on paths and a gradual increase strategy based on flows are introduced. This routing algorithm is a proactive routing protocol because it picks alternate node disjoint paths from the routing table. However, it fails to note how the multiple node disjoint paths are identified between the source and the sink. The traffic is equally distributed among the multiple paths. This mechanism is feasible for resource constrained networks such as multimedia sensor networks.

The multipath routing protocol has been explored to increase the probability of reliable data delivery that is appropriate for WMSNs. Therefore, the **Energy Balancing Multipath Routing (EBMR)** in [100] is proposed as a node-disjoint routing protocol based on the node's residual energy and distance between the node and the sink. The protocol is composed of two phases. First, to find the multiple node-disjoint routing paths from the source to the sink while excluding the source node. Second, the next hop selection mechanism allows common sensor nodes to more evenly consume energy. This leads to an increase in the performance of EBMR in energy balancing and network lifetime, respectively, by calculating the cost function value. More precisely, the current node selects its neighboring nodes, whose cost function value is as small as the next hop node. The cost function considers not only the distance between the selected node and the sink but also the neighbor node's residual energy. However, when the neighbor node's energy is less than the mean residual energy of the neighbor set, its cost function is added. Otherwise, its cost function value is subtracted.

Agrakhed *et al.* [101] presented an inter-cluster based on an **Adaptive Multi-Constraint Multipath Routing (AMPMCR)** to decrease loss rate, energy consumption, and delay with the help of link quality. The cost function between the links is calculated using the delay, loss rate and remaining energy. Initially, a cluster-based architecture is constructed for the WSN in which the cluster-head is determined based on energy level and capacity. However, a cluster based architecture is considered where inter cluster routing is performed based on a weight cost function. During routing, the cluster head in each level of clustering selects its higher level cluster with a cost function value. The nodes that are not part of routing are placed in sleep mode to save energy. Simulation results display several advantages in terms of a lower delay and higher delivery ratio than other QoS protocols, and decreased number of dropped packets.

The major challenge in WMSNs is the transmission of video. Because of the large data size, video transmission consumes the node's energy. Moreover, conventional routing finds a relatively shorter path between the source and the sink, however this approach is unviable for multimedia applications. To solve the problem, a cross-layer and multipath routing based video transmission scheme (CMVT) reported in [77] presents the idea of differentiated service and multipath routing operating in both the application layer and network layer. Through collaboration between the application and network layers, CMVT combines the advantages of differentiated service and multipath routing to provide different paths for different applications. The combination starts from the application layer, which is responsible for video gathering and encoding frames and then distinguishing them according to their importance by marking them with different tags. Once they arrive at the network layer that was considered as the core of CMVT, the routing protocol assigns them to different paths, and all of the important frames are guaranteed with reliable paths. CMVT has an obvious superiority in media transmission, especially in large-scale WMSNs.

Interference information can be used not only to determine the routing path conditions but also to establish the new routing path. Reference [102] proposes a novel **Interference-Aware Multipath Routing for Video Delivery (IAMVD)** in the realm of WMSNs. The proposed routing algorithm discovers two node-disjoint, interference-minimized paths for a single pair of the source nodes and the sink. Then, the routing mechanism is performed without any special hardware support for localization, making it practical for resource-constrained WMSNs. IAMVD uses a sleeping mechanism to create a block area of nodes preventing additional energy consumption. Moreover, the effects of different QoS requirements for multi-priority packets is considered in the process of path construction and video transmission by dedicating various multiple paths to various priorities.

2) Discussion: There are many research challenges when using WSNs in real-world interactions because of constraints imposed by energy consumption and unreliable wireless channels. Moreover, other QoS constraints that may also be important for particular applications, such as security, density deployment overlap should be considered too at the different layers of the protocol stack. Although a few studies focusing on supporting QoS constraints in WMSNs have been reported [95], [100], [101], [102]. There are several interesting studies regarding supporting QoS of real-time applications [78], [80], [81], [84]–[92]. These studies proposed different mechanisms and protocols for the different layers of the network protocol stack to enforce QoS metrics since access to information from lower layers and from higher layers may be required. Nearly, all of these mechanisms have been developed and tested with various network simulators such as network simulator-2, and omnetpp [78], [79], [84].

Because supporting multi-constrained QoS parameters in WMSNs is affected by design choices at the various layers such as physical, medium access, and network, the multipath strategy provides an integrated approach to manage QoSs. The multipath strategy is in the right direction when sensor operations are involved in real world as long as the strategy provides reliable communication and load balancing for deadlines associated with end-to-end routing. The multipath routing strategy should be designed with a tradeoff between energy

TABLE IV
COMPARISON OF MULTIPATH UNICAST FORWARDING QoS CONSTRAINTS FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

Routing Protocol	Scalability	Energy Efficiency	Reliability	Network Topology	Data Delivery Model	Network Dynamic	Resources Reservation	Data Aggregation	QoS	Localization
SAR[85]	Restricted	High	Restricted	Flat	Query driven	†	†	†	†	
SPEED[86],[87]	Restricted	Low	Restricted	Geo.	Query driven	†			†	
EE-SPEED[88]	High	High	Restricted	Flat	Hybrid	†			†	
REAR[91]	Restricted	High	Restricted	Flat	Geographic	†			†	
RTLD[92],[93]‡	High	High	Restricted	Flat	Query driven	†	†		†	
EADR[94]	High	High	Restricted	Hierarch	Query driven	†	†	†	†	
QuESt[95]	Moderate	High	Moderate	Tree	Query driven		†	†	†	
RRR[96]	Restricted	Moderate	High	Tree	Event driven	†	†	†		
RPAR[97]	High	High	High	Flat	Query driven	†	†		†	†
THVR[98]	Restricted	High	High	Flat	Query driven	†	†		†	
SONS[99]	High	High	Restricted	Hierarch.	Event driven	†	†	†	†	†
TAP[101]	Restricted	Moderate	Restricted	Flat	Query driven	†	†			
Disjointed Multipath routing protocol[102]	Restricted	High	Restricted	Ring	Hybrid	†	†		†	†
EBMR[108]	Restricted	High	Moderate	Flat	Event driven	†	†	†	†	†
AMPMCR[109]	Restricted	High	Restricted	Flat	Hybrid	†	†	†	†	†
IAMVD[111]	Restricted	High	Moderate	Flat	Hybrid	†	†	†	†	†

‡:All protocols satisfy the soft real-time QoS constraints; however, the RTLD protocol satisfies both hard/soft real-time QoS constraints

TABLE V
SUMMARY OF MULTIPATH MECHANISM FOR UNICAST FORWARDING QoS CONSTRAINTS FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

Routing Protocol	Path Disjointedness	Number of Paths	Path Selection	Traffic Distribution	Path Maintenance
SAR[85]	partially disjoint	based on the desired reliable tree	sink	traffic-condition-base-selector	discover new path
SPEED[86],[87]	partially disjoint	based on the desired reliability discovered paths	source and intermediate nodes	packet-info-based	discover new path
EE-SPEED[88]	partially disjoint	based on the desired reliability discovered paths	source and intermediate nodes	packet-info-based	discover new path
REAR[91]	braided multipath	based on the desired reliability discovered paths	sink	traffic-condition-base-selector	discover new path
RTLD[92],[93]	localized braided	based on the desired reliability discovered paths	source and intermediate nodes	network-condition-selector	discover new path
EADR[94]	path disjointedness	based on the desired reliability discovered paths	sink	traffic-condition-based-selector	discover new path
QuESt[95]	disjoint paths	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path
RRR[96]	node-disjoint paths	based on the desired reliable routing function	source	packet-info-based	discover new path
RPAR[97]	perfect braided	based on the desired reliable discovered path	source	traffic-condition-based-selector	discover new path
THVR[98]	node-disjoint	based on the desired reliable routing discovered path	source and intermediate nodes	traffic-condition-based-selector	discover new path
SONS[99]	idealized algorithm-node-disjoint	based on the desired reliable tree	source and intermediate nodes	network-condition-based-selector	discover new path
TAP[101]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path
Disjointed Multipath routing protocol[102]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path
EBMR[108]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path
AMPMCR[109]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path
IAMVD[111]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	discover new path

efficiency and multi-constrained QoS parameters to guarantee an efficient usage of the amount of energy available at each sensor node and to achieve an efficient resource allocation. The design of multipath routing protocols depends on the load distribution forwarding models, which involves dynamic traffic engineering to exploit the multiple paths discovered that facilitate network provision to facilitate high-quality network services and to guarantee multi-constrained QoSs. Because it provides load balancing, without dynamic loading, traffic engineering may heavily incur use of the multipath routing. Therefore, designing a multipath routing strategy configuration for forwarding multimedia data in a sensor network should be engineered by traffic splitting and the mechanism of path selection in heterogeneous traffic environment. This approach is used by several QoS routing algorithms to compute multi-constrained multiple paths by trading between the optimality of the multipaths and the complexity of the load distribution forwarding model [84]–[92].

A multipath mechanism is pursued to develop routing solutions that also comply with QoS constraints in the design methods. Tables IV and V depict a comparison among the aforementioned multipath unicast forwarding routing protocols for real-time issues on the basis of QoS constraints, data delivery, network architecture and other parameters.

Most reported routing protocols did not address the computational complexity and lack an analytical load distribution model for the network performance because of the multi-constrained QoS parameters that are faced with time complexity and/or space complexity.

This section concludes that a multipath routing approach should formulate the problem of finding a path subject to additive/multiplicative multi-constraints of QoS routing in an analytical way. The model then provides a routing protocol for dynamic traffic engineering that implements capacity provision based on the distribution of end-to-end QoS parameters using different optimization approaches.

B. Multipath Reliability Constraint for Reliable Data Transmission

In many contemporary applications, both real-time and reliability characteristics are essential. Reliability is a real challenge in WSNs as the nodes are exposed to many failure modes because of hardware failure, energy depletion, and communication link errors [2], [8]. Furthermore, each failure mode decreases the performance of the network.

In WMSN, reliability exists at many layers, such as a software layer, hardware layer, communication link layer, applications layer, and even at the network layer. At the network layer, reliability implies that the routing protocol provides fault tolerance by increasing the probability of a data packet sent by a source node, via alternatives of selected paths, arriving at the destination sink with minimum packet loss [13]. Any real-time application over WSN should consider resource constraints, global time varying network performance, and communication reliability [103].

1) Principal Protocols for Multipath Reliability Constraint: As far as multipath reliability constraint is concerned, there are several principal protocols that are utilized to achieve reliable data transmission.

Multipath Multi-SPEED (MMSPEED) [104] is the extension of the SPEED protocol. The MMSPEED routing protocol provides several improvements and modifications to guarantee QoS parameters in WSNs over the network and MAC layers. First, a packet data delivery mechanism that provides QoS differentiation in two quality domains, timeliness and reliability,

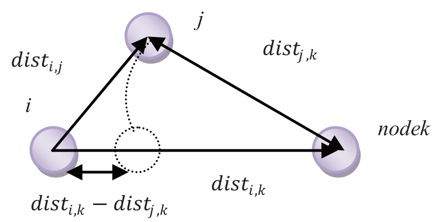


Fig. 13. Progress speed between two intermediate nodes.

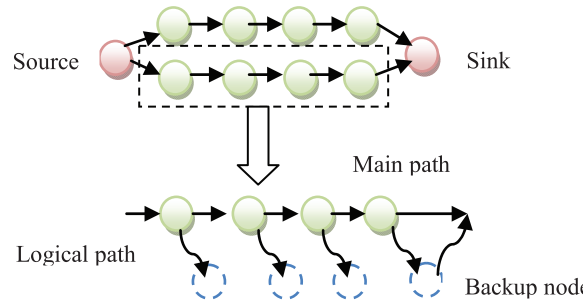


Fig. 14. NC-RMR topology.

is proposed. Second, an end-to-end QoS reliability according to the local decisions for each intermediate sensor node is proposed. This end-to-end QoS reliability is considered an important property for large-scale sensor networks. The timeliness domain provides a classifier from various traffic types to classify the multiple network-wide speed options for processing the packet. Classifying works properly by choosing the speed options depending on the data packet deadlines as shown in Fig. 13. The disadvantage is that the protocol is not compatible with large-scale, long-distance transmission as the time estimation of reachabilities of the nodes increases exponentially with respect to the hop distance between the current neighborhood and the sink.

Reliable Information Forwarding Multiple Paths (ReInForM) protocol in [105] employs a probabilistic flooding to deliver information awareness packet and service at the desired priority levels of reliability at a proportional cost for sensor networks through dynamic and randomized multipath forwarding mechanism to forward multiple copies of the same information packet in multipath routing according to the decision of the source to route the packets towards the sink. The routing mechanism is based on the local knowledge of network conditions such as channel errors, hops counting to sink, and out-degree. Information on network conditions is stored in the head of the packets header without requiring any data caching at any sensor node by using the dynamic packet state (DPS) method that causes an increase in the probability of information delivery. The disadvantage of the protocol is the duplication of packets that might cause a high cost of energy consumption and occupying a useful channel bandwidth utilization.

Network Coding-Reliable Multipath Routing (NC-RMR) protocol for WSNs was presented in [106]. The NC-RMR protocol employs computations of paths and next-hop node selection as in the ReInForM protocol, with differences from ReInForM being shown in Fig. 14. The first difference is avoiding the redundancy of packet copies. NC-RMR applies the network coding mechanism in delivering packets through a multipath from the source to the sink. Second, to increase the level of reliability, the NC-RMR protocol employs a hop-to-hop mechanism to establish a disjointed and braided multipath routing protocol. Third the NC-RMR protocol includes load balancing by the braided multipath and optimal next hop-to hop node selection. Fourth, the security analysis is based on the coding division of an initial message into partitions and then combines the coding partitions at the intermediate nodes. The disadvantage is that although node-disjoint multipath routing conserves energy, the path selection may yield more hops to reach the destination. Conversely, NC-RMR saves around 67% in maintenance and complexity of overhead problems, which provides 50% higher resilience to node failure.

Energy Efficient Reliable Multipath Routing (EERMR) protocol for data gathering was proposed in [107] for WSNs. This protocol achieves a reliable transmission with low energy consumption by utilizing the energy of intermediate nodes to gather and distribute data to the sink, based on their requirements. The authors propose a heuristic algorithm, the energy efficient multipath tree construction, to maximize the minimum residual energy among the nodes. The packet dispersion mechanism is used for splitting data packets at the source into segments and distributes them on multiple parallel paths to reduce the packet loss. The packets are re-assembled and aggregated at the destination. The disadvantage of the protocol is that it is suitable only for large-scale areas, as the greedy algorithm suffers from high computational complexity. Moreover, the greedy algorithm fails sometimes to find the optimal local solution, therefore it might produce the worst possible solution.

Dynamical Jumping Real-Time Fault-Tolerant (DMRF) routing protocol was proposed in [108]. DMRF protocol focuses on reliability at the network layer and attempts to reduce the effect of the sensor node failure from the empty congestion area in the network domain to guarantee real-time performance. DMRF assumes that the node uses the remaining transmission time of each sensor for the packets, and then the state of the candidate node in the forwarding path dynamically selects the next hop through a constrained transmission interval. Discarding data packets due to sensor node failure might cause wastage of transmission energy. To avoid energy waste, the DMRF protocol proposes that the transmission mode be set to jump in a way to reduce the transmission time as shown in Fig. 15. Based on the feedback from downstream node, every node adjusts the jumping probabilities to raise the ratio of successful transmissions. The disadvantage of the DMRF is the dynamic jumping which continues in a large-scale area in order to select the next hop that might lead to an increase in energy cost. Therefore, the whole network lifetime cannot be prolonged.

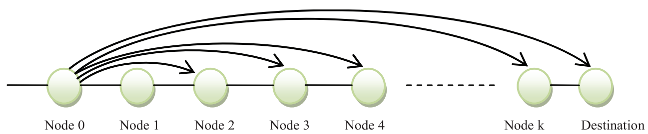


Fig. 15. Jumping transmission.

Self-Organizing and Collaborative Energy-Efficient Sensor Networks was developed from a study that was a part of the European Education Youth Environment Susbtainability (EYES) project (IST-2001-34734) on self-organizing and collaborative energy-efficient sensor networks [93]. The proposal of an approach that ensures gathering of information at the sink as sensor nodes may not be available during the procedure as reported in [109]. The algorithm begins with discovering k-multiple paths from the source to the destination. Calculation of these paths is based on the reputation coefficient of the nodes using the Bernoulli-distributed parameter. If a node has a low reputation coefficient, that is, frequently fails to route the packets, then it should be avoided in the routing scheme. The reputation coefficient increases with each successfully routed packet. Forward error correcting codes (FECC) are used to split the original data packet into sub-packets and allow the re-construction of the original message by adding the redundancy.

Quality of Service Multipath Routing (QoSMR) protocol proposed in [110] considers only reliability as the constraint without tackling the delay constraint. The QoSMRP is an extension of Secure and Energy-Efficient Multipath Routing (SEEMR) [111]. QoSMRP starts with the same adoption mechanisms as SEEMR with topology construction. To guarantee the reliability constraint, QoSMRP uses two mechanisms to reduce collision that occurs when the source nodes send data packets to the sink node at the same time. First, a query seeks specific data through a simple flood; then the sink finds the paths after receiving a reply from the sensor nodes that match the flood query. Second, if no disjoint paths are available, then the sink schedules the data transmission of each source node. To avoid having the sharing nodes instantaneously receive plenty of packets from multiple source nodes, the revised Breadth First Search (BFS) algorithm is used for searching and re-scheduling individual paths for other different sensor nodes if there are no disjoint multipaths available. The disadvantage of this protocol is the space and time complexity for topology during search and re-scheduling. The space complexity is expressed as $O(|V|)$, where V is the number of available multiple paths, while $(|V|^2)$ is the time required for searching independent braided multipaths for different source nodes.

Multi-Constrained QoS MultiPath (MCMP) [112] focuses on providing soft-End-to-End (soft-E2E) QoS (reliability and delay) in multipath routing using an analytical formulation. In MCMP, the end-to-end soft QoS problem has been formulated rigorously using stochastic programming. The interpretation of the scheme is based on a combination of resources of multiple paths for traffic flow. The delay constraint, denoted as d_1 associated with data packet delivery is considered. If there is no single feasible path for satisfying reliability, r_1 multipath routing can improve it. The probabilistic delay-reliability constraints problems $\forall path \in P(Source, Destination)$, is expressed as

$$min \sum_{j=1}^{P} x_j \tag{1}$$

Then the first constraint is

$$x_j * d_j \leq Delay \tag{2}$$

The second constraint is

$$r = 1 - \prod_{j=1}^{P} 1 - x_j * r_j \geq Reliability \tag{3}$$

where $x_j = 0$ or 1 for all $j = 1, 2, \ldots, P$ x_j is defined as the decision variable, whether the selected route is j or not. Many other constraints are assembled to increase the energy efficiency of multipath routing. For example, power consumption, maximizing throughput, etc. By focusing on fulfilling the requirements of the soft-E2E QoS for a long feasible path raises many questions. First, "How can the reliability achieved by a subset of be paths quantified?" Second, "How can the energy-efficient path set subject to the delay constraint been chosen?" These questions are considered as non-linear programming problems. In an attempt to solve these problems, a model based on the probability exploration to provide soft-E2E QoS under multiple constraints for a multipath routing protocol was proposed in [9]. The authors suggested a distributable manner as the main requirements to achieve the high level of soft-E2E QoS of the selection path. The partition was obtained from the hop requirements for both the additive delay and multiplicative reliability, which is formulated as

$$L_\iota^d = \frac{Bounded\ Delay - Delay\ node_\iota}{Hop\ count} \tag{4}$$

where *Hopcount* is a counter of hops from the source to the sink; $Delaynode_\iota$ is the value of the delay engrossed for processing data at $node_\iota$, and *BoundedDelay* is the definition of the total delay from the source to the sink. Reliability formation is formed as

$$L_\iota^d = \sqrt[Hopcount]{Re_\iota} \tag{5}$$

where Re_ι is the reliability requirement assigned to the path through $node_\iota$. The focus is on the definition of the non-linear programming problem and where it should be started. Some problems depend only on the source node based on information on the end-to-end solution, while other problems depend approximately on the intermediate node based on hop information. Both problems attempt to reduce the complexity of constraints. Thus, the authors estimated the probability of the constraints according to the one-tailed version of Chebyshec's Inequality. The proposed protocol was evaluated through the Parallel Simulation Environment for a Complex System (PARSEC) that supports parallel discrete-event simulation capability. The disadvantage of the protocol is the dependence on linear and nonlinear programming to solve

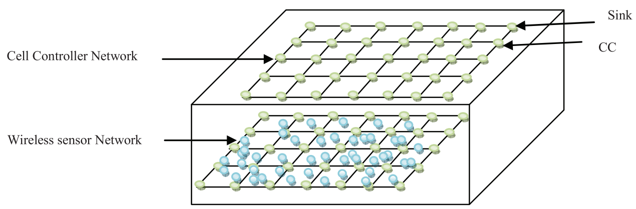


Fig. 16. Two-layer overview of the wireless sensor networks.

optimization problem. These methods are inefficient for multi-constrained optimization problems owing to the large number of calculations required for an efficient search of an optimal multipath solution.

In *Energy Constrained MultiPath (ECMP)* energy, delay, and reliability become competitive constraints in WSNs raising a tradeoff between the single-path and multipath routing deployments, where minimizing energy and delay and maximizing reliability is at stake. Bagula and Mazandu [113] extended the models proposed in [112] into a model referred to as ECMP by building upon geo-spatial energy propagation to formulate QoS routing in WSNs. The MCMP model proposes an arbitrary selection link with a random choice if it is the optimal selection for minimizing energy consumption. Thus, the ECMP model tries to find a subset from a set of sensor nodes with lower expected energy transmission, while achieving the QoS requirements. The ECMP searches for the subset of multipath from the source to the sink, which satisfies the QoS and the total energy of transmission requirements. The disadvantage of this protocol is the geo-spatial energy propagation approach, which depends on the Pythaorean Theorem that leads to the overhead messages control problem.

An integrated QoS network for a routing protocol in large-scale WSNs [114] is a new routing protocol (QoSNet) that increases the network lifetime using the percolation theory while satisfying the hard-QoS constraints. The system model considered sensor nodes deployed inside a two-dimensional area formed by a grid network architecture. The approximate location of each sensor node's coordinates is obtained through triangulation or multi-lateralization. The proposed system model presents the same method of Fractal Theory Iterated Function System (IFS) which has the ability in mobile indoor/out-door environments of GPS-enabled devices but appears to be costly in real deployment. IFS is compatible with a large-scale sensor area to discretize the wireless sensor area into constructor cells, and each cell is equipped with a Cell Controller (CC) that supports a simple sensor node whose only role consists of performing data forwarding. The explanation behind the proposed QoS-network model is related to the goals. First, each cell is equipped with a CC responsible for managing the cell QoS-path selection operation and second, supports the management to integrate powerful entities as shown in Fig. 16, which, for a square, creates two layers of sensor nodes: the lower represents the entire network, while the upper is composed exclusively of CC.

Data is forwarded through typical scenarios when an abnormal event is detected. It is necessary to forward through a group of feasible paths via the intermediate sensor nodes until reaching its destination. For this purpose, each sensor node maintains a table for records and data processing reporting session. The authors added a new constraint definition, namely End-to-End Path Battery Cost (EEPBC), to extend the lifetime of each individual sensor node and to prevent early failures.

An Energy Efficient and QoS-based Routing (EQSR) protocol was proposed in [115] for WSNs. EQISR is an extension of REER: Robust and Energy Efficient Multipath Routing protocol [116]. REER was used to examine traffic allocation by two methods. Firstly, a single-path among the discovered paths was used to transfer the message. Secondly, the transmitted message is split into several equal-size segments including Exclusive-OR (XOR)-based on Error Correction Codes (ECCs), and then these segments are simultaneously transmitted across multiple paths to increase the probability of receiving enough portions of the packet at the destination without increasing the delay.

The authors extended their protocol to restore failures in the node and to balance the load by splitting the traffic across a group of node-disjoint paths to balance the energy consumption among the sensor nodes. The reliability of data delivery increases by sending the data with ECCs computation data.

EQSR utilizes available buffer size, Signal-to-Noise Ratio (SNR), and residual energy to predict the next hop during the path construction phase. During path discovery phase, the link cost function was used to examine the decision for the recent link performance; then, predictions of path stability may be made. EQSR employs the WFQ presented in [117] to handle both real-time and non real-time traffic. Two queues are used: a high priority queue for real-time traffic and FIFO queue for non-real-time traffic. The EQSR protocol has two disadvantages: WFQ is a highly-complex approach for packet scheduling, and overhead complexity might occur during the decision on path stability.

Real-Time and Robust Routing (RTRR) protocol was proposed in [118] for fire emergency in indoor building scenarios. Each sensor node is defined by four state messages: safe, lowsafe, infire, and unsafe. In the RTRR protocol, a simple delay value is used, and the forwarding decision must satisfy the slack where it is less than the average delay.

Adaptive reliable routing based on cluster hierarchy for WMSNs is necessary to adapt to the differences in energy consumption in WSNs and WMSNs. WMSNs consumes energy in the sensing status and in processing multimedia data, while WSNs consume energy only in the communication links. These differences are considered in the **Adaptive Reliable Routing based on Clustering Hierarchy (ARRCH)** [119] to handle challenges faced in WMSN routing such as energy consumption, limited computing power, memory availability, and QoS constraints. The authors presented a self-adaptive power allocation mechanism as a metric to meet the reliability requirement.

An energy efficient QoS routing in a two-tiered WSNs was proposed by a **Multi-Objective Genetic Algorithm (MOGA)**. A protocol for energy efficient QoS-routing based on a Non-dominated Sorting Genetic Algorithm (NSGA-II) for WMSNs was reported in [120]. In NSGA-II, the ranks of chromosomes

TABLE VI
COMPARISON OF MULTIPATH UNICAST FORWARDING RELIABILITY CONSTRAINTS FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

Routing Protocol	Scalability	Energy Efficiency	Reliability	Network Topology	Data Delivery Model	Network Dynamic	Resources Reservation	Data Aggregation	QoS	Localization	Mobility
MMSPEED[113]	Restricted	Low	Restricted	Flat	Geographic	†			†	†	
ReInFor[114]	High	Low	High	Flat	Query driven	†			†	†	
NC-RMR[115]	Restricted	Moderate	High	Flat	Query driven	†					
EERMR[116]	Restricted	High	Restricted	Flat	Query driven			†	†		
DMRF[117]	Restricted	Moderate	High	Flat	Query driven	†	†	†	†		
SOCEE[118]	Restricted	Moderate	High	Flat	Query driven	†	†	†	†		
QoSMR[119]	Restricted	High	High	Flat	Query driven		†	†	†		
MCMP[121]	Restricted	Low	High	Flat	Event driven	†	†	†			
ECMP[122]	Restricted	High	High	Flat	Event driven	†	†	†	†	†	
QoSNET[123]‡	High	High	High	Mesh	Event driven	†	†	†	†	†	†
EQSR[124]	Restricted	High	High	Flat	Event driven		†	†	†		
RTRR[127]	Restricted	Moderate	High	Flat	Event driven	†		†	†		
ARRCH[128]	High	High	High	Star	Event driven	†	†	†			
NSGA-II[129]	Moderate	High	Moderate	Tree	Query driven		†	†	†		
ICPSOA[130]	Restricted	High	High	Flat	Query driven		†	†			
PMR[9]	Restricted	High	High	Flat	Event driven	†	†		†		

‡:all protocols are satisfying the soft real-time QoS constraints, except the QoSNET protocol, which is satisfying the hard real-time QoS constraints

are presented in the same manner as in MOGA. Optimizing a particular objective function for the end-to-end delay, reliability and energy consumption were considered in [88]. The main objective is to find a solution that satisfies the best trade-off among the three objectives, called Pareto Optimal.

An Immune Cooperative Particle Swarm Optimization Algorithm (ICPSOA) for fault-tolerant routing optimization in heterogeneous WNSs which uses a hybrid routing scheme to calculate and maintain k-disjoint multipaths from source to sink [121]. ICPSOA was presented as a model to solve the fault-tolerant optimization routing for sensor nodes that are densely distributed in a heterogeneous wireless environment. ICPSOA is an intelligent swarm algorithm that provides a faster way to recover the k-disjoint multipath from failure. The authors used a simple form of fault tolerance proposed in [122], which is defined as sub-trees of modeling directed connected graph. Usually, the construction of topological heterogeneous WSNs consists of two types of sensor equipment, arranged in two layers. The lower layer is formed by traditional sensor nodes with restricted resources, which respond for any task, such as processing, transmission, and sensing data. The second layer consists of macro-nodes with more capabilities in energy, processing, and storage and have the responsibility of decision routing. The metric for selecting the optimal path from the k-disjoint path spanning in the sub-trees connected graph is defined as the ratio of the total energy consumption of the valid path from the sensor node to the macro-node/root to the summation of the energy consumption path function, communication delay function, and distance function between all nodes in the sub-tree. ICPSOA abrogates the problem of converging to an undesired optimal solution, although ICPSOA derives better diversity. The increasing diversity depends on developing a searching mechanism inspired by the Immune Cooperative, which defines each particle as an antibody to generate a new search in the space population. ICPSOA provides accuracy in finding the optimal solution by jumping out to the local optimal solution, with minimum energy consumption, and shorting end-to-end delay for packets delivery. The algorithm suffers from lack of robustness for link failure in the network and is computational complexity.

Partitioning Multipath Routing (PMR) protocol was proposed in [9] for WMSNs. The authors proposed a routing metric to determine the optimal path and to select the intermediate sensor nodes for routing packets from a source to a sink. The metric prioritizes the sensor nodes according to the link quality based on a generic routing protocol. The mechanism of path selection is based on defining critical parameters to control the adaptive switching of hop-by-hop QoS routing protocols using mixed integer programming (MIP). The embedded criteria for each objective function related to decision constraints are used to select path from the source to the sink.

2) Discussion: In addition to the traditional QoS requirements such as delay and throughput, the diverse reliability constraint should also be considered in WMSNs. Reliable communication is defined as another challenge facing a WSNs because of some constraints, such as the characteristics of time-varying channel for low-power wireless links, interferences, and dynamic network topology. As previously mentioned, the multipath routing strategy appears to be an essential feature for supporting QoS in WMSNs. Thus, this strategy improves the chances of data transmission and reception during transmission to the sink without any interruption, even in the case of path failure by using different approaches to provide reliable data transmission in alternative paths. There are various approaches to provide a reliable transmission. First, transmitting multiple copies of data packets as long as the discovered multipaths exist to ensure recovery from several path failures. The second uses an erasure coding technique where each source adds some additional information to the original packets, and then the data packets are distributed over multipaths.

The multipath configurations, which can be established in several different ways, as shown in Fig. 9, influence the performance benefits achieved to guarantee integration with other networks. Many existing network topologies with various environments are depicted in Fig. 10. To provide a reliable data transmission in each situation, multipaths are generated that may be established by using a totally different approaches.

Tables VI and VII summarize and provide comparisons of the aforementioned multipath unicast forwarding routing protocols for reliability issues based on QoS constraints, data delivery, network architecture, and other parameters.

VII. ALTERNATIVE MULTIPATH BROADCAST FLOODING

As mentioned before, one goal of any WSN is to prolong the lifetime of the sensor node in the network. To achieve this goal, it is necessary to construct an energy-efficient path

TABLE VII
SUMMARY OF MULTIPATH MECHANISMS FOR UNICAST FORWARDING RELIABILITY CONSTRAINT FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

Routing Protocol	Path Disjointedness	Number of Paths	Path Selection	Traffic Distribution	Reliability Mechanism
MMSPEED[113]	partially disjoint	based on the desired reliable tree	sink	packet-condition-info-based	copying the original packets
ReInFor[114]	link disjoint	based on the desired reliability discovered paths	source	packet-info-based	multiple copies of the original packets
NC-RMR[115]	partially disjoint	based on the desired reliability discovered paths	source and intermediate nodes	packet-info-based	multiple copies of each packet
EERMR[116]	partially disjoint	based on the desired reliability discovered paths	source and intermediate nodes	packet-info-based	multiple copies of each packet
DMRF[117]	braided multipath	based on the desired reliability discovered paths	sink	traffic-condition-base-selector	per-packet hopping
SOCEE[118]	k-disjoint paths	based on the desired reliability discovered paths	sink	traffic-condition-base-selector	per-packet hopping
QoSMR[119]	partially disjointed	based on the desired reliable discovered path	sink	traffic-condition-based-selector	per-packet for each path
MCMP[121]	partially disjoint	based on the desired reliable	intermediate nodes	packet-info-based-based	multiple copies of each packet
ECMP[122]	partially disjoint	based on the desired reliable and energy consumption	intermediate nodes	packet-info-based	multiple copies of each packet
QoSNET[123]	k-disjoint paths	based on the probability of discovered path	source and intermediate nodes	traffic-condition-based-selector	multiple copies of each packet
EQSR[124]	node-disjoint	based on the probability of successful data transmission	source	distributed traffic splitting	multiple copies of each packet
RTRR[127]	idealized algorithm-node-disjoint	based on the desired reliable tree	source and intermediate nodes	network-condition-based-selector	per-packet each message
ARRCH-II[128]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	copying the original packets
NSGA-II[129]	node-disjoint	based on the desired reliable tree	sink	traffic-condition-based-selector	copying the original packets
ICPSOA[130]	k-disjoint paths	based on the desired reliable tree	sink	traffic-condition-based-selector	copying the original packets
PMR[9]	partially disjoint	based on the desired reliable and energy consumption	source and intermediate nodes	traffic-condition-based-selector	copying the original packets

without imposing stringent QoS requirements from the source node to the sink node, possibly over multiple hops. This is usually performed by collecting or distributing information to all nodes in the wireless domain by a broadcasting operation.

Owing to various mechanisms in the Broadcasting Flooding (BF) operation and its low-rate flooding in discovering the entire available multipaths, multipath BF subtaxonomy can be classified into two partitions depending on the main operation: indicator-based and indicator-free [123]. In the indicator-based partition, there is always an initialization phase where an indicator-generation algorithm is applied. According to the algorithm, every node generates an indicator to help determine the routes.

There are different types of indicators that further categorize this type of operation into subclasses, namely data-centric protocol, where indicators are built for sensors in a setup stage. They then follow those indicators to make decisions while routing. In the indicator-free partition, the algorithm has no initialization phase and the packets are transmitted in an on-demand or random fashion, which is not applicable for WMSNs [123]. It is essential to describe the meaning of the flooding operation and grossing problem and highlight the basic idea before describing a few proposed protocols of the data-centric protocol and on-demand fashion.

A. Data-Centric Protocol Operation

Flooding is considered as the multihop routing algorithm for wireless communication environments [124]. Whenever a node receives a packet, the node broadcasts this packet to all of its neighbors. Broadcasts continue until all of the nodes in the network receive the packet. As a result, a packet can be flooded through the whole network. The flooding operation can be controlled by limiting the re-broadcasts until the packet reaches the destination or the maximum number of hops has been reached. Flooding is classified as a reactive operation, and its implementation is straightforward. The flooding enjoys the advantages of simplicity since a node does not require neighborhood information, does not require costly topology maintenance and complex route-discovery algorithms [124].

B. Data-Centric Protocol Problem

An example of a realistic scenario is the forest fire detection. The information packet that contains the 1000F temperature is more important than sensing the temperature on a spring day with 60F. The high temperature might cause a forest fire and thus it should reach the sink with high reliability, low latency, high bandwidth, and packet delivery ratio. BF can be used to deliver important packets with high reliability, but the overhead incurred is significant and consumes energy of sensor node because of the duplicate messages during the broadcasting operation. The deployed mechanism (i.e., the network density) and the number of hops from source to sink might cause very low delivery of a packet to the sink because it is not feasible to assign global identities to each node.

1) Principal Protocols: Sensor Protocols for Information via Negotiation (SPIN) [125] was the first protocol in a data-centric family using meta-data negotiation-based, data-centric, and time-driven flooding operation protocols. SPIN created a family of different routing operations classified as Point-to-Point (SPIN-PP), Energy Consumption (SPIN-EC), BroadCast networks (SPIN-BC), and Reliability (SPIN-RL). The Rumor Routing Protocol (RRP) [126] was defined as a classic flooding operation that can be described as an event flooding. Query flooding describes the process used to propagate queries to all nodes in the network when no localization information is available to steer the query toward the appropriate sensors. The Gradient-Based Routing (GBR) [127] is considered the third data-centric protocol where a gradient is determined based on the number of hops to the sink.

Directed Diffusion (DD) is proposed in [128] for WSNs and is considered as one of the flat routing protocols. DD paved the way to many protocols based on DD or following similar concepts [26], [129]. Generally, DD consists of several elements: interests, data messages, gradients, and reinforcements, as seen in Fig. 17. An interesting message is a query defined by a list of attribute-value pairs, such as the name of the object, interval, duration, geographical area, etc. Such data can be an event occurring, which is a short description of the sensed phenomenon. The interest is disseminated by a sink through the network, hop-by-hop, to its neighbors. Each node receiving the interest can do caching of it for later use. Each sensor node that receives the interest setup is a gradient toward the sensor nodes from which it receives the interest. This process continues until the gradients are setup from the sources back to the sink sensor node. A gradient is a reply link that specifies an attribute value, a direction and expiration time derived from the field of the received interest. After the initial interest and gradients, multipath is established so that one of the paths is selected by reinforcement. The sink node resends

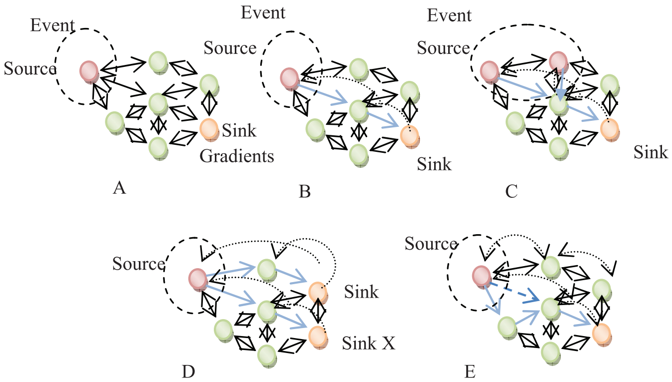


Fig. 17. The construction of DD routing protocol: (A) Gradient establishment, (B) Reinforcement, (C) Multiple sources, (D) Multiple sinks (E) Repair.

the original interest messages through the selected path with a smaller interval, so it reinforces the source sensor node on that path to send data more frequently. The authors claimed that the DD achieves its full potential, and careful attention has to be paid to the design of sensor radio MAC layers. Many principles are used in the design of WSN protocols, such as self-detection of link quality, lower power availability, and in-network processing. An improved distributed algorithm that can dynamically select optimal paths, called ETX-Delay GrEedy (EDGE), was presented in [130]. The proposed algorithm was based on DD for computing an aggregate link layer metric, namely Expected Transmission Count (ETX), for path selection to increase end-to-end throughput in transmission for supporting demanding applications.

Many restrictions in supporting real-time multimedia streaming applications in WSNs exist. Multiple Description Coding (MDC) was considered in [131] as a recent advance in multimedia source coding and inexpensive hardware, such as Complementary Metal-Oxide-Semiconductor (CMOS) cameras and microphones have made a multimedia transmission over a multipath routing wireless sensor protocol possible.

Choe and Kim [129] focused on energy efficiency by proposing the **Energy Aware Directed Diffusion (EADD)** protocol. The protocol prevents the Duplication of Forwarding Messages (DFM) that causes reduction of the energy consumption of sensor node and causes the imbalance of Available Energy (AE) distribution of the network. To avoid both DFM and AE, EADD selects the path to forward a packet according to the average AE value of each sensor node that is distributed in the overall sensor node network. Therefore, if a sensor node has a surplus energy, the sensor node can get a faster response time. Then, the EADD begins to run after receiving the interest message. Through the original protocol that has caused the unbalanced energy distribution, the EADD achieves faster gradient setup and reinforcement.

2) Discussion: Data are routed between multiple sources and sinks in multihop architecture in the sensor network. The sink connects directly to the task manager via satellite or Internet gateway. The design of multihop architecture is different from traditional Ad-hoc routing and is influenced by many factors such as fault-tolerance, scalability, network topology, hardware constraints, power consumption,

TABLE VIII
COMPARISON OF MULTIPATH BROADCAST ROUTING /DATA-CENTRIC ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

Routing Protocol	Scalability	Energy Efficiency	Reliability	QoS
DD[137]	Low	High	Moderate	†
EADD[138]	Low	High	High	†
EDGE[139]	Low	Moderate	Moderate	†

and the transmission media. Consequently, the design of routing protocols that work in the network layer of the sensor network is usually achieved according to many principles such as sensor networks that are mostly data-centric, the functionality of data aggregation, the attribute-based addressing and location awareness and energy efficiency.

Generally, the advantages of data-centric routing are based on provisions of the nodes from individual addresses, which increase energy efficiency, aggregation and caching data, and minimizing the delay during data transmission through multiple paths. Data-centric routing uses attribute-based naming to carry out queries by using the attributes of the phenomenon [132].

This attribute basis creates broadcasting, multi-casting and any-cast for sensor network techniques. Unlike traditional end-to-end QoS routing, data-centric routing tries to find multipaths from a source or multiple sources and then applies the aggregation function at the sink node. Thus, the sink diffuses some interest messages to describe a task that must be performed by the network in multihop fashion. This process repeats until the sink is reached. Unfortunately, this technique does not take into account constraints such as energy, unreliability of low-power wireless links, etc., which are imposed by WMSNs. Therefore, data-centric routing uses the data aggregation to overcome the implosion problem that is caused from the duplication of packets that are sent to the same node.

In addition to the implosion problem, the data-centric routing used another technique known as gossiping to overcome the overlapping problem by the sensor node to randomly select one of its neighbors and to send the packets to it. This procedure repeats until all nodes receive these packets. Although this technique tackles the implosion problem by having just one copy of a message at any node, there is a significant delay to propagate the packet to reach all sensor nodes in a network.

The major disadvantage of data-centric routing is that it is usually based on a flat-topology structure that causes many problems such as scalability, increased traffic congestion among the nodes much closer to the sink (known as the broadcast storm), and an increase in overhead complexity. Therefore, clustering was introduced to subdivide the broadcast area into smaller cluster areas. Another disadvantage is in the distributed aggregation mechanisms, which are more applicable for query application models in WSNs. At the same time, directed diffusion is not a perfect choice for time-driven (continuous) models and even for environmental monitoring, an important application in WSNs. Several routing protocols in WSNs are data-centric. However, it is difficult to enumerate all of them in this survey. Therefore, Tables VIII and IX depict summaries and compare the aforementioned multipath-broadcast

TABLE IX
SUMMARY OF MULTIPATH MECHANISM FOR ALTERNATIVE MULTIPATH BROADCAST FLOODING/DATA-CENTRIC ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

Routing Protocol	Path Disjointedness	Number of Paths	Path Selection	Traffic Distribution
DD[137]	partially disjoint	not limited	sink	not applicable
EADD[138]	node disjoint	not limited	sink	not applicable
EDGE[139]	partially disjoint	not limited	sink	not applicable

forwarding-routing protocols that are most related to the data-centric problem based on the QoS constraints, data delivery, network architecture, and other parameters.

C. On-Demand Fashion

Four additional categories, reactive, proactive, hybrid and geographic, depending on how the source and the route to the final destination route are discovered [133]. In the proactive method, all paths are computed before they are really needed. This calculation is required for periodic information exchange to update the cause generating a large number of control messages. For this reason, the proactive method is not suitable for a mobile Ad-hoc network. Somehow, it is preferable for WSNs when the sensor nodes are static [65]. In the reactive methods, the paths are based on discover on-demand.

Tarique *et al.* [65] surveyed multipath routing protocols for mobile ad hoc networks through classification that depends on many objectives of a multipath routing protocol such as high end-to-end delay, unreliable data packet transfer, energy inefficiency, high overhead, and scalability.

This section limits discussion only to proactive and reactive multipath protocols that are preferable for WSNs QoS-routing protocols, and are mostly cited to originate from Dynamic Source Routing (DSR) and the Ad-hoc On Demand Vector (AODV). Although there are similarities between the MANETs and WSNs, most multipath-routing protocols are designed without explicitly considering the QoS parameters of the paths that they generate. That is, not only the selected path from source to destination is optimized, but the end-to-end QoS requirements are also guaranteed often in terms of reliability, overhead reduction, power consumptions, delay and throughput.

1) Dynamic Source Routing (DSR) Principal Protocols: One of the many routing wireless Ad-hoc characteristics are in allowing an Ad-hoc network to establish on-the-fly building of unconstrained connectivity and fault tolerance. Leung *et al.* [134] focused on designing QoS metric and end-to-end reliability through distributed on-demand Multipath Dynamic Source Routing (MP-DSR).

Robust Multipath Routing for dynamic topology in WSNs is discussed in [135]: "*Such characteristics allow an Ad-hoc net-work to be established on-the-fly with built-in fault tolerance and unconstrained connectivity.*" The authors provided efficient fault tolerance using a Robust Multipath Dynamic Source Routing (RMDSR) for WSNs to increase the recovering operation from route failure in the dynamic network domain.

Dulman *et al.* [136] introduced a routing algorithm for WSNs. This work was performed as a part of the European EYESproject (IST-2001-34734) on self-organizing and collaborative energy-efficient sensor networks. The algorithm addresses the convergence of distributed information processing, wireless communication, mobile computing, and maintaining the amount of overhead traffic at a low value.

Shah and Rabaey [137] introduced a new metric called network survivability for the reactive-routing protocol performance. This metric implies that the protocol should ensure that connectivity in a network is maintained for as long as possible, and that the energy health of the entire network should be of the same order. It is necessary to take care of network balancing, connectivity and energy level. Leaving the network might cause a wide disparity in the energy levels of the nodes and eventually may lead to network partition.

2) Ad-Hoc on Demand Vector (AODV) Principal Protocols: An Ad-hoc protocol builds on the idea of the distance-vector table algorithm with little modification in both route discovery and route maintenance by minimizing the number of required broadcasts using routes on an on-demand basis. A few of the studies whose scopes are in the multipath routing approach are presented below.

Jung *et al.* [138] proposed a Tiny Optimal Node-Disjoint Multipath Routing (TinyONDMR) that is suitable for transmission of larger multimedia with better performance, reliability, and efficiency in a WSN. The routing protocol optimizes the node-disjoint by finding multi-nodes disjoint between the sources and the sink that lead to an optimal load balancing. The TinyONDMR, inspired by the modification of Split Multipath Routing and the DSR, achieves low-routing overhead during route discovery.

The concept of route coupling, which means transmission interference between the multipath routing or even the single path routing between two node-disjoints was discussed in [139]. This interference leads to degradation of network performance, limiting the QoS parameters, etc. This phenomenon occurs when two paths are located within each other during the beginning of transmissions. Therefore, to save power of the sensor node, traffic when routed along the multipath does not interfere with other traffic. The authors have also proposed optimized cross-layers between the MAC layer and network routing for a new energy-efficient multipath approach [140], which was inspired by the Ad-hoc Multipath Demand Vector (AOMDV) and [139].

A Resilient Multipath Routing Protocol (RMRP) was presented in [141]. RMRP uses a scheme for maintaining broken links by reducing the flooding range of the control messages.

3) Proactive Routing: In the proactive routing protocols (or table-driven routing protocols), each node attempts to maintain consistency before establishing paths with every other node in

TABLE X
COMPARISON OF MULTIPATH MECHANISM FOR ALTERNATIVE MULTIPATH BROADCAST FLOODING/ON DEMAND FASHION ROUTING PROTOCOL FOR WIRELESS SENSOR NETWORKS

Routing Protocol	Scalability	Energy Efficiency	Reliability	Network topology	Latency	Network Dynamic	Localization
MPDSR[143]	Low	Low	High	Flat	Low	†	†
RMDSR[144]	Low	Low	High	Flat	Moderate	†	†
Opt.node[147]	Low	Low	High	Flat	Low	†	†
RMRP[150]	Low	Low	High	Flat	Low	†	†
SHRP[152]	Low	High	High	Hierarcy	Low	†	†

TABLE XI
SUMMARY OF MULTIPATH MECHANISM FOR ALTERNATIVE MULTIPATH BROADCAST FLOODING/ON DEMAND FASHION ROUTING PROTOCOL FOR WIRELESS SENSOR NETWORKS

Routing Protocol	Path Disjointedness	Number of Paths	Path Selection	Traffic Distribution
MPDSR[143]	k-disjoint path	not limited	sink	not applicable
RMDSR[144]	partially disjoint	not limited	sink	not applicable
Opt.node[147]	node disjoint	not limited	sink	not applicable
RMRP[150]	node disjoint	not limited	sink	not applicable
SHRP[152]	node disjoint	not limited	sink	not applicable

the network with up-to-date routing information [142]. The main advantage of this approach is that the routes are available whenever they are needed, and no delays are incurred in searching for routes in on-demand routing protocols. The proactive approach responds to changes in the network topology or another metric such as bandwidth and interference by propagating updates throughout the network to maintain a consistent network [142]. The main disadvantages are that the overheads involved in building and maintaining potentially very large routing tables and that stale information in these tables may lead to routing errors.

The architecture of TCP/IP in traditional wire network is not suitable for WSNs for many reasons such as limitation on storage against a small size, low-cost, power consumption, reliability etc. Thus to involve sensor network in monitoring and controlling activities faces many challenges which are addressed by a new protocol SHRP [143]. This hierarchical and proactive routing protocol models the performance of the energy of the sensor and reliability metrics to maintain the WSN topology. This protocol monitors the battery availability and link quality. The mechanism of monitoring is based on two measured metrics, Link Quality Indicator (LQI) and Received Signal Strength Indicator (RSSI) that are offered by the data link layer.

D. Discussion

The differences between Ad-hoc and sensor networks should be considered as the primary concern in designing an efficient routing algorithm based on an Ad-hoc manner for a WSN. Usually, Ad-hoc wireless networks possess high network dynamic topology specifications owing to mobility and failures. The design of distributed efficient algorithms to dynamically update the routing structures is considered as critical issue in the implementation of WSNs. For example, the proactive routing protocol is periodically required for each node to maintain and update one or more tables to store routing information during changes in network topology, which leads to an extraneous energy consumption and wastage in bandwidth because of the higher control packet overhead. Reactive protocols are on-demand routing protocols. This means that they do not periodically update and hence require less routing information for each node. Therefore, the provision of energy and bandwidth is better than proactive routing protocols during inactivity [144].

In real-time applications, proactive routing protocols are more appropriate because they do not require a latency in route discovery unlike reactive routing protocols [8]. However, there is a latency for discovering the route that is called acquisition delay that may not be suitable for real-time applications [26]. Traffic loading in WSNs could be either broadcast or convergecast, i.e., high loads or bursts of traffic. Usually, the broadcast traffic is widely used in various wide networks queries and updates. That is the reason why broadcast traffic is often observed when multi-sources have detected the same event and transmit the data packet to a node that does require data aggregation [145]. Therefore, reactive routing protocols are mainly optimized for light traffic loads if the routing information changes frequently and if route discoveries are not needed for those routes changes [146]. Otherwise, reactive routing protocols may result in a large volume of messaging overhead [133].

Unlike the reactive route protocols, the availability of changing route information is considered a key advantage of the proactive routing protocols. The protocols become faster in routing decisions, more power efficient, packet delivery ratio, and consequently latency in route discovery for heavy traffic loads compared to reactive protocols.

Another important advantage of proactive routing protocols is that periodic routing updates which keeps the routing for each node up-to-date. This advantage reduces the cost of higher signaling traffic than the required by reactive routing protocols. Furthermore, the sensor nodes spend more energy because of their periodic update messages. However, there are variations for other operations such as route reconfiguration after failure that depend on the mechanism that the routing protocols use to perform these operations.

For reactive routing protocols, certain QoS parameters do not ensure construction of an optimal route from the source to the sink with guaranteed delivery packets within the specified time. Tables X and XI depict a summary and comparison of the afore-mentioned multipath-broadcasting forwarding-routing protocol for nodes in a genetic and Ad-hoc manner on QoS constraints, data delivery, network architecture, and other parameters.

TABLE XII
DEFINITION OF PARAMETERS IN SIMULATION SCENARIOS

Parameter	Value
The overhead energy due to the sensing, receiving and processing	$50nJ/bit$
The loss coefficient related to p bit transmission propagated over single-path model	$10pJ/bitm^2$
The loss coefficient related to p bit transmission propagated over multipath model	$0.0013pJ/bitm^2$
Topology structure	Urban highway, sensor node distributed uniformly
Total number of sensor nodes	50 sensor nodes
Message payload	64 bytes
Data length p	2000 bits
Transmission range	$12.00m$
Total distance	$150m$

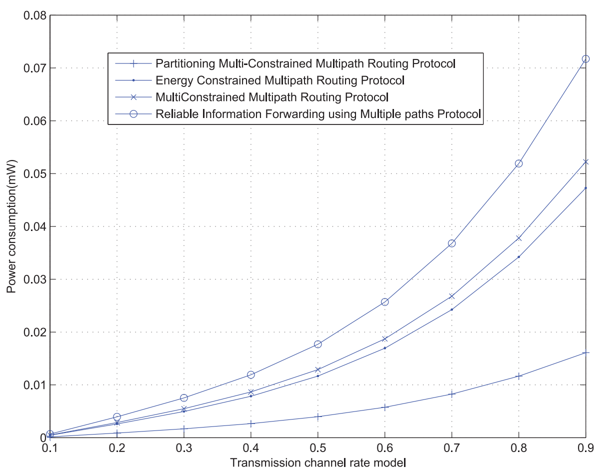


Fig. 18. Power consumption comparison.

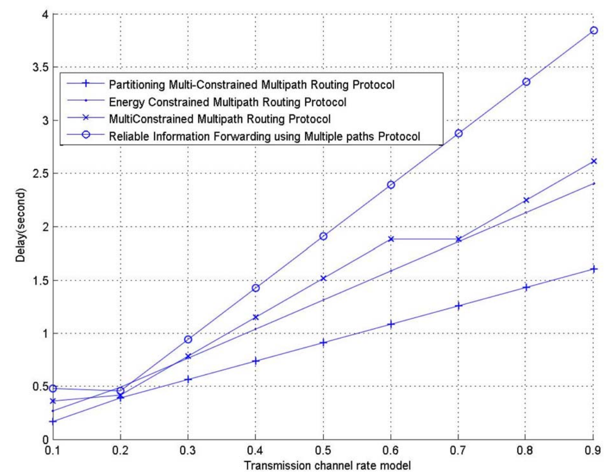


Fig. 19. Average delivery end-to-end delay comparison.

VIII. SIMULATION COMPARISONS

This section provides a comprehensive analysis of major multipath routing approaches for WMSNs. Multipath routing mechanism is considered as an efficient approach to improve network capacity and resource utilizations under heavy traffic conditions [147]. Therefore, there is certainly an urgent need to analyze the significance as well the performance analysis in order to identify the challenges pertaining to the design of multipath routing protocols for WMSNs. To demonstrate the effect of selection for multipath routing mechanism, we have conducted some simulations of major multipath routing approaches namely ReInForM [105], MCMP [112], ECMP [113], and PMR [9] in terms of several performance parameters. These parameters include the power consumption, the average end-to-end delay, and the successfully received packet ratio. The success probability of the transmission channel is chosen from 0.1 to 0.8, which implies a good state for the link quality [9]. We used the LINGO optimization module [148] considering a linear WSN with an area ($1000m * 1000m$) composed of n sensor nodes. The source sensor node and the sink are placed inside the wireless sensor area; each sensor node has a connectivity that is associated with two positive QoS constraints. We evaluated the object-tracking scenario by studying the behavior of cars passing along the highway in a one-dimensional sensor network topology. The parameters used in the proposed model are presented in Table XII.

Results in Fig. 18 shows the total power consumption in the network with four multipath routing algorithms. The PMR model performs better than the ECMP and MCMP, due to the fact that both the ECMP and MCMP are deterministic zero-one problems with linear objective functions and constraints. The ECMP model uses a smaller group of longer multipaths than the MCMP model. The MCMP model consumes more energy than the ECMP model, which lowers the average end-to-end delay as seen in Fig. 19. The similarity of the performances of the ECMP and the MCMP justifies that the trade-off between power consumption and average end-to-end delay is affected by the number of selected multipaths. This finding reveals that the ECMP model uses a smaller or longer multipath resulting in lower power consumption with a higher average end-to-end delay than the MCMP model. The PMR model outperforms the other models since it uses preferred selected multipath with an optimal hop number. This result reveals that PMR uses the multipath with the optimal hop number. Therefore, the PMR model is more likely to lead to a lower average end-to-end delay than the other two models. All multipath routing approaches perform equally in terms of the PRR for the reliability of transmission channels as seen in Fig. 20. To have a close view of the PRR, the curves of all models display the PRR on a log scale. Among all the models, the PMR protocol achieves the best PRR of approximately 96%. The ECMP, MCMP, and ReInForm models achieve PRR values of 94%, 92%, and 88%, respectively. The packets reception ratio usually increases logarithmically as the reliability of the channel transmission rate increases because of the confirmation of more packets that are successfully delivered to the sink, with a small expiration ratio for the lost packets.

TABLE XIII
SIMULATION COMPARISON OF MULTIPATH ROUTING PROTOCOL FOR WMSNs

Protocol	Approach used	Simulator Type	Performance Metrics	Comparison Results	State Complexity
SAR[85]	load balancing and support for multiple priorities	Parsec	QoS and node lifetime	SAR has achieve a better performance than the minimum metric algorithm.	Mod.
SPEED[86],[87]‡	Back-pressure rerouting to control congestion	Theoretical analysis,GloMoSim and real implementation on Berkeley motes	Delay and packet loss ratio	SPEED performs better in terms of end-to-end delay ratio and packet lost ratio.	Mod.
REAR[91]	establish multipath routing for reducing energy consumption	Not specified	Delay and network lifetime	REAR prolongs the network life cycle better than SAR.	High
RPAR[97]	to achieve application specified communication delay at low energy cost by dynamically adjusting transmission power and routing decisions.	Matlab-based network simulator called Prowler	Energy and delay	RPAR employs a novel neighborhood management mechanism which is more efficient than the periodic beacon scheme adopted by SPEED and MMSPEED	High
MMSPEED[113]‡	Supports multipath routing and multiple network-wide packet delivery speeds	J-SIM network simulator	Delay and reliability	MMSPEED could use its redundant path selection scheme for load balancing, which is not only for reliability enhancement, but also to improve the overall network lifetime.	Mod.
ReIForM[114]	propose approaches based on multipath routing to provide reliability.	Not specified	Energy and reliability	ReInForM achieved packet delivery probability with 40 and 70% reliability target compared with two other schemes flooding broadcasting, and sending only a single packet over a single path.	High
NC-RMR[115]	presents network coding based reliable disjoint and braided multipath routing for sensor networks in which improving reliability of multipath routing with network coding is the primary aim	OMNet++	energy and reliability	the protocol improves data transmission reliability and saves energy consumption. The performance of reliability and normalized energy consumption is studied by analysis and simulation methods.	High
DMRF[117]	demonstrate a dynamical jumping real-time fault tolerant routing protocol	JProwler simulation platform	Delay and packet received ratio	DMRF can achieve the successful transmission ratio up to 92% than SPEED and MMSPEED	Low
MCMP[121]	utilize the multiple paths between the source and sink pairs for QoS provisioning	Theoretical analysis and PARSEC	Delay and packet received ratio	MCMP outperforms single path routing remarkably, and approaches approximately 95% of which for God routing and braided multipath routing	Low
ECMP[122]	models QoS routing in WSNs to achieve energy efficiency	Theoretical analysis	Delay and packet received ratio	MCMP algorithm shares its traffic on more paths than the ECMP algorithm, however the ECMP algorithm can achieve more energy savings compared to the MCMP model	Low
PMR[9]	partitioning multipath routing to achieve QoS parameters	Theoretical analysis	Energy consumption, delay and packet received ratio	PMR provides sufficient information about the links between sensor nodes to determine the optimal path and to select the intermediate sensor node for routing the packets from source to sink. The results demonstrate that PMR improves the PRR from the source to the sink, increasing the lifetime and minimizing the end-to-end delay.	Low
DD[137]	to describe and illustrate one instantiation of the paradigm for sensor query dissemination and processing. To empirically adapt to a small subset of network paths, and achieve significant energy savings when intermediate nodes aggregate responses to queries	Theoretical analysis and NS-2 Simulator	energy, average delay, and distinct-event delivery ratio	DD has noticeably better energy efficiency than omniscient multicast, moreover DD reduces data transmission delay caused by path failure by decreasing the frequency of path rediscovery [116].	Mod.

‡:Both SPEED and MMSPEED have a common deficiency: energy consumption metric has not been taken into account.

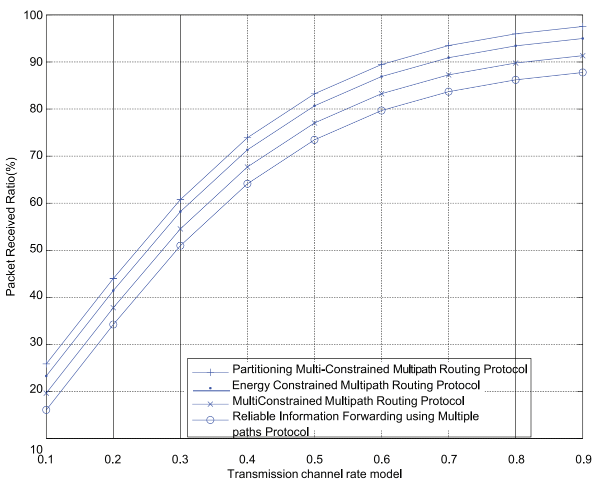


Fig. 20. Comparison of received packet ratio.

A summary of the comparative performance analysis among major multipath routing protocols is listed in Table XIII. These simulation comparisons address the problem of providing load balancing efficiency, high bandwidth utilization efficiency, and packet order preservation in WMSNs. In particular, we are interested in providing the reader with an understanding of reliable real-time applications, by focusing on the design of a multipath routing protocol for WMSNs that operates efficiently under heavy traffic situations. We describe performance evaluations in terms of the number of paths allowed for transmission toward the sink and not just the best path. This should be achieved without imposing an excessive overhead control problem in maintaining these paths to indicate the performance of the multipath routing protocol. Therefore, the absolute performance is interpreted under the degree for the state of complexity for discovering, selecting and maintaining multiple paths. The state of complexity is categorized as High, Mod., and Low, which can be interpreted as follows. High means that the performance of the routing protocol degrades dramatically due to a problem in routing operations. Mod. indicates the problem may not occur. Low means that the problem does not cause any significant impact.

IX. OPEN RESEARCH PROBLEMS

In spite of the numerous research activities and the remarkable progress in recent years, multipath routing protocols in WMSNs still harbor many open issues which are still awaiting to be resolved. The main goals of multipath routing protocol include carrying out data communication while maximizing data delivery, extending the network lifetime, minimizing energy expenditure and preventing connectivity degradation. These goals can be achieved by employing data aggregation, energy management, and efficient control of path selection techniques. Additionally, there are restrictions on the nodes and multimedia content which impose additional challenges. Therefore, there are extensive research issues that should further be explored in the field of multipath routing protocols for WMSNs. In this section, a broad range of research issues are outlined for future investigation.

A. Data Sensing and Delivery Model

The data sensing and delivery model affects the performance of the multipath routing protocols. Especially with regard to energy consumption and path selection, i.e., if a node is continually capturing a video content and sending it to the sink, the node consumes more energy. Therefore, it reduces its own lifetime and, consequently that of the whole system as well. Depending on the type of the multipath routing protocol, continuous data transmission causes a path selection. A similar kind of behavior occurs with scalar data transmissions.

B. Node Deployment

The distance between two sensor nodes affects link quality. In the case of a network in which some nodes have a small number of neighborhoods, this node rapidly exhausts its battery. Additionally, for a non-uniform distribution, an optimal position of the sources and the sink are necessary to allow connectivity that can enable an energy-efficient network operation. Because multimedia sensor nodes are sensitive to direction of acquisition and have limited coverage, a multimedia sensor node must be deployed in the best place to optimize the coverage and avoid obstacles. Moreover, several multimedia sensor nodes are equipped with a camera and there is a need to study the best place to deploy them to ensure an optimal coverage. The other nodes can be deployed in a random way, although with a uniform distribution [149].

C. Node Capabilities

Several sensor nodes can have different role or capability according to the application, which is related to the capacity of the nodes in terms of computation, communication, power and multimedia support. Most of the applications use homogeneous nodes, which have equal capabilities, or are produced by the same manufacturer. However, in some applications the network is considered to be heterogeneous, because some/all of the nodes have different capabilities or roles. In this context, they are able to perform special functions, such as sensing, aggregation, or the retrieval of multimedia content. Therefore, in the case of heterogeneous network, the node that is able to perform many tasks, e.g., sensing, aggregation, or retrieval of multimedia content is likely to end up its source of energy in a short period of time. As mentioned previously, several of the nodes are constrained in terms of their processing capability, which makes it difficult to carry out many tasks. To overcome challenges arising from multimedia content and the restrictions of the sensor node, the use of a heterogeneous network can be an alternative solution.

D. Link Quality Estimators (LQEs)

Wireless links in WMSNs are unreliable and unpredictable. This is mainly due to the fact that the nodes use low-power radios, which are sensitive to noise, interference, and multipath distortion. Therefore, it is necessary to quantify a metric for communications between neighborhoods. This metric is obtained through a Link Quality Estimator (LQE). A path is considered to be good when a link has the highest value. Several multipath routing protocols rely on LQEs as a mechanism for selecting the most stable routes, and the accuracy of the selected LQE has an impact on their performance. Thus, LQE is a fundamental building block in the design of routing protocols for WMSN.

E. Mobility

Mobility is one of the key challenges in wireless communications, since the problem of routing messages raises through the network. Because paths are continually changing, this leads to an important issue regarding optimization, as well as achieving improvements in energy saving and bandwidth. Moreover, in case of dense WMSNs, this is one of the main challenges since it would be very difficult for a sensor node to keep track of all the neighboring nodes due to the fact that every node may have a large number of mobile neighbors that dynamically change the network topology. Therefore, more research into an efficient mobility management scheme would enhance the performance of the WMSNs in terms of energy saving and bandwidth utilization.

F. Scalability

Scalability is one of the main design attributes of WMSNs, and must be encompassed by the routing protocols. However, the routing protocol should be scalable enough to enable it to work with a large number of sensor nodes, and continually ensures the correct behavior of the application. Furthermore, it must be adapted to scalability changes in a transparent way, i.e., without requiring intervention of the user. To achieve efficient data processing, aggregation, storage and querying in WMSNs, the scalability must be taken into account especially when this involves a large amount of multimedia data. Therefore, network designers must employ a hierarchical architecture that offers considerable advantages with respect to a flat architecture in terms of scalability, lower costs, better coverage, higher functionality, and greater reliability.

G. Multimedia Content

Multimedia content produces a large amount of data, the nodes in a WMSN have capability to capture and transmit multimedia content, which can either be a snapshot or streaming content. Actually, a snapshot contains data from an event that was triggered in a short time period. Streaming multimedia content is generated over a longer time period. Thus, transmitting video as snapshot or streaming requires a high data rate over the WMSNs link which is extremely difficult. Because of the limitations of the sensor nodes process video coding/compression with a low complexity, produces a bandwidth with a low output, which can tolerate loss, and consumes as little power as possible. Furthermore, the predictive schemes for video coding techniques are not suitable for WMSN as they require complex encoders, powerful processing algorithms, and entail high energy consumption. However, a multipath routing mechanism can be adopted to increase the bandwidth. The multimedia content will only be sent when events occur to reduce the amount of data.

H. Energy Efficiency Considerations

Multimedia produce a large amount of data which has to be delivered over the network. Hence, the majority of routing protocols in WMSNs considered energy efficiency as the main objective and assumed data traffic with unconstrained delivery requirements [18]. Because there is a risk that the node routing multimedia data might quickly drain its energy, the main challenge is to achieve reliability in data delivery packets, with a minimal consumption of energy, while increasing the lifetime of the network.

I. Multi-Constrained QoS Guarantee

QoS specification can be used to provide various priorities to guarantee a certain level of performance to a data flow in accordance with requests from the application. However, QoS guarantee is considered necessary especially when the network capacity is limited. For example, real-time streaming multimedia applications require fixed bit rate and are delay sensitive [18]. Therefore, routing algorithms offering QoS guarantee for multimedia traffic should be flexible to support different application-specific QoS requirements (such as energy efficiency, end-to-end delay, reliability, delay jitter, bandwidth consumption) in the heterogeneous traffic environment [21].

J. Cognitive Radio (CR)

CR is based on Dynamic Spectrum Access (DSA) which has been proved to yield a promising approach for communications [150]. CR has positive impacts on power consumption level and network lifetime [151]. Capabilities such as sensing the spectrum, determining the vacant band and improving the overall utilization, may be exploited by WMSN to employ spectrum allocation and processing resource constraints of low-end of WMSN sensor nodes [152]. In other words, WMSNs are enriched with these additional capabilities of CR and may lead to an evolution of Cognitive Radio Sensor Networks (CRSNs) according to the applications such as defense, utility metering and home automation [153], [154]. Each sensor node may be equipped with DSA to detect an event-driven communication pattern that generates trusty traffic that needs to efficiently utilize the channel [154]. Due to CRSNs having large bandwidth requirements, WMNSs can be integrated with low-cost hardware and enjoy the benefits of CR to satisfy the network and applications requirements [154]. CRSNs face certain challenges which must be investigated for specific design considerations, existing approaches and open research issues of each different layer in the protocol stack of sensor network [155]. For example, the goal of most existing CR routing protocols is to provide joint spectrum and routing decisions, but do not consider the inherent resource constraints of CRSNs [156]. However, the network designer should focus on developing new metrics such as channel access delay, interference, and bandwidth and mechanisms that consider resource constraints, and dense deployment in order to design new energy-efficient routing protocols whether be single-path or multipath approach [156].

X. Conclusion

The emergence of multipath-routing techniques in supporting a wide range of real-time multimedia applications has attracted the attention of several researchers worldwide. The common objective is to develop new protocols that guarantee network performance by providing QoS. In this survey, we have introduced a new taxonomy on multipath-routing protocols. The structure of the taxonomy is based on the employed path utilization methods that are used by multipath routing to improve the capacity and resource utilization of the network. We have highlighted the advantages and disadvantages of several routing mechanisms and algorithms. Development of efficient multipath routing protocols with multi-constraints for WMSNs is an open research area that is promising for future research.

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References

[1] S. Prabhavat, H. Nishiyama, N. Ansari, and N. Kato, "On load distribution over multipath networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 662–680, 3rd Quart., 2012.
[2] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, "A survey on wireless multimedia sensor networks," *Comput. Netw.*, vol. 51, no. 4, pp. 921–960, 2007.
[3] A. Alanazi and K. Elleithy, "An optimized hidden node detection paradigm for improving the coverage and network efficiency in wireless multimedia sensor networks," *Sensors*, vol. 16, no. 9, pp. 1438–1454, 2016.
[4] E. Al Nuaimi, H. Al Neyadi, N. Mohamed, and J. Al-Jaroodi, "Applications of big data to smart cities," *J. Internet Services Appl.*, vol. 6, no. 1, pp. 1–15, 2015.
[5] B. Rashid and M. H. Rehmani, "Applications of wireless sensor networks for urban areas: A survey," *J. Netw. Comput. Appl.*, vol. 60, pp. 192–219, Jan. 2016.
[6] M. A. Alsheikh, D. T. Hoang, D. Niyato, H.-P. Tan, and S. Lin, "Markov decision processes with applications in wireless sensor networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1239–1267, 3rd Quart., 2015.
[7] M. Abazeed, N. Faisal, S. Zubair, and A. Ali, "Routing protocols for wireless multimedia sensor network: A survey," *J. Sensors*, vol. 2013, pp. 1–11, Nov. 2013.
[8] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2004.
[9] M. Z. Hasan and T. C. Wan, "Optimized quality of service for real-time wireless sensor networks using a partitioning multipath routing approach," *J. Comput. Netw. Commun.*, vol. 2013, p. 18, Jan. 2013. [Online]. Available: http://dx.doi.org/10.1155/2013/497157
[10] I. T. Almalkawi, M. G. Zapata, J. N. Al-Karaki, and J. Morillo-Pozo, "Wireless multimedia sensor networks: Current trends and future directions," *Sensors*, vol. 10, no. 7, pp. 6662–6717, 2010.
[11] D. Niyato, E. Hossain, and A. Fallahi, "Sleep and wakeup strategies in solar-powered wireless sensor/mesh networks: Performance analysis and optimization," *IEEE Trans. Mobile Comput.*, vol. 6, no. 2, pp. 221–236, Feb. 2007.
[12] A.-V. Sutagundar, S.-S. Manvi, and K.-B. Balavalad, "Energy efficient multipath routing protocol for WMSNs," *Int. J. Comput. Elect. Eng.*, vol. 2, no. 3, pp. 503–510, 2010.
[13] M. Radi, B. Dezfouli, B. K. Abu, and M. Lee, "Multipath routing in wireless sensor networks: Survey and research challenges," *Sensors*, vol. 12, no. 1, pp. 650–685, 2012.
[14] S. Ehsan and B. Hamdaoui, "A survey on energy-efficient routing techniques with QoS assurances for wireless multimedia sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 2, pp. 265–278, 2nd Quart., 2012.
[15] W. Lou, W. Liu, and Y. Zhang, "Performance optimization using multipath routing in mobile ad hoc and wireless sensor networks," in *Combinatorial Optimization in Communication Networks*, vol. 18, M. X. Cheng, Y. Li, and D.-Z. Du, Eds. New York, NY, USA: Springer, 2006, pp. 117–146.
[16] N. Mishra and A. Kumar, "Comparative analysis: Energy efficient multipath routing in wireless sensor network," *Int. J. Comput. Sci. Mobile Comput.*, vol. 3, no. 9, pp. 627–632, 2014.
[17] P. Gopi, "Multipath routing in wireless sensor networks: A survey and analysis," *IOSR J. Comput. Eng.*, vol. 16, no. 4, pp. 27–34, 2014.
[18] T. Vairam and C. Kalaiarasan, "Interference aware multi-path routing in wireless sensor networks," *Int. J. Emerg. Sci. Eng.*, vol. 1, no. 10, pp. 74–78, 2013.
[19] M. Korkalainen, M. Sallinen, N. Kärkkainen, and P. Tukeva, "Survey of wireless sensor networks simulation tools for demanding applications," in *Proc. 5th Int. Conf. Netw. Services (ICNS)*, Valencia, Spain, Apr. 2009, pp. 102–106.

[20] C. P. Singh, O. P. Vyas, and M. K. Tiwari, “A survey of simulation in sensor networks,” in *Proc. Int. Conf. Comput. Intell. Model. Control Autom.*, Vienna, Austria, 2008, pp. 867–872.

[21] Y. Li, C. S. Chen, Y.-Q. Song, and Z. Wang, “Real-time QoS support in wireless sensor networks: A survey,” in *Proc. 7th IFAC Int. Conf. Fieldbuses Netw. Ind. Embedded Syst.*, vol. 40. Toulouse, France, 2007, pp. 373–380.

[22] J. A. Stankovic, T. E. Abdelzaher, C. Lu, L. Sha, and J. C. Hou, “Real-time communication and coordination in embedded sensor networks,” *Proc. IEEE*, vol. 91, no. 7, pp. 1002–1022, Jul. 2003.

[23] A.-D. Zhan, T.-Y. Xu, G.-H. Chen, B.-L. Ye, and S.-L. Lu, “A survey on real-time routing protocols for wireless sensor networks,” *Chin. J. Comput. Sci.*, vol. 3, no. 11, pp. 234–238, 2008.

[24] P. Hambarde, R. Varma, and S. Jha, “The survey of real time operating system: RTOS,” in *Proc. Int. Conf. Electron. Syst. Signal Process. Comput. Technol. (ICESC)*, Nagpur, India, 2014, pp. 34–39.

[25] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002.

[26] K. Akkaya and M. Younis, “A survey on routing protocols for wireless sensor networks,” *Ad Hoc Netw.*, vol. 3, no. 3, pp. 325–349, 2005.

[27] J. Lessmann, P. Janacik, L. Lachev, and D. Orfanus, “Comparative study of wireless network simulators,” in *Proc. ICN 7th Int. Conf. Netw.*, Cancún, Mexico, 2008, pp. 517–523.

[28] Z. Jin, Y. Jian-Ping, Z. Si-Wang, L. Ya-Ping, and L. Guang, “A survey on position-based routing algorithms in wireless sensor networks,” *Algorithms*, vol. 2, no. 1, pp. 158–182, 2009.

[29] C. Li, H. Zhang, B. Hao, and J. Li, “A survey on routing protocols for large-scale wireless sensor networks,” *Sensors*, vol. 11, no. 4, pp. 3498–3526, 2011.

[30] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados, “Energy-efficient routing protocols in wireless sensor networks: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 551–591, 2nd Quart., 2013.

[31] Z. Hamid and F. B. Hussain, “QoS in wireless multimedia sensor networks: A layered and cross-layered approach,” *Wireless Pers. Commun.*, vol. 75, no. 1, pp. 729–757, 2014.

[32] E. Gürses and Ö. B. Akan, “Multimedia communication in wireless sensor networks,” *Annales Des Télécommun.*, vol. 60, no. 7, pp. 872–900, 2005.

[33] S. Misra, M. Reisslein, and G. Xue, “A survey of multimedia streaming in wireless sensor networks,” *IEEE Commun. Surveys Tuts.*, vol. 10, no. 4, pp. 18–39, 4th Quart., 2008.

[34] M. M. M. Masdari and M. T. M. Tanabi, “Multipath routing protocols in wireless sensor networks: A survey and analysis,” *Int. J. Future Gener. Commun. Netw.*, vol. 6, no. 6, pp. 181–192, 2013.

[35] S. K. Singh, T. Das, and A. Jukan, “A survey on Internet multipath routing and provisioning,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2157–2175, 4th Quart., 2015.

[36] P. Goyal, X. Guo, and H. M. Vin, “A hierarchical CPU scheduler for multimedia operating systems,” in *Proc. 2nd USENIX Symp. Oper. Syst. Design Implement.*, Seattle, WA, USA, Oct. 1996, pp. 491–505.

[37] S. C. Nelson, R. Kravets, and Y.-C. Hu, “Understanding and developing a dynamic manycast solution for DTNs,” Comput. Sci. Dept. Comput. Sci. College Eng. Univ. Univ. Illinois, Champaign, IL, USA, Res. Tech. Rep. 2011-03-07, 2011.

[38] I. Lee, W. Shaw, and X. Fan, “Wireless multimedia sensor networks,” in *Guide to Wireless Sensor Networks*. London, U.K.: Springer, 2009, pp. 561–582.

[39] F. Akhtar and M. H. Rehmani, “Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review,” *Renew. Sustain. Energy Rev.*, vol. 45, pp. 769–784, May 2015.

[40] N. Ostadabbasi, “Analysis of routing algorithms for energy harvesting wireless sensor network,” M.S. thesis, DTU Comput. Sci. Eng., Tech. Univ. Denmark, Lyngby, Denmark, 2013.

[41] F. M. Al-Turjman, H. S. Hassanein, and M. Ibnkahla, “Towards prolonged lifetime for deployed WSNs in outdoor environment monitoring,” *Ad Hoc Netw.*, vol. 24, pp. 172–185, Jan. 2015.

[42] M. H. Anisi, G. Abdul-Salaam, M. Y. I. Idris, A. W. A. Wahab, and I. Ahmedy, “Energy harvesting and battery power based routing in wireless sensor networks,” *Wireless Netw.*, vol. 23, no. 1, pp. 1–18, 2017.

[43] E. Setton, T. Yoo, X. Zhu, A. Goldsmith, and B. Girod, “Cross-layer design of ad hoc networks for real-time video streaming,” *IEEE Wireless Commun.*, vol. 12, no. 4, pp. 59–65, Aug. 2005.

[44] A. J. Goldsmith and S. B. Wicker, “Design challenges for energy-constrained ad hoc wireless networks,” *IEEE Wireless Commun.*, vol. 9, no. 4, pp. 8–27, Aug. 2002.

[45] M. Abazeed *et al.*, “A review of secure routing approaches for current and next-generation wireless multimedia sensor networks,” *Int. J. Distrib. Sensor Netw.*, vol. 2015, p. 3, Jan. 2015.

[46] P. Sinha, “QoS issues in ad-hoc networks,” in *Ad Hoc Networks*, P. Mohapatra and S. V. Krishnamurthy, Eds. New York, NY, USA: Springer, 2005, pp. 229–247.

[47] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, “Wireless multimedia sensor networks: Applications and testbeds,” *Proc. IEEE*, vol. 96, no. 10, pp. 1588–1605, Oct. 2008.

[48] M. A. Hamid, M. M. Alam, and C. S. Hong, “Design of a QoS-aware routing mechanism for wireless multimedia sensor networks,” in *Proc. IEEE Glob. Telecommun. Conf. (GLOBECOM)*, New Orleans, LA, USA, 2008, pp. 1–6.

[49] D. Chen and P. K. Varshney, “QoS support in wireless sensor networks: A survey,” in *Proc. Int. Conf. Wireless Netw. (ICWN)*, Las Vegas, NV, USA, Jan. 2004, pp. 227–233.

[50] W. Dargie and C. Poellabauer, *Fundamentals of Wireless Sensor Networks: Theory and Practice*. Chichester, U.K.: Wiley, 2010.

[51] G. T. Singh and F. M. Al-Turjman, “A data delivery framework for cognitive information-centric sensor networks in smart outdoor monitoring,” *Comput. Commun.*, vol. 74, pp. 38–51, Jan. 2016.

[52] M. A. Yigitel, O. D. Incel, and C. Ersoy, “QoS-aware MAC protocols for wireless sensor networks: A survey,” *Comput. Netw.*, vol. 55, no. 8, pp. 1982–2004, 2011.

[53] G. T. Singh and F. M. Al-Turjman, “Cognitive routing for information-centric sensor networks in smart cities,” in *Proc. Int. Conf. Wireless Commun. Mobile Comput. (IWCMC)*, Nicosia, Cyprus, 2014, pp. 1124–1129.

[54] F. Al-Turjman and M. Gunay, “CAR approach for the Internet of Things,” *Can. J. Elect. Comput. Eng.*, vol. 39, no. 1, pp. 11–18, Jan. 2016.

[55] R. V. Kulkarni, A. Forster, and G. K. Venayagamoorthy, “Computational intelligence in wireless sensor networks: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 13, no. 1, pp. 68–96, 1st Quart., 2011.

[56] R. Pabst *et al.*, “Relay-based deployment concepts for wireless and mobile broadband radio,” *IEEE Commun. Mag.*, vol. 42, no. 9, pp. 80–89, Sep. 2004.

[57] J. Jeong, D. Culler, and J.-H. Oh, “Empirical analysis of transmission power control algorithms for wireless sensor networks,” in *Proc. 4th Int. Conf. Netw. Sens. Syst. (INSS)*, Brunswick, Germany, 2007, pp. 27–34.

[58] K. Dimitris, “High-speed multimedia networks: Critical issues and trends,” in *Handbook of Research on Telecommunications Planning and Management for Business*, I. Lee, Ed. Hershey, PA, USA: IGI Glob., 2009, pp. 775–787.

[59] Z. Bojkovic and D. Milovanovic, “Challenges in mobile multimedia: Technologies and QoS requirements,” in *Proc. 7th WSEAS Int. Conf. Math. Methods Comput. Tech. Elect. Eng.*, Sofia, Bulgaria, 2005, pp. 7–12.

[60] S. Aswale and V. R. Ghorpade, “Survey of QoS routing protocols in wireless multimedia sensor networks,” *J. Comput. Netw. Commun.*, vol. 2015, no. 17, pp. 1–29, 2015.

[61] S. M. Zin, N. B. Anuar, M. L. M. Kiah, and I. Ahmedy, “Survey of secure multipath routing protocols for WSNs,” *J. Netw. Comput. Appl.*, vol. 55, pp. 123–153, Sep. 2015.

[62] D. Goyal and M. R. Tripathy, “Routing protocols in wireless sensor networks: A survey,” in *Proc. 2nd Int. Conf. Adv. Comput. Commun. Technol. (ACCT)*, Rohtak, India, 2012, pp. 474–480.

[63] M. Gupta and N. Kumar, “Node-disjoint on-demand multipath routing with route utilization in ad-hoc networks,” *Int. J. Comput. Appl.*, vol. 70, no. 9, pp. 29–33, 2013.

[64] J. Pu, E. Manning, and G. C. Shoja, “Routing reliability analysis of partially disjoint paths,” in *Proc. IEEE Pac. Rim Conf. Comput. Signal Process. (PACRIM)*, vol. 1. Victoria, BC, Canada, 2001, pp. 79–82.

[65] M. Tarique, K. E. Tepe, S. Adibi, and S. Erfani, “Survey of multipath routing protocols for mobile ad hoc networks,” *J. Netw. Comput. Appl.*, vol. 32, no. 6, pp. 1125–1143, 2009.

[66] T. Watteyne, A. Molinaro, M. G. Richichi, and M. Dohler, “From MANET to IETF ROLL standardization: A paradigm shift in WSN routing protocols,” *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 688–707, 4th Quart., 2011.

[67] S. Mueller, R. P. Tsang, and D. Ghosal, "Multipath routing in mobile ad hoc networks: Issues and challenges," in *Performance Tools and Applications to Networked Systems*, vol. 2965, M. C. Calzarossa and E. Gelenbe, Eds. Heidelberg, Germany: Springer, 2004, pp. 209–234.

[68] S. Adibi and R. Jain, S. Parekh, and T. Tofigh, Eds., *Quality of Service Architectures for Wireless Networks: Performance Metrics and Management*. Inf. Sci. Pub., 2010.

[69] G. Spanogiannopoulos, N. Vlajic, and D. Stevanovic, "A simulation-based performance analysis of various multipath routing techniques in ZigBee sensor networks," in *Ad Hoc Networks*, vol. 28, J. Zheng, S. Mao, S. F. Midkiff, and H. Zhu, Eds. Heidelberg, Germany: Springer, 2010, pp. 300–315.

[70] V. Bhandary, A. Malik, and S. Kumar, "Routing in wireless multimedia sensor networks: A survey of existing protocols and open research issues," *J. Eng.*, vol. 2016, pp. 1–27, Mar. 2016.

[71] T. Cevik, A. Gunagwera, and N. Cevik, "A survey of multimedia streaming in wireless sensor networks: Progress, issues and design challenges," *Int. J. Comput. Netw. Commun.*, vol. 7, no. 15, pp. 95–114, 2015.

[72] J. Chen, M. Díaz, L. Llopis, B. Rubio, and J. M. Troya, "A survey on quality of service support in wireless sensor and actor networks: Requirements and challenges in the context of critical infrastructure protection," *J. Netw. Comput. Appl.*, vol. 34, no. 4, pp. 1225–1239, 2011.

[73] A. Jayashree, G. Biradar, and V. Mytri, "Review of multipath routing protocols in wireless multimedia sensor network—A survey," *Int. J. Sci. Eng. Res.*, vol. 3, no. 7, pp. 1–9, 2012.

[74] S. K. Gurung and D. K. Saikia, "A survey of multipath routing schemes of wireless mesh networks," *Int. J. Comput. Appl.*, vol. 125, no. 14, pp. 12–20, 2015.

[75] N. S. Nandiraju, D. S. Nandiraju, and D. P. Agrawal, "Multipath routing in wireless mesh networks," in *Proc. IEEE Conf. Int. Mobile Adhoc Sensor Syst. (MASS)*, Vancouver, BC, Canada, 2006, pp. 741–746.

[76] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-resilient, energy-efficient multipath routing in wireless sensor networks," *SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 5, no. 4, pp. 11–25, 2001.

[77] J. Guo, L. Sun, and R. Wang, "A cross-layer and multipath based video transmission scheme for wireless multimedia sensor networks," *J. Netw.*, vol. 7, no. 9, pp. 1334–1340, 2012.

[78] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie, "Protocols for self-organization of a wireless sensor network," *IEEE Pers. Commun.*, vol. 7, no. 5, pp. 16–27, Oct. 2000.

[79] T. He, J. A. Stankovic, C. Lu, and T. Abdelzaher, "SPEED: A stateless protocol for real-time communication in sensor networks," in *Proc. 23rd Int. Conf. Distrib. Comput. Syst.*, Providence, RI, USA, 2003, pp. 46–55.

[80] T. He, J. A. Stankovic, T. F. Abdelzaher, and C. Lu, "A spatiotemporal communication protocol for wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 16, no. 10, pp. 995–1006, Oct. 2005.

[81] M. S. Kordafshari, A. Pourkabirian, K. Faez, and A. M. Rahimabadi, "Energy-efficient SPEED routing protocol for wireless sensor networks," in *Proc. 5th Adv. Int. Conf. Telecommun. (AICT)*, Mestre, Italy, 2009, pp. 267–271.

[82] K. Sha, J. Du, and W. Shi, "WEAR: A balanced, fault-tolerant, energy-aware routing protocol in WSNs," *Int. J. Sensor Netw.*, vol. 1, nos. 3–4, pp. 156–168, 2006.

[83] L. Gan, J. Liu, and X. Jin, "Agent-based, energy efficient routing in sensor networks," presented at the 3rd Int. Joint Conf. Auton. Agents Multiagent Syst., vol. 1. New York, NY, USA, 2004, pp. 472–479.

[84] L. Yao, W. Wenjing, and G. Fuxiang, "A real-time and energy aware QoS routing protocol for multimedia wireless sensor networks," in *Proc. 7th World Congr. Intell. Control Autom. (WCICA)*, 2008, pp. 3321–3326.

[85] A. A. Ahmed, L. A. Latiff, M. A. Sarijari, and N. Fisal, "Real-time routing in wireless sensor networks," in *Proc. 28th Int. Conf. Distrib. Comput. Syst. Workshops (ICDCS)*, Beijing, China, 2008, pp. 114–119.

[86] A. A. Ahmed and N. Fisal, "A real-time routing protocol with load distribution in wireless sensor networks," *Comput. Commun.*, vol. 31, no. 14, pp. 3190–3203, 2008.

[87] K. Akkaya and M. Younis, "Energy-aware delay-constrained routing in wireless sensor networks," *Int. J. Commun. Syst.*, vol. 17, no. 6, pp. 663–687, 2004.

[88] N. Saxena, A. Roy, and J. Shin, "QuESt: A QoS-based energy efficient sensor routing protocol," *Wireless Commun. Mobile Comput.*, vol. 9, no. 3, pp. 417–426, 2009.

[89] E. Gelenbea, E. Ngaib, and P. Yadav, "Routing of high-priority packets in wireless sensor networks," in *Proc. IEEE 2nd Int. Conf. Comput. Netw. Technol.*, vol. 66. 2008, pp. 1–9.

[90] O. Chipara *et al.*, "Real-time power-aware routing in sensor networks," in *Proc. 14th IEEE Int. Workshop Qual. Service (IWQoS)*, New Haven, CT, USA, 2006, pp. 83–92.

[91] Y. Li, C. S. Chen, Y.-Q. Song, Z. Wang, and Y. Sun, "Enhancing real-time delivery in wireless sensor networks with two-hop information," *IEEE Trans. Ind. Informat.*, vol. 5, no. 2, pp. 113–122, May 2009.

[92] M. S. Al-Fares and Z. Sun, "Self-organizing routing protocol to achieve QoS in wireless sensor network for forest fire monitoring," in *Proc. IEEE 9th Malaysia Int. Conf. Commun. (MICC)*, Kuala Lumpur, Malaysia, 2009, pp. 211–216.

[93] M. S. Al-Fares, Z. Sun, and H. Cruickshank, "A reliable multi-hop hierarchical routing protocol in wireless sensor network (WSN)," in *Proc. 6th Int. Conf. Inf. Technol. New Gener. (ITNG)*, Las Vegas, NV, USA, 2009, pp. 1604–1605.

[94] J. Zhu, M. Jo, D. Seong, and J. Yoo, "Tasks allocation for real-time applications in heterogeneous sensor networks for energy minimization," presented at the 18th Int. Conf. Softw. Eng. Artif. Intell. Netw. Parallel Distrib. Comput., vol. 2. 2007, pp. 20–25.

[95] J. Park, M. Jo, D. Seong, and J. Yoo, "Disjointed multipath routing for real-time data in wireless multimedia sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 2014, p. 8, Jan. 2014.

[96] Y. M. Lu and V. W. S. Wong, "An energy-efficient multipath routing protocol for wireless sensor networks," *Int. J. Commun. Syst.*, vol. 20, no. 7, pp. 747–766, 2007.

[97] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[98] X. Liu, "Atypical hierarchical routing protocols for wireless sensor networks: A review," *IEEE Sensors J.*, vol. 15, no. 10, pp. 5372–5383, Oct. 2015.

[99] M. Xie and Y. Gu, "Multipath routing algorithm for wireless multimedia sensor networks within expected network lifetime," in *Proc. Int. Conf. Commun. Mobile Comput. (CMC)*, Shenzhen, China, 2010, pp. 284–287.

[100] E. Y. Sun, X. J. Shen, and H. P. Chen, "Energy balancing multipath routing protocol in wireless multimedia sensor networks," *Appl. Mech. Mater.*, vols. 155–156, pp. 245–249, Feb. 2012.

[101] J. Agrakhed, G. S. Biradar, and V. D. Mytri, "Adaptive multi constraint multipath routing protocol in wireless multimedia sensor network," in *Proc. Int. Conf. Comput. Sci. (ICCS)*, Phagwara, India, 2012, pp. 326–331.

[102] I. Nikseresht, H. Yousefi, A. Movaghar, and M. Khansari, "Interference-aware multipath routing for video delivery in wireless multimedia sensor networks," in *Proc. 32nd Int. Conf. Distrib. Comput. Syst. Workshops (ICDCSW)*, 2012, pp. 216–221.

[103] K. Mizanian, H. Yousefi, and A. H. Jahangir, "RETRACTED: Worst case dimensioning and modeling of reliable real-time multihop wireless sensor network," *Perform. Eval.*, vol. 66, no. 12, pp. 685–700, 2009.

[104] E. Felemban, C.-G. Lee, and E. Ekici, "MMSPEED: Multipath multi-SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 6, pp. 738–754, Jun. 2006.

[105] B. Deb, S. Bhatnagar, and B. Nath, "ReInForM: Reliable information forwarding using multiple paths in sensor networks," in *Proc. 28th Annu. IEEE Int. Conf. Local Comput. Netw. (LCN)*, Bonn, Germany, 2003, pp. 406–415.

[106] Y. Yang, C. Zhong, Y. Sun, and J. Yang, "Network coding based reliable disjoint and braided multipath routing for sensor networks," *J. Netw. Comput. Appl.*, vol. 33, no. 4, pp. 422–432, 2010.

[107] U. B. Mahadevaswamy and M. N. Shanmukhaswamy, "An energy efficient reliable multipath routing protocol for data gathering in wireless sensor networks," *Int. J. Comput. Sci. Inf. Security*, vol. 8, no. 2, pp. 59–64, 2010.

[108] G. Wu *et al.*, "Dynamical jumping real-time fault-tolerant routing protocol for wireless sensor networks," *Sensors*, vol. 10, no. 3, pp. 2416–2437, 2010.

[109] S. Dulman, T. Nieberg, J. Wu, and P. Havinga, "Trade-off between traffic overhead and reliability in multipath routing for wireless sensor networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, vol. 3. New Orleans, LA, USA, 2003, pp. 1918–1922.

[110] Y. Chen and N. Nasser, "Enabling QoS multipath routing protocol for wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Beijing, China, 2008, pp. 2421–2425.

[111] N. Nasser and Y. Chen, "SEEM: Secure and energy-efficient multipath routing protocol for wireless sensor networks," *Comput. Commun.*, vol. 30, nos. 11–12, pp. 2401–2412, 2007.

[112] X. Huang and Y. Fang, "Multiconstrained QoS multipath routing in wireless sensor networks," *Wireless Netw.*, vol. 14, no. 4, pp. 465–478, 2008.

[113] A. B. Bagula and K. G. Mazandu, "Energy constrained multipath routing in wireless sensor networks," in *Ubiquitous Intelligence and Computing*. Heidelberg, Germany: Springer, 2008, pp. 453–467.

[114] T. Houngbadji and S. Pierre, "QoSNET: An integrated QoS network for routing protocols in large scale wireless sensor networks," *Comput. Commun.*, vol. 33, no. 11, pp. 1334–1342, 2010.

[115] J. Ben-Othman and B. Yahya, "Energy efficient and QoS based routing protocol for wireless sensor networks," *J. Parallel Distrib. Comput.*, vol. 70, no. 8, pp. 849–857, 2010.

[116] B. Yahya and J. Ben-Othman, "REER: Robust and energy efficient multipath routing protocol for wireless sensor networks," in *Proc. IEEE Glob. Telecommun. Conf. (GLOBECOM)*, Honolulu, HI, USA, 2009, pp. 1–7.

[117] K. Akkaya and M. Younis, "An energy-aware QoS routing protocol for wireless sensor networks," in *Proc. 23rd Int. Conf. Distrib. Comput. Syst. Workshops*, Providence, RI, USA, 2003, pp. 710–715.

[118] Z. Yuanyuan, C. J. Sreenan, and L. Sitanayah, "A real-time and robust routing protocol for building fire emergency applications using wireless sensor networks," in *Proc. 8th IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PERCOM Workshops)*, Mannheim, Germany, 2010, pp. 358–363.

[119] K. Lin, M. Chen, and X. Ge, "Adaptive reliable routing based on cluster hierarchy for wireless multimedia sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2010, pp. 1–13, Jan. 2010.

[120] G. H. EkbataniFard, R. Monsefi, M.-R. Akbarzadeh-T, and M. H. Yaghmaee, "A multi-objective genetic algorithm based approach for energy efficient QoS-routing in two-tiered wireless sensor networks," presented at the 5th IEEE Int. Symp. Wireless Pervasive Comput. (ISWP), Modena, Italy, 2010, pp. 80–85.

[121] Y. Hu, Y. Ding, and K. Hao, "An immune cooperative particle swarm optimization algorithm for fault-tolerant routing optimization in heterogeneous wireless sensor networks," *J. Math. Problems Eng.*, vol. 2012, p. 19, Aug. 2011.

[122] M. Liu, S. Xu, and S. Sun, "An agent-assisted QoS-based routing algorithm for wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 35, no. 1, pp. 29–36, 2012.

[123] S.-L. Wu and Y.-C. Tseng, *Wireless Ad Hoc Networking: Personal-Area, Local-Area and the Sensory-Area Networks*. Boca Raton, FL, USA: Auerbach, 2007.

[124] N. Bulusu and S. Jha, *Wireless Sensor Network Systems: A Systems Perspective* (Artech House Mems and Sensors Library). Norwood, MA, USA: Artech House, Inc., 2005, p. 326.

[125] J. Kulik, W. Heinzelman, and H. Balakrishnan, "Negotiation-based protocols for disseminating information in wireless sensor networks," *Wireless Netw.*, vol. 8, no. 2, pp. 169–185, 2002.

[126] D. Braginsky and D. Estrin, "Rumor routing algorithm for sensor networks," presented at the 1st ACM Int. Workshop Wireless Sensor Netw. Appl., Atlanta, GA, USA, 2002, pp. 22–31.

[127] J. Faruque and A. Helmy, "Gradient-based routing in sensor networks," *SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 7, no. 4, pp. 50–52, 2003.

[128] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, and F. Silva, "Directed diffusion for wireless sensor networking," *IEEE/ACM Trans. Netw.*, vol. 11, no. 1, pp. 2–16, Feb. 2003.

[129] J. Choe and K. Kim, "EADD: Energy aware directed diffusion for wireless sensor networks," in *Proc. Int. Symp. Parallel Distrib. Process. Appl. (ISPA)*, Sydney, NSW, Australia, 2008, pp. 779–783.

[130] S. Li, A. Lim, S. Kulkarni, and C. Liu, "EDGE: A routing algorithm for maximizing throughput and minimizing delay in wireless sensor networks," in *Proc. IEEE Conf. Mil. Commun. (MILCOM)*, Orlando, FL, USA, 2007, pp. 1–7.

[131] S. Li, R. K. Neelisetti, C. Liu, and A. Lim, "Efficient multipath protocol for wireless sensor networks," *Int. J. Wireless Mobile Netw.*, vol. 2, no. 1, pp. 110–130, 2010.

[132] C.-C. Shen, C. Srisathapornphat, and C. Jaikaeo, "Sensor information networking architecture and applications," *IEEE Pers. Commun.*, vol. 8, no. 4, pp. 52–59, Aug. 2001.

[133] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, "A review of routing protocols for mobile ad hoc networks," *Ad Hoc Netw.*, vol. 2, no. 1, pp. 1–22, 2004.

[134] R. Leung, J. Liu, E. Poon, A.-L. C. Chan, and B. Li, "MP-DSR: A QoS-aware multi-path dynamic source routing protocol for wireless ad-hoc networks," in *Proc. 26th Annu. IEEE Conf. Local Comput. Netw. (LCN)*, Tampa, FL, USA, 2001, pp. 132–141.

[135] P. Huang, H. Tian, M. Zhang, and P. Zhang, "Robust multi-path routing for dynamic topology in wireless sensor networks," *J. China Univ. Posts Telecommun.*, vol. 14, no. 1, pp. 1–5, 2007.

[136] S. Dulman, J. Wu, and P. M. Havinga, *An Energy Efficient Multipath Routing Algorithm for Wireless Sensor Networks*. Enschede, The Netherlands: Univ. Twente, 2003, p. 6.

[137] R. C. Shah and J. M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Proc. IEEE Conf. Wireless Commun. Netw. (WCNC)*, vol. 1. Orlando, FL, USA, 2002, pp. 350–355.

[138] S.-R. Jung, J.-H. Lee, and B.-H. Roh, "An optimized node-disjoint multi-path routing protocol for multimedia data transmission over wireless sensor networks," presented at the IEEE Int. Symp. Parallel Distrib. Process. Appl., Sydney, NSW, Australia, 2008, pp. 958–963.

[139] P. Hurni and T. Braun, "Energy-efficient multi-path routing in wireless sensor networks," in *Ad-hoc, Mobile and Wireless Networks*, vol. 5198, D. Coudert, D. Simplot-Ryl, and I. Stojmenovic, Eds. Heidelberg, Germany: Springer, 2008, pp. 72–85.

[140] P. Hurni and T. Braun, "Evaluation of wiseMAC on sensor nodes," in *Wireless and Mobile Networking*, vol. 284, Z. Mammeri, Ed. Boston, MA, USA: Springer, 2008, pp. 187–198.

[141] K.-H. Kim *et al.*, "A resilient multipath routing protocol for wireless sensor networks," in *Proc. 4th II Int. Conf. Netw.*, Reunion Island, France, Apr. 2005, pp. 1122–1129.

[142] E. M. Royer and C.-K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Pers. Commun.*, vol. 6, no. 2, pp. 46–55, Apr. 1999.

[143] C. J. B. Abbas, N. Cárdenas, G. Lobalsamo, and N. Davila, "SHRP: A new routing protocol to wireless sensor networks," in *Advances in Computer Science and Engineering*, vol. 6, H. Sarbazi-Azad, B. Parhami, S.-G. Miremadi, S. Hessabi, Eds. Heidelberg, Germany: Springer, 2009, pp. 138–146.

[144] S. Sesay, Z. Yang, and J. He, "A survey on mobile ad hoc wireless network," *Inf. Technol. J.*, vol. 3, no. 2, pp. 168–175, 2004.

[145] R. Benlamri, "Networked digital technologies," in *Proc. II 4th Int. Conf. (NDT)*, vol. 294. Dubai, UAE, Apr. 2012, pp. 1–12.

[146] C. Mbarushimana and A. Shahrabi, "Comparative study of reactive and proactive routing protocols performance in mobile ad hoc networks," in *Proc. 21st Int. Conf. Adv. Inf. Netw. Appl. Workshops (AINAW)*, Niagara Falls, ON, Canada, 2007, pp. 679–684.

[147] S. Lipsa, "An empirical study of multipath routing protocols in wireless sensor networks," *Int. J. Comput. Sci. Inf. Technol.*, vol. 5, no. 4, pp. 5375–5379, 2014.

[148] L. Schrage, *Optimization Modeling With LINGO*. Chicago, IL, USA: LINDO Syst., 1998.

[149] F. M. Al-Turjman, H. S. Hassanein, and M. Ibnkahla, "Quantifying connectivity in wireless sensor networks with grid-based deployments," *J. Netw. Comput. Appl.*, vol. 36, no. 1, pp. 368–377, 2013.

[150] M. H. Rehmani and A.-S. K. Pathan, *Emerging Communication Technologies Based on Wireless Sensor Networks: Current Research and Future Applications*. Boca Raton, FL, USA: CRC Press, 2016.

[151] S. H. R. Bukhari, M. H. Rehmani, and S. Siraj, "A survey of channel bonding for wireless networks and guidelines of channel bonding for futuristic cognitive radio sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 924–948, 2nd Quart., 2016.

[152] O. B. Akan, O. B. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Netw.*, vol. 23, no. 4, pp. 34–40, Jul./Aug. 2009.

[153] A. O. Bicen, V. C. Gungor, and O. B. Akan, "Delay-sensitive and multimedia communication in cognitive radio sensor networks," *Ad Hoc Netw.*, vol. 10, no. 5, pp. 816–830, 2012.

[154] A. Fallahi and E. Hossain, "QoS provisioning in wireless video sensor networks: A dynamic power management framework," *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 40–49, Dec. 2007.

[155] T. J. S. Khanzada and M. F. Shahid, "Realizing cognitive radio technology for wireless sensor networks," in *Emerging Communication Technologies Based on Wireless Sensor Networks*. Boca Raton, FL, USA: CRC Press, 2016, pp. 259–272.

[156] F. M. Al-Turjman, "Information-centric sensor networks for cognitive IoT: An overview," *Ann. Telecommun.*, vol. 72, no. 1, pp. 3–18, 2017.

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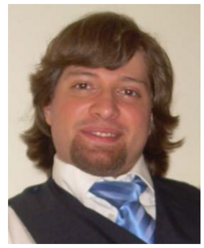

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