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Review Article

Survey of QoS Routing Protocols in Wireless Multimedia Sensor Networks

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The emergence of Wireless Multimedia Sensor Networks (WMSNs) has stimulated the refocusing of research from conventional scalar Wireless Sensor Networks (WSNs) to WMSNs. Currently, because of their prevalence WMSNs are used in different applications. Due to the unique features of WMSNs, fulfilling Quality of Service (QoS) requirements for a variety of applications is the challenge. QoS routing is a backbone of WMSNs and plays a vital role in satisfying QoS requirements. The performance of QoS routing depends upon the selection of an optimal path or paths. Path selection is based on evaluation of a cost function using various routing metrics. A careful blend of such metrics in a routing cost function guarantees a committed level of QoS. This survey uses number of routing metrics as criteria for categorizing state-of-the-art QoS WMSNs routing techniques. In addition, open issues and future research directions to further develop efficient routing protocols to guarantee QoS are discussed.

1. Introduction

In the past decade, Wireless Sensor Networks (WSNs) have been a focus of researchers due to advances in Micro-Electro-Mechanical Systems (MEMS) technology [1]. Advances in digital electronics, MEMS technology, and radio communication have facilitated the design and development of physically small, low-cost, multifunctional, low-power smart sensor nodes. A WSN consists of a large number of randomly and densely deployed sensor nodes that can interact with one another and with the surrounding environment to sense, measure, and control scalar physical parameters of interest. Growing interest in WSNs has already facilitated a wide range of applications including habitat monitoring, military, environmental control, logistics support, human-centric applications, industrial control, and disaster relief [2–4].

Over the past few years, progress in Complementary Metal-Oxide Semiconductor (CMOS) technology has facilitated the development of low-cost, physically small smart sensors to sense multimedia data [5]. This development gave rise to a new type of network called a Wireless Multimedia Sensor Network (WMSN), which is composed of smart sensor nodes that collect and route multimedia streams, still images, and scalar sensor data in real-time and nonreal time. In recent years, many applications based on WMSNs have been developed for surveillance, advanced health care, smart homes, and environmental and industrial monitoring [6, 7].

Although WMSNs evolved from WSNs, the former can be differentiated from their predecessor in terms of greater energy consumption, stringent real-time performance, high bandwidth requirement, high packet loss rate, and more processing capability. In WMSNs, a large amount of data is generated. Handling multimedia data with limited available resources and guaranteeing the variable Quality of Service (QoS) are difficult tasks to achieve. In WMSNs, routing is a fundamental mechanism that offers a QoS guarantee for multimedia traffic; this need has been an active area of research for the past few years. Metric based path selection and management of routing metrics are two most important concerns of the routing scheme. Appropriate selection of routing metrics with proper grouping and mathematical properties of the path-weight calculation (cost function) is a prerequisite for satisfying the routing requirements of network traffic [5, 8, 9]. Optimal links, or optimal paths, are characterized by the perfect fusion of a number of routing metrics with the help of a cost function. Optimal functioning of all existing routing protocols directly depends upon the proper combination of different routing metrics. An odd combination of these metrics may result in the degradation of routing performance; for example, permutation of any arbitrary routing metrics in a routing protocol may lead to failure and creation of routing loops, resulting in suboptimal paths [8]. For this reason, this survey considers the number of routing metrics used by routing protocol as criteria to categorize into distinct classes.

Several surveys have been conducted on sensor networks and routing protocols [10–17]. Current survey is different from previous surveys based on two aspects. First, WMSNs QoS routing protocols are categorized based on a number of metrics used to find link/path costs for the selection of the next forwarding node or optimal path. An increase in the number of metrics adds to the complexity of route computation but shows partial improvements in QoS routing. Second, this survey is more extensive as it analyzes more parameters for comparison of WMSNs QoS routing protocols compared to previous works. Additionally, this survey highlights the performance-related issues of every QoS routing technique. Finally, current and future research topics in the area of real, practical WMSNs are discussed.

The remainder of the paper is organized as follows: Section 2 presents various routing metrics used in the design of WMSNs routing link/path selection. Section 3 categorizes and surveys most existing WMSNs QoS routing schemes. Also merits, demerits, and performance of each scheme are discussed. An extensive comparative summary of various WMSNs QoS routing schemes is provided in tabular form in chronological order. In Section 4, related open issues and future research directions are outlined. Section 5 presents the conclusion.

2. Routing Metrics Associated with Link/Path Cost

In general, a metric is a system or standard of measurement defined as a parameter or measure for quantitatively assessing a method, event, and entity by using special procedures to perform measurements [9]. The performance of any WMSNs routing protocol depends upon limited available resources and the dynamic nature of the sensor network. A routing metric is a parameter or measure used to choose the best next neighbor node or an optimal path between source and destination node. Metric values are affected by environmental factors and network-imminent factors [18]. Mathematically, metrics can be categorized into static or dynamic, symmetric, or asymmetric and single dimensional or multidimensional. This section briefly outlines a set of routing metrics that are used in combination to find the weight/cost of a link/path. All routing metrics outlined in this section are discussed in the context of the WMSNs QoS protocols surveyed in Section 3.

(i) *Distance*. Distance is the geographical distance from the next forwarding neighboring node to the sink node or is the geographical distance between a current node and subsequent forwarding neighboring node. This is the most widely used basic metric [19–43]. On its own, the use of this metric may result in suboptimum performance but positively influences performance when used in combination with other metrics.

(ii) *Residual or Remaining Energy*. This metric represents the energy remaining in a sensor node at a specific time after the network is deployed. Residual energy is used extensively in routing decision [24, 25, 29, 32–40, 42–63]. It plays a crucial role in load balancing and extending the lifetime of the network. Certain routing techniques also consider average residual energy of sensor nodes along a single path [56, 57].

(iii) *Expected or Transmission Energy*. This metric represents the required energy to route a message between two sequential sensor nodes [48].

(iv) *Initial Energy*. This metric represent the energy in a sensor node at the beginning of the network deployment [63].

(v) *Bandwidth*. Bandwidth indicates bit rate of the available or consumed data capacity that can be used to send data over a link or a path in a given period [36, 41, 45, 59, 64–66].

(vi) *Hop Count or Number of Links*. This metric represents number of links a packet must travel from the next forwarding neighboring node to the sink or number of links a packet has travelled already to reach the current sensor node or number of links on a path from source to sink [4–26, 26–35, 35–38, 38, 39, 39–43, 50, 55, 60, 61, 63, 67–69]. This metric is independent of the quality and characteristics of the link.

(vii) *Delay or Latency*. The delay metric measures the time to transmit and receive a packet from sender to receiver. The delay is derived from the queuing delay, processing delay, propagation delay, and transmission delay [20, 21, 23, 27, 29–34, 42, 44, 47, 51, 58, 59, 61, 62, 65–67, 69].

(viii) *Packet Service Time (PST)*. It is a combination of queuing time, network layer processing time, MAC layer processing time, and the transmission time of a node at each sensor node [54, 61].

(ix) *Sleeping Delay*. In duty cycle based sensor network, a node can be in active or sleeping state. To forward the packet, current node must wait for the neighboring node to wake up. This delay is called sleeping delay [22].

(x) *Current Traffic Load or Number of Active Paths*. During new route establishment, the next forwarding node is selected based on the number of active paths through the neighboring node [46, 50].

(xi) *History*. History reports the history of packets belonging to the same flow on which the next routing decision is made [38, 39, 43].

(xii) *Reliability Requirement*. Reliability is a key factor for the performance of any routing protocol. Reliability requirement is the required probability of any packet reaching its destination [56–58, 68].

(xiii) *Reaching Probability*. Reaching probability represents the likelihood of a packet reaching a destination, expressed as a number between zero and one [30, 31, 56, 57].

(xiv) *Jitter*. Jitter represents packet delay variation or latency variation over time, which results in fluctuating packet interarrival times [65, 66]. A network with a consistent delay will have no jitter; however, with variable delay, it will have high jitter. Jitter is a paramount factor in multimedia routing.

(xv) *Buffer Size or Queue Length*. Every sensor node maintains queues for incoming packets and outgoing packets [52, 55]. The state of these queues decide the performance of the routing protocol.

(xvi) *Trust Value*. Based on this value, every node will have a trust or confidence in another node. In addition, it is based on level of service provided by its neighbors [53, 60]. Trust value can be computed directly or indirectly from neighboring nodes.

(xvii) *Data Correlation*. To reduce traffic redundancy and to optimize energy consumption a data fusion technique is used. The data correlation coefficient is used to characterize the fusion technique [53, 60].

(xviii) *Traffic Priority*. In multipath routing, multiple paths are found between source and sink. These paths can be shortest paths in terms of hop count or energy efficient paths or high throughput reliable paths. Based on the requirement of application data traffic can be prioritized to be distributed along different paths [40, 43].

(xix) *Inclination Angle*. Inclination angle is the angle formed by the line that connects the current node and the neighbor node and the line that connects the current node and the sink node [28].

(xx) *Path Contract Angle*. This angle is computed from deviation angle, number of hops from source to sink, and current hop number. Deviation angle is defined as the angle that specifies how much a path is expected to deviate from the reference line at the origin point. Reference line is defined as the straight line between the origin of the virtual coordinate system and the sink [41].

(xxi) *Included Angle*. Included angle is defined as the angle between the current node and the pairwise node with respect to x-axis. Pairwise node is a node in the 360° scope around sink node [41].

(xxii) *Transmission Radius*. The communication range of a sensor node depends on transmission radius [49, 64]. This metric is directly responsible for Link Interference. Although interference is associated with the MAC and physical layers, it plays a significant role in the routing process. Interflow interference and intraflow interference are two types of interferences. Interflow interference is interference among neighboring nodes contending for the same busy channel. Intraflow interference is interference between intermediate nodes sharing the same flow path.

(xxiii) *Channel Utilization*. Channel utilization indicates the contention level around a node [54, 61].

(xxiv) *Packet Loss Rate*. Packet loss rate represents the number of packets lost with respect to the number of packets sent. Packets are lost due to congestion or due to a damaged link [37, 51, 55, 59, 62, 66]. Packet loss rate is an important metric for measuring the performance of routing protocol.

(xxv) *Expected Transmission Count (ETX)*. To deliver packets effectively over a specific wireless link, number of transmission attempts are required; this number of attempts is called ETX and is based on the forward delivery ratio and reverse delivery ratio [52, 69]. ETX is an important metric that directly affects throughput but is independent of link data rate. A summation of the ETX value of each link along a path is the ETX value of the path.

(xxvi) *Packet Delivery Ratio*. The link quality is determined by the Packet Delivery Ratio (PDR) based on both data and control packets. PDR is the ratio of the number of transmitted packets to the number of acknowledged packets [58].

(xxvii) *Bit Error Rate*. Bit Error Rate (BER) metric is used to access the performance of the link [42, 68]. It is defined as the rate at which errors occur in a particular link.

(xxviii) *Link Quality Identifier (LQI)*. This metric characterizes the quality and strength of the received packet on a specific link [40]. LQI value ranges from 0 to 255, indicating lowest and highest quality of the link.

(xxix) *Signal-to-Noise Ratio (SNR)*. The signal-to-noise ratio is used to measure the quality of the channel and quality of the link [62]. The presence of noise will determine how much information can be transferred on the channel.

(xxx) *Airtime Link Metric*. Airtime link metric is default link metric used by Hybrid Wireless Mesh Protocol (HWMP) [70] to discover the efficient radio-aware path [63]. It reflects the amount of channel resources utilized during frame transmission over a particular link.

3. Survey of QoS Routing Protocols for WMSNs

As discussed earlier in the introduction and based on metrics outlined in Section 2, WMSNs QoS routing schemes can be categorized broadly into single-metric link/path cost-dependent routing protocols, dual-metric link/path cost-dependent routing protocols, triple-metric link/path cost-dependent routing protocols, quartet-metric link/path cost-dependent routing protocols, and five and more-metric

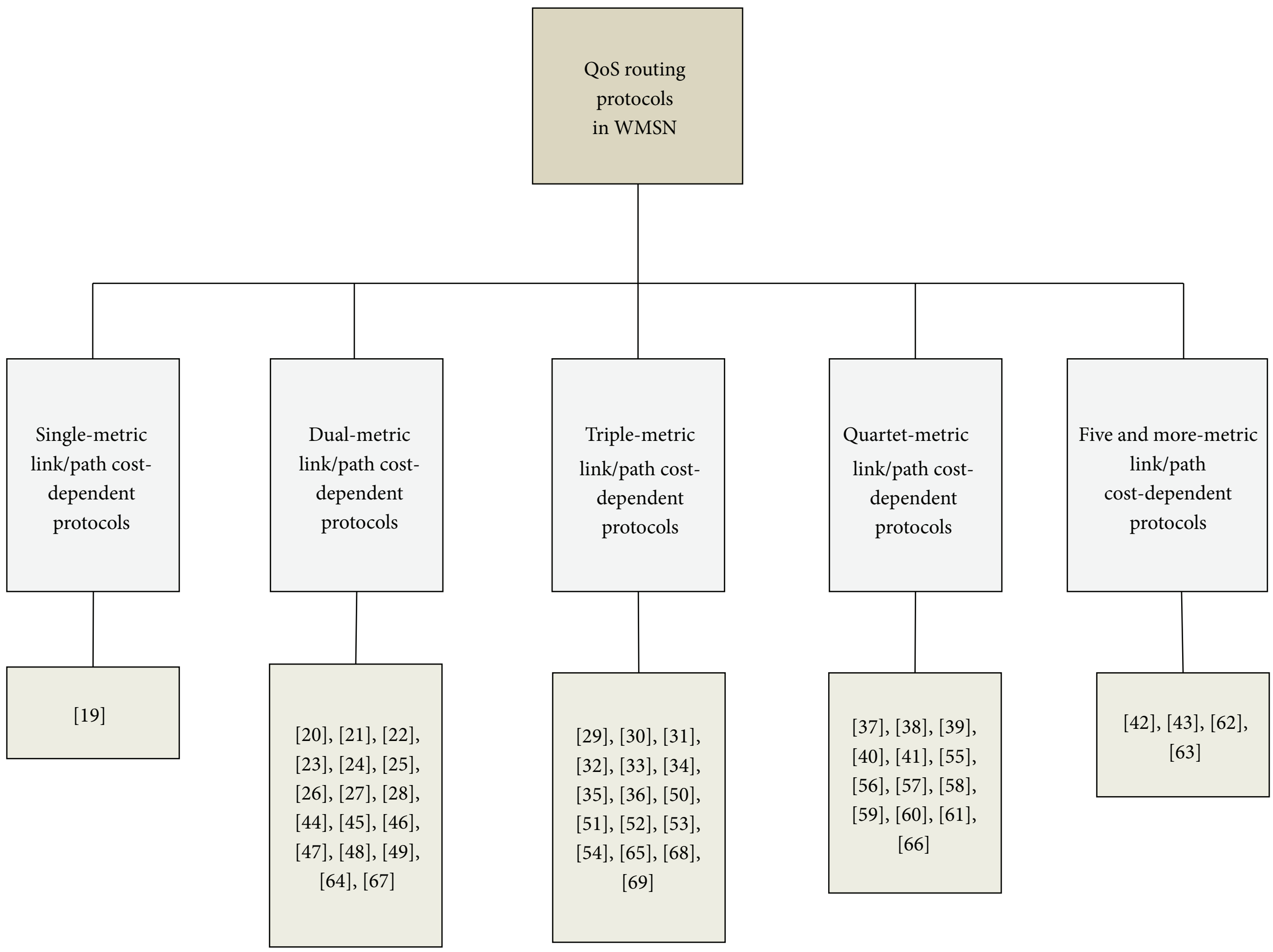


Figure 1: Metrics-aware classification of QoS routing protocols for WMSNs.

link/path cost-dependent routing protocols. Figure 1 shows the metrics-aware classification of QoS routing protocols along with the references. All WMSNs QoS routing protocols are covered in this section under their respective category. At the end of every subsection, an extensive comparative summary of QoS routing protocols is listed in tabular form (Tables 1–5). This summary compares the QoS routing protocols based on following features: network architecture, metrics used for link/path cost, multipath support, service differentiation, hole bypassing, security support, location awareness, the data delivery model, cross-layer support, scalability, mobility support, types of QoS constraints, congestion support, reduce packet loss rate, priority basis, adopted transmission power, interference awareness, simulator used, comparison with previous work, strengths, and weaknesses.

3.1. Single-Metric Link/Path Cost-Dependent Routing Protocols. These types of QoS routing protocols make routing decision based on a single metric. Such schemes which determine link/path cost with only one metric are categorized as single-metric link/path cost-dependent routing schemes. Due to paucity of single metric schemes in context of WMSNs, only one protocol is available for survey in this subsection.

Two-Phase Geographic Greedy Forwarding (TPGF) is the first pure geographic greedy forwarding routing protocol that supports multipath data transmission and hole bypassing features [19]. TPGF consists of two phases, namely, geographic forwarding and path optimization. In the first phase, the next hop is selected based on the shortest distance from the 1-hop neighbor to the sink. Static holes and dynamic holes are handled by using a step-back-and-mark method instead of face routing. The path optimization phase removes all path circles from the path, releasing redundant unnecessary nodes. These released nodes can be considered during the next path exploration. Therefore, TPGF can be executed multiple times to obtain more node-disjoint paths. This protocol is a good candidate for multimedia transmissions but requires knowledge of the entire topology before transmission. Additionally, it selects the same path in a fixed topology, which reduces network lifetime. Along with other details, Table 1 summarizes merits and demerits of TPGF. To increase the lifetime of the network, a concept called duty cycle sensor network is considered in which nodes are either in sleep state

Table 1: Single-metric link/path cost-dependent QoS routing protocol for WMSNs.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
TPGF [19] Springer 2010	Flat	(1) Distance	√	—	√	—	√	—	—	√	—	—	—	—	—	—	—	—	—	NetTopo [71]	GPSR [74]	(1) Shortest path transmission (2) Hole bypassing (3) Multipath (4) Scalable (5) 3D support (6) Pure geographic routing	(1) Less N/W lifetime (2) Require knowledge of entire topology

Table 2: Comparison of dual-metric link/path cost-dependent QoS routing protocols for WMSNs.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
SAR [44] IEEE-2000	Flat	(1) Delay (2) Remaining energy	√	√	—	—	—	Query	—	—	√	√	√	—	—	—	√	—	—	Parsec [75]	Classic shortest path algorithm	(1) Multipath (2) Energy efficient	(1) Not scalable (2) Unreliable (3) Packet priorities are constant
RAP [20] IEEE-2002	Flat	(1) Distance (2) Delay	—	—	—	—	√	Query, event	—	√	—	—	—	—	—	—	√	—	—	GloMoSim [76]	DSR [77] GPSR [74]	(1) Real-time (2) Deadline aware (3) Scalable	(1) No multipath support (2) Depleting bandwidth quickly
SPEED [21] IEEE-2003	Flat	(1) Distance (2) Delay	—	√	—	—	√	Query	—	√	—	—	√	—	√	√	—	—	—	GloMoSim [76]	AODV [78] DSR [77]	(1) Soft real-time guarantee (2) Congestion control support (3) Scalable	(1) Constant speed (2) Unreliable (3) No priority
Politis et al. [45] Springer 2008	Hierarchical	(1) Remaining energy (2) Bandwidth	√	—	—	—	—	—	—	—	—	√	√	√	—	—	√	—	—	—	Self-baseline scheduling	(1) Optimized video QoS (2) High PSNR (3) Energy efficient	(1) More complexity (2) No comparison with previous schemes
McTPGF [22] IEEE 2010	Flat	(1) Distance (2) Sleeping delay	—	—	√	—	√	—	—	√	—	√	√	—	—	—	—	—	—	NetTopo [71]	TPGF [19]	(1) Low delay (2) Improve N/W lifetime (3) Scalable	(1) Clock drift problem (2) Require knowledge of entire topology
MPMP [23] Springer 2010	Flat	(1) Distance (2) Delay	√	√	√	—	√	—	√	√	—	—	—	√	—	—	√	—	—	NetTopo [71]	TPGF [19]	(1) Context-aware (2) End-to-end delay guarantee (3) Scalable	(1) No congestion control (2) Less N/W lifetime
EA-TPGF [24] IEEE 2013	Flat	(1) Distance (2) Residual energy	√	—	√	—	√	—	—	√	—	√	√	—	—	—	—	—	—	NetTopo [71]	TPGF [19]	(1) Improve N/W lifetime (2) Scalable	(1) High delay (2) More number of hops (3) No congestion control
CQR [64] IEEE 2010	Flat	(1) Bandwidth (2) Transmission radius	√	—	—	—	—	Event	—	—	—	—	√	—	—	—	—	—	√	—	GQR [79, 80]	(1) Bandwidth efficient (2) Higher admission rate (3) Low delivery cost	(1) More iterations to converge
Haiping and Ruchuan [25] IEEE 2010	Hierarchical	(1) Remaining energy (2) Distance	—	—	—	—	√	—	—	√	—	√	√	√	—	—	√	—	—	MATLAB [81]	ASCENT [82] GAF [83]	(1) Improve N/W lifetime (2) Efficient load balancing (3) Layered architecture	(1) No congestion support (2) High delay
MPDT [46] IEEE 2010	Flat	(1) Remaining energy (2) Number of active paths through node	√	—	√	√	—	—	—	—	—	√	√	√	—	√	—	—	—	Qualnet [84]	Conventional protocol	(1) Improve N/W lifetime (2) Secure (3) Efficient load balancing	(1) High delay (2) Extra overhead

Table 2: Continued.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
MREEP [26] IEEE 2011	Flat	(1) Hop count (2) Distance	—	—	—	—	√	Event	—	—	—	√	—	√	√	—	√	—	—	Opnet [85]	REEP [86]	(1) Supports real- time and nonreal-time traffic (2) Improve N/W lifetime (3) Energy efficient	(1) Restricted applications (2) Table-driven (3) Not scalable
CBRP-L [47] IEEE 2011	Hierarchical	(1) Link delay (2) Residual energy	—	—	—	—	√	—	—	√	—	√	√	√	√	—	—	—	—	NS-2 [87]	CBRP [88]	(1) Improve N/W lifetime (2) Congestion control support	(1) Extra overhead (2) More complexity
MHDMwTS [67] IEEE 2011	Flat	(1) Hop count (2) Delay	√	—	—	—	—	Event	—	—	—	√	√	√	√	—	—	—	—	OMNet++ [89]	MHC [90]	(1) Congestion control support (2) Reliable (3) Improve N/W lifetime	(1) Clock synchronization problem (2) Performance drops with higher data rates
PEMuR [48] Elsevier 2011	Hierarchical	(1) Residual energy (2) Required energy	—	—	—	—	—	Event	—	√	—	√	√	—	—	—	√	—	—	TRUE TIME [91]	TEEN [92]	(1) Optimized video QoS (2) High PSNR (3) Energy efficient	(1) Contention-free and error-free assumption for channel (2) Extra overhead
GEAM [49] Elsevier 2013	Flat	(1) Residual energy (2) Transmission radius	√	—	√	—	√	Event	—	√	—	—	√	√	—	—	—	—	√	NS-2 [87]	TPGF [19] GPSR [74] NI [93]	(1) Interference-free transmission (2) Efficient load balancing	(1) High delay (2) More energy consumption (3) More hop counts
PASPEED [27] IEEE 2014	Flat	(1) Distance (2) Delay	—	—	√	—	√	—	—	—	—	√	—	√	—	√	√	√	—	Castalia [94] Evalvid [95]	GPSR [74] SPEED [21]	(1) Energy efficient (2) Less delay (3) Less control packets overhead	(1) Clock synchronization problem (2) No load balancing
ADRS [28] IEEE 2015	Flat	(1) Distance (2) Inclination angle	√	—	√	√	√	—	—	—	—	—	√	√	—	—	—	—	—	OMNet++ [89]	Shortest path algorithm	(1) Improve N/w lifetime (2) Dynamic (3) Providing source location secrecy	(1) Higher latency (2) No priority

Table 3: Comparison of triple-metric link/path cost-dependent QoS routing protocols for WMSNs.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
ReInForM [68] IEEE 2003	Flat	(1) Hop count (2) Desired reliability (3) Channel error rate	√	—	—	—	—	—	—	—	—	—	√	√	—	—	√	—	—	—	Flooding	(1) Reliable (2) Efficient load balancing (3) Dynamic	(1) Higher bandwidth utilization (2) More energy consumption
Mahapatra et al. [29] Elsevier 2006	Flat	(1) Distance (2) Delay (3) Remaining energy	√	√ (simple)	—	—	√	Query	—	—	√	√	—	√	√	—	√	—	—	NS-2 [87]	GEAR [96]	(1) Reliable (2) Improve N/w lifetime (3) Deadline aware (4) Congestion control support	(1) Extra overhead (2) Unacceptable path discovery latency for some random packets
MMSPEED [30] IEEE 2006	Flat	(1) Delay (2) Distance (3) Reaching probability	√	√	—	—	√	Query	√	√	√	—	—	√	—	—	√	—	—	J-SIM [97]	SPEED [21]	(1) Reliable (2) Timeliness (3) Multispeed	(1) More energy consumption (2) Less N/w lifetime
Multimedia-aware MMSPEED [31] IEEE 2008	Flat	(1) Delay (2) Distance (3) Reaching probability	√	√	—	—	√	Query	√	√	√	—	√	√	—	—	√	—	—	J-SIM [97] Evalvid [95]	MMSPEED [30]	(1) High PSNR (2) Reliable (3) Timeliness	(1) More energy consumption (2) Less N/w lifetime
RPAR [32] IEEE 2006	Flat	(1) Distance (2) Delay (3) Remaining energy	—	—	√	—	√	Query	—	√	—	√	—	—	—	—	√	√	—	Prowler [98]	Self-baseline MaxV and MinE	(1) Real-time (2) Energy efficient (3) Improve N/W lifetime	(1) Pathological behavior of congested nodes (2) Performance degrades with large holes
REAR [33] IEEE 2008	Flat	(1) Remaining energy (2) Distance (3) Delay	—	—	—	—	√	Event	—	—	—	√	√	—	—	—	√	—	—	—	SAR [44]	(1) Real-time (2) Improve N/W lifetime	(1) Unreliable (2) Use of metadata for routing decision
Dong et al. [65] Springer 2009	Hierarchical	(1) Bandwidth (2) Delay (3) Jitter	—	—	—	—	—	—	—	—	—	—	—	√	—	√	—	—	—	Waxman Model [99]	—	(1) Multiple constraint based (2) High routing successful ratio	(1) Convergence rate is uncertain (2) Less N/w lifetime
ASARC [34] IEEE 2011	Hierarchical	(1) Residual energy (2) Distance (3) Delay	√	—	—	√	√	Event	—	—	—	√	√	√	—	—	√	—	—	NS-2 [87]	REAR [33] M-IAR [100]	(1) Reliable (2) Secure (3) Low latency	(1) More complexity (2) Extra overhead (3) Energy consumption due to extra overhead
EEIAMR [35] IEEE 2011	Flat	(1) Hop count (2) Distance (3) Residual energy	√	—	√	—	—	Event	—	—	—	√	√	√	—	—	—	—	√	NS-2 [87]	MR2 [101]	(1) Reliable (2) Interference aware transmission	(1) Partial node-disjoint paths (2) Less number of paths
HLEAR [50] IEEE 2011	Flat	(1) Hop count (2) Current traffic load (3) Residual energy	√	—	√	—	—	Event	—	—	—	√	√	√	—	—	—	—	—	NS-2 [87]	TINY AODV	(1) Increasing throughput (2) Traffic load aware (3) Avoid creation of holes near sink	(1) At low data rates more energy consumption (2) Partial node-disjoint paths

Table 3: Continued.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
Kim et al. [36] Springer 2011	Hierarchical	(1) Residual energy (2) Distance (3) Bandwidth	√	—	√	√	—	—	—	—	—	—	√	√	√	—	—	—	—	—	—	(1) Secure (2) Congestion control support (3) Separate control and data paths	(1) More energy consumption (2) Less N/w lifetime (3) More complexity
AMPMCR [51] IEEE 2012	Hierarchical	(1) Delay (2) PLR (3) Remaining energy	√	—	—	—	—	—	—	—	—	—	√	√	—	√	—	—	—	NS-2 [87]	HQAX [62]	(1) Low delay (2) High PDR (3) Less packet drops (4) Adaptive multiconstraint	(1) Clock synchronization problem (2) More energy consumption due to flooding
SPEA [69] Elsevier 2015	Flat	(1) Node delay (2) ETX (3) Number of hops	—	—	—	—	—	—	—	—	—	—	—	√	—	√	—	—	√	NS-2 [87]	DSR [102]	(1) Multiobjective (2) High throughput (3) Low delay	(1) Less N/w lifetime (2) More complexity
MAEE [52] IEEE 2015	Flat	(1) Remaining energy (2) ETX (3) Buffer size	√	—	√	—	—	Event	—	—	—	√	√	√	—	√	√	—	—	NS-2 [87]	EEPMQR [103]	(1) Reliable (2) Low delay	(1) Not scalable (2) Not completely efficient
EEQAR [53] IEEE 2015	Hierarchical	(1) Remaining energy (2) Trust value (3) Data correlation coefficient	√ Only intercluster	—	√	—	√	—	—	—	√	√	√	—	—	—	—	√	—	NS-2 [87]	—	(1) Improve N/w lifetime (2) Mobility support	(1) Complex (2) No priority (3) No comparison with previous schemes
CUDAR [54] Springer 2015	Flat	(1) Average PST (2) Channel utilization (3) Remaining energy	—	—	√	—	—	Event	√	√	—	—	√	√	√	√	—	—	—	NS-2 [87]	GPSR [74] HLEAR [50]	(1) Multisource (2) High throughput (3) Low delay	(1) Less N/W lifetime (2) No service differentiation

Table 4: Comparison of quartet-metric link/path cost-dependent QoS routing protocols for WMSNs.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
Akkaya and Younis [37] Springer 2005	Hierarchical	(1) Distance (2) Residual energy (3) PLR (4) Delay		√	—	—	—	Query	—	√	—	√	√	—	—	—	√	—	—	—	—	(1) Best-effort transmission (2) High throughput (3) Low delay	(1) Require complete knowledge of topology (2) Not scalable (3) No adaptive bandwidth sharing (4) No comparison with previous schemes
GEAMS [38] IEEE 2009	Flat	(1) Remaining energy (2) Hop count from source till current node (3) Distance with neighbors (4) History of current stream	√	—	√	—	√	Event	—	√	√	√	√	√	—	√	—	—	—	OMNET++ [89]	GPSR [74]	(1) Low delay (2) Less packet drops (3) Scalable (4) Improve N/w lifetime	(1) Performs poorly in less dense network (2) No packet priority
AGEM [39] IEEE 2010	Flat	(1) Remaining energy (2) Hop count from source till current node (3) Distance with neighbors (4) History of current stream	√	—	√	—	√	Event	—	√	√	√	√	√	—	√	—	—	—	OMNET++ [89]	GPSR [74]	(1) Low delay (2) Less packet drops (3) Scalable (4) Improve N/w lifetime	(1) Performing poorly in less dense network (2) No packet priority
S-AOMDV [55] IEEE 2010	Flat	(1) Residual energy (2) Hop count (3) Free buffer size (4) PLR	√	—	—	—	√	—	√	—	—	—	√	√	√	√	√	—	—	NS-2 [87] Evalvid [95]	AOMDV [104]	(1) Good PSNR (2) Less frame loss	(1) Extra overhead (2) More energy consumption
REP [56] IEEE 2010	Flat	(1) Remaining energy of node (2) Average remaining energy of all nodes (3) Reaching probability (4) Reliability requirement	—	—	—	—	—	—	—	—	—	√	√	√	—	—	—	√	—	—	Baseline REP	(1) Reliable (2) Energy prediction (3) Adjusting transmit power based on remaining energy	(1) Intrapath interference at high power level (2) No comparison with previous schemes (3) No congestion control
ARCH [57] Hindawi 2010	Hierarchical	(1) Remaining energy of node (2) Average remaining energy of all nodes (3) Reaching probability (4) Reliability requirement	√ Only intercluster	—	—	—	—	—	—	√	—	√	√	√	—	—	—	√	—	—	Baseline ARCH	(1) Reliable (2) Energy prediction (3) Adjusting transmit power	(1) Intrapath interference (2) No congestion control (3) No comparison with previous schemes

Table 4: Continued.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
IQAR [58] IEEE 2011	Flat	(1) Residual energy (2) PDR (3) Delay (4) Reliability requirement	—	—	√	—	√	Event	—	—	—	√	√	√	—	—	√	—	—	J-SIM [97]	MMSPEED [30]	(1) Good PSNR (2) Reliable (3) Low delay when a number of flows are more	(1) Prioritization limited to only images (2) Performance not good when a number of flows are less
ACOWMSN [59] IEEE 2011	Flat	(1) Bandwidth (2) Delay (3) PLR (4) Remaining energy	—	—	—	—	—	—	—	√	—	√	√	√	—	√	—	—	—	NS-2 [87]	M-IAR [100] AODV [78]	(1) Low delay (2) Improve N/w lifetime (3) High PDR	(1) Generates extra heavy traffic (2) Slow convergence
EEQAR [60] IEEE 2011	Hierarchical	(1) Remaining energy (2) Trust value (3) Data correlation coefficient (4) Hop count	√	—	√	—	√	—	—	√	√	√	√	√	—	—	—	√	—	—	ARCH [57]	(1) Improve N/w lifetime (2) Mobility support (3) Data fusion support	(1) Path-interference at high power level (2) No congestion support
CR-WMSN [61] IEEE 2012	flat	(1) PST (2) Channel utilization (3) Hop count (4) Remaining energy	√	—	—	—	√	Event	√	—	—	—	—	√	√	—	—	—	—	NS-2 [87]	Min hop algorithm	(1) Low delay (2) High throughput	(1) Restricted N/W lifetime (2) Restricted load balancing (3) No priority
Dong et al. [66] IEEE 2012	Flat	(1) Bandwidth (2) Delay (3) Jitter (4) PLR	√	—	—	—	—	—	—	—	—	—	—	√	—	√	—	—	—	Waxman Model [99]	—	(1) Multiobjective optimization (2) Increase in probability to find optimal solution	(1) Output depends on Pareto solution set (2) More complexity
Bae et al. [40] IJMUE 2014	Flat	(1) Distance (2) Remaining energy (3) LQI (4) Traffic priority	√	√	—	—	—	—	—	—	—	—	√	√	√	√	√	—	—	Visual Studio [105]	—	(1) Reliable (2) Low delay (3) Service differentiation	(1) Extra overhead (2) No comparison with previous schemes
PWDGR [41] IEEE 2015	Flat	(1) Number of hops (2) One-hop distance (3) Path contract angle (4) Included angle	√	—	—	—	√	Event	—	√	—	—	√	√	—	—	—	√	—	Opnet [85]	DGR [106]	(1) Improve N/w lifetime (2) More paths (3) Energy sensitive	(1) High delay (2) More hop counts (3) Poor performance in small density networks

Table 5: Comparison of five and more-metric link/path cost-dependent QoS routing protocols for WMSNs.

Protocol and publication year	Architecture	Metric for link/path selection	Multipath support	Service diff.	Hole bypassing	Security	Location aware	Data delivery model	Cross-layer support	Scalability	Mobility	Energy efficiency	Load balancing	Reliability	Congestion support	Reduce packet drops	Priority	Adjust TX power	Avoid interpath interference	Simulator/software	Compared with	Strengths	Weaknesses
HQAX [62] Springer 2009	Hierarchical	(1) Delay (2) SNR (3) PLR (4) Remaining energy of Tx (5) Remaining energy of Rx	—	—	—	—	—	—	√	√	—	—	√	√	—	√	—	—	—	NS-2 [87]	AODV [78]	(1) High throughput (2) Less PLR (3) Less overhead (4) Utility theory based cost function	(1) Less delay efficient (2) No priority
LBA-EA [63] IEEE 2010	Flat	(1) Residual energy (2) Initial energy (3) Number of nodes (4) Number of links (5) Enhanced airtime link metric	—	—	—	—	—	—	—	—	—	√	√	√	√	—	—	—	√	NS-3 [107]	Baseline default Airtime metric	(1) High throughput (2) Improve N/w lifetime (3) High PDR	(1) Extra overhead (2) No comparison with previous schemes
POWQR [42] IEEE 2013	Flat	(1) Number of hops (2) BER (3) Remaining energy (4) Distance (5) Delay	√	—	—	—	√	Event	—	—	—	√	√	√	√	—	—	√	—	Castalia [94]	EARQ [108] LOCALM-OR [109]	(1) Reliable (2) Load balancing (3) Improve N/w lifetime	(1) Extra overhead (2) Not scalable
Serhan and Diab [43] IEEE 2015	Flat	(1) Remaining energy (2) Hop count- source till current node (3) Distance with neighbors (4) History of current stream (5) Traffic priority	√	√	√	—	√	—	—	—	—	√	√	√	√	√	√	—	—	—	AGEM [39]	(1) Reliable (2) Low delay	(1) Extra overhead (2) Results shown with very less number of nodes and packets

or in active state. Based on CKN [72] scheduling, the effect of the duty cycle is studied using the TPGF algorithm [73]. The results show that there is little effect from sensors waking up on the total number of transmission paths or the average length of transmission paths between the source and the sink. However, the lifetime of the network is improved.

3.2. Dual-Metric Link/Path Cost-Dependent Routing Protocols. Many routing schemes formulate routing decision based on a combination of two routing metrics. Such schemes which determine link/path cost using proper blend of two metrics are categorized as dual-metric link/path cost-dependent routing schemes. Under this category, a comparative summary of routing schemes surveyed is shown in Table 2.

Sequential Assignment Routing (SAR) is a priority based, table-driven, multipath routing algorithm [44]. Multiple paths are generated from each node to the sink node. These multiple paths are generated by creating multiple trees, each rooted from a one-hop neighbor of the sink. The remaining energy and delay are QoS metrics considered during the branching of the trees. After branching, out of all of the paths found, the source will choose the final path. To route a packet in the network, weighted QoS metric is calculated as the product of additive QoS metrics (remaining energy and delay) and a weight coefficient associated with the priority level of that packet. According to simulations, SAR performance is better than that of the minimum metric algorithm. However, because this approach is table driven, it requires a great deal of memory and does not scale efficiently for large networks. Additionally, the priority of the packet remains the same during transit from source to destination.

RAP is a real-time, priority-based communication architecture designed for large-scale networks, providing high-level query and event services for distributed microsensing applications [20]. The network stack of sensors consists of Location Address Protocol (LAP) in the transport layer, Geographic Forwarding (GF) protocol in the routing layer, Velocity Monotonic Scheduling (VMS) layer, and prioritized MAC layer. The heart of this algorithm is VMS policy, which computes the deadline-aware and distance-aware priority for each packet. Furthermore, VMS is divided into two scheduling policies called static velocity monotonic and dynamic velocity monotonic. At the source, static velocity monotonic computes a fixed requested velocity for each packet. The dynamic velocity monotonic scheduling policy computes the velocity at each intermediate node after the arrival of each packet. Packets generated by multiple sources and competing for shared communication channels at intermediate nodes must be handled by enforcing packet prioritization at the MAC layer. This function is performed with the help of modification of the initial wait time after the channel becomes idle and the back-off window increase function [110]. Simulation results show RAP reduces the end-to-end deadline ratio substantially. In RAP, the number of hops metrics is not considered in the evaluation of the priority of a packet. In addition, it does not support multipath routing.

SPEED provides a soft-real-time guarantee with desired delivery speed across a sensor network [21]. To maintain an end-to-end delay proportional to the distance between the source and the destination, it provides support for uniform delivery speed. SPEED supports three types of services, namely, real-time unicast, real-time area multicast, and real-time area anycast. It uses three types of beacons, namely, periodic beacon, delay-estimation beacon, and backpressure beacon. The last two are on-demand beacons. A backpressure beacon is used to reduce congestion in the network layer. SPEED uses Stateless Nondeterministic Geographic Forwarding (SNGF), which provides soft, real-time, end-to-end delivery. Additionally, SNGF does load balancing over a larger area, which helps to reduce congestion. SNGF adapts the MAC layer to reduce congestion further. SPEED is scalable, but although some portion of a network might support more speed, it cannot be increased beyond the maximum end-to-end delivery speed. No priority is considered for packets, and it does not ensure reliabile delivery of the packets.

In another work presented by Politis et al., multipath video transmission is optimized with the help of packet scheduling algorithms [45]. This work improves the power efficiency of the network and perceived video quality at the receiver. In this work, the LEACH [111] protocol is modified and explored to establish bandwidth-efficient multiple paths between all cluster heads. Multiple paths are selected between source and destination based on video stream transmission rate requirements [112]. Based on an inbuilt feature of the H.264/AVC encoder, the protocol uses a recursive distortion prediction model that considers isolated errors, burst errors, and lag errors along with other parameters. For packet scheduling, two algorithms are used, namely, baseline packet scheduling and power-aware packet scheduling. Both scheduling algorithms drop packets based on a distortion prediction model. Power-aware packet scheduling uses the energy efficiency of cluster heads and bandwidth limitations of the channel to decide whether the packet should be transmitted or dropped. The model presented in this work was tested against real measurements and found to be extremely competent for WMSNs, but the performance of this scheme is very complex for larger transmission windows.

Another work derived from TPGF [19] is McTPGF, which finds a single routing path in random duty-cycled WMSNs [22]. In this case, the next forwarding node is decided based on the distance between the sink and the neighboring node as well as the sleeping delay of the neighbor. Sleeping delay is the delay required to wake the respective neighbor node from a dormant state. Additionally, the second phase of TPGF is completely removed; to avoid path circles, it binds node ID and packet ID before forwarding the packet. During routing, the node forwards the packet only to an unbounded neighbor. This work shows improved average end-to-end delay compared with TPGF. However, in the duty-cycled network, clock drift affects the accuracy of wake-up time for sensor nodes; thus, the duty-cycling concept is not suitable for critical real-time applications.

MPMP is a context aware, multipriority-based, optimized multipath cross-layer transmission technique that guarantees end-to-end delay [23]. The maximum number of node-disjoint paths is found in the network layer using TPGF [19]. Out of these paths, the maximum number of paths are selected by Context Aware Multipath Selection (CAMS) in the transport layer. Here, the video stream is split into an audio stream and an image stream. Context information, namely, noise and brightness level, is used to decide the importance levels of image and audio streams. Two types of priorities are used in the CAMS algorithm: context-aware multimedia content-based priority and end-to-end transmission delay-based priority. These priorities are used by the CAMS algorithm to find the maximum number of paths that satisfy the end-to-end delay for each stream. For multiple sources and a single destination, 1-hop neighboring nodes may be overloaded and congested. This scheme does not support congestion control.

As mentioned earlier, TPGF selects the same path in a fixed topology. Nodes on the same path are depleted very quickly compared with other nodes, causing further holes and reducing the lifetime of the network. This problem is overcome in EA-TPGF by considering the residual energy of the node along with distance [24]. This extended work of TPGF improves the lifetime of the network, but it is not suitable for time-critical applications because of more number of hops and more delay. EA-TPGF does not support scalar and multimedia data at the same time.

Collaborative Quality of Service Routing (CQR) is designed for real-time flows to achieve bandwidth-efficient collaborative QoS routing [64]. This technique boasts of good admission rate with low cost for traffic compared with traditional Greedy QoS Routing (GQR) techniques [79, 80]. Multiple flows are scheduled in parallel, considering bandwidth requirements and noninterference of the links. Additionally, a subgradient optimization-based search algorithm is used to obtain optimal results. This technique addresses bandwidth resource fragmentation, which is observed in GQR techniques. It achieves a hard real-time guarantee compared with GQR but takes more time to find the optimal solution.

A scheme with the objective of designing a layer-based cluster control algorithm along with routing is presented by Haiping and Ruchuan [25]. Based on geographic location, every layer is divided into fan-shaped fields. Additionally, every cluster is separated into twelve virtual cells, each differing from the next by a 30° angle. The priority of coverage for any node is calculated based on the current position of that node and the center position of the virtual cell (distance). Additionally, the probability of sending a test packet is calculated based on the ratio of remaining energy to the priority of coverage. This probability is used to determine the selection of the cluster head. ASCENT [82] is used for multimedia data transmission and is enhanced further with the introduction of a detection channel and data transmission channel in the wake-up mechanism. Here, intermediate nodes are used for the backbone path in case of higher packet loss. This work shows a network lifetime improvement over the ASCENT and Geographical Adaptive Fidelity (GAF) protocols [83]. However, the results for other performance metrics as claimed in this paper are not presented by the authors. In addition, due to wake-up mechanism this protocol is limited to nonreal-time applications.

The Multi-Path Data Transfer (MPDT) protocol supports simultaneous multipath data transfer between any two nodes [46]. Multiple paths are explored in the route setup phase, which is based on a threshold value of residual energy of a node and number of already established paths through that node. After multiple paths are explored, the data is split into m parts (m paths) and encoded with the Reed-Solomon encoding technique at the source in the data transmission phase. This routing ensures distribution of work in a uniform manner among sensor nodes to boost network lifetime. However, multiple routing paths are not optimized, resulting in high end-to-end delay, which is not suitable for time-critical applications. Additionally, splitting data at the source on multiple paths causes extra overhead for data collection at the sink node.

Based on REEP [86], Multimedia Reliable Energy Efficient routing Protocol (MREEP) is a data-centric protocol designed for constraint-based routing for real-time and nonreal-time traffic flows [26]. It consists of four different phases, namely, data dissemination, event report, route establishment, and data forwarding phase. In the data dissemination phase, Multimedia Location Aided Flooding (MLAF) is used by the sink [113]. MLAF considers energy and end-to-end delay as metric parameters to achieve reliability. MLAF defines four different priorities out of which two are used for directional forwarding, and the remaining two are used for delay-sensitive forwarding. During the route establishment phase for MREEP, two priority levels are considered, namely, high priority for real-time traffic and low priority for nonreal-time traffic. Routing tables for both real-time and nonreal-time traffic are created at each node at the end of this phase. Thus, routing tables store the highest priority record as the first record in the table. Next hop selection is based on the probability value of the record, which is the ratio of the length of the record path (distance) to the number of hops of the record. Compared with REEP, simulation results show that MREEP is more energy efficient, but because it uses MLAF, which is based on a grid arrangement, MREEP is restricted to a few applications. In addition, because of a table-driven approach it is not scalable.

CBRP-L is a Cluster-Based Real-Time Protocol that combines two previous protocols, LEACH [111] and CBRP [88], in its implementation [47]. In high node density areas, end-to-end delay is very high, which causes congestion. This algorithm focuses on detecting this congestion through affected links. Congested links with more than average delay will be disconnected by a node removing an entry from its table. Additionally, the LEACH algorithm is executed to elect a new cluster head to maintain the reliability of the entire network. CBRP-L shows better performance compared with its predecessor CBRP, but uneven virtual grid-based clustering and different cluster-head selection increase overhead, resulting in more complexity.

MHDMwTS is a reliable Minimum Hop Disjoint Multipath routing algorithm With a Time-Slice load balancing congestion control scheme [67]. Three routing paths are formed based on minimum time delay and hop count from source to sink, namely, primary path, alternate path, and backup path. In normal operation, only the primary and alternate paths are used according to a time slice. The source will alternatively switch data on both of these paths per time slice. The time slice for the primary path is greater compared with the alternate path. Congestion is avoided by setting time slice appropriately at the major node. If the buffer space of the major node's queue reaches a threshold value, it sends a congestion notification message to the source node. In turn, the source stops transmitting data on this path by switching to another path. This algorithm works well at lower data rates, but at higher data rates performance drops significantly.

Based on Scalable Hierarchical Power Efficient Routing (SHPER) [114], PEMuR is a fusion of video packet scheduling with an energy-aware hierarchical routing protocol [48]. During the initialization phase, the base station forms cluster heads based on their residual energy. Cluster heads are divided into two types, namely, upper-level cluster heads and lower-level cluster heads. Lower-level cluster heads are away from the base station, and based on the routing index, they use upper-level cluster heads to communicate with the base station. The routing index is derived from residual energy and required energy to route a message between two chronological cluster heads. In the case of an event, the cluster head selects a node with the highest threshold residual energy to transmit multimedia data to itself. For packet-scheduling algorithm, it uses a distortion prediction model. According to this model, it drops packets when the transmission rate is greater than the available rate. PEMuR is a good choice for surveillance applications but causes extra overhead due to centralized cluster creation. Additionally, in case the transmission window is large, according to the distortion prediction model, the source requires more power and time to compare each packet with other packets.

GEAM is a multipath routing scheme with interpath interference-free transmission [49]. Here, the entire topology is divided into various districts between source and sink; further districts are divided into three groups. During transmission, multipath interference is avoided by setting the distance between any two districts to more than two times the transmission radius. An intermediate node forwards a packet to the next node that belongs to the same district; likewise, it is forwarded toward the sink. During transmission, a packet is piggybacked with location and energy information of a node along with data. The sink sends this information to the source. Furthermore, the source adjusts the load in each district. When the source detects the presence of network holes, it changes the district boundary to accommodate the routing path. GEAM shows good performance for real-time traffic, but multipath noninterference criteria may incur a penalty of a greater hop count.

The Power Adaptive SPEED (PASPEED) protocol is extended from SPEED [21], which adapts the power control transmission to reduce energy consumption [27]. A forwarding node is selected that can satisfy the required delivery speed to guarantee end-to-end delay. A neighboring node that makes the most progress toward the sink is the next forwarding node. Progress is calculated based on the distance and the delay with respect to the neighboring node. Here, every node also determines the amount of transmission power required to send the packet to each neighbor. Based on this requirement, a node adapts transmission power out of eight different levels. This adaption of transmission power reduces energy consumption, resulting in an increase in network lifetime. Packet priorities are considered based on the type of frame (I-frame, P-frame, and B-frame). When congestion occurs, lower priority (importance) packets are dropped, improving the reliability of important packets, which results in better video quality. However, clock synchronization may cause a problem on the performance of the PASPEED.

Angle-Based Dynamic Routing Scheme (ADRS) provides source location privacy against an adversary [28]. It guarantees transmission with average latency and improves the lifetime of the network. A set of forwarding neighboring nodes is selected based on the distance and inclination angle with respect to the sink node. Each time next forwarding node is selected randomly from the set. This random selection of node boosts the lifetime of the network. Latency constraint can be adjusted by controlling inclination angle and the distance between the current node and the neighboring node. Implicitly, it supports the hole-bypassing feature. ADRS lacks support for packet priority and has higher latency that is not suitable for real-time applications.

3.3. Triple-Metric Link/Path Cost-Dependent Routing Protocols. These types of QoS routing protocols make routing decision based on three metrics. Such schemes which determine link/path cost by a proper fusion of three metrics are categorized as triple-metric link/path cost-dependent routing schemes. Table 3 shows comparative summary of routing schemes under this category.

ReInForM provides end-to-end reliability in the presence of channel errors using a packet duplication technique over randomly chosen multipaths [68]. Path selection is based on hop count toward the sink node, desired reliability, and local channel error rate. The source adds information in the packet header about these three metrics as the Dynamic Packet State (DPS) field. Along with the data, it transmits multiple copies of the same packet through multiple paths. At every intermediate node, DPS controls a number of paths for desired reliability; that is, after receiving each packet, every intermediate node will decide how many copies of the packet should be forwarded to neighboring nodes. Multiple path selection is performed randomly, which helps in load balancing. However, this protocol achieves reliability by duplicating packets, which consumes more bandwidth and more energy.

Mahapatra et al. explore a reliable, dual path, energy-aware, real-time routing scheme [29]. This scheme provides simple service differentiation using an adaptive, prioritized MAC layer. It finds the next forwarding node based on remaining distance, delay, and remaining energy. Here, the source node computes the priority for each neighboring node based on delay and remaining energy. Based on computed priority, the best two nodes are selected by the source node, which forwards a copy of the data packet to each of them. Intermediate nodes forward the data packet to only one best neighboring node, which results in minimization of duplicate data packets in the network. Current load or congestion in the neighboring nodes will be known from the exchange of HELLO_PKT. Simple service differentiation is implemented using a prioritized MAC layer, which assigns higher priority to real-time packets. For random urgent packets, this scheme results in unacceptable path discovery latency.

MMSPEED is a multipath, multispeed geographic protocol that guarantees reliability and timeliness with service differentiation [30]. In this work, the idea of SPEED [21] is extended to provide multiple delivery speed options for each incoming packet at the node. These speed options are mapped to MAC layer priority class. For timeliness, various speed options are available of which different traffic flows can choose options based on an end-to-end deadline. Probabilistic multipath forwarding is used, which compensates for local decision inaccuracies during the journey of a packet from source to destination. Intermediate nodes enhance the speed of the packet, resulting in meeting the delay deadline for that packet. Depending upon the reliability requirement, each node forwards multiple copies of a packet to selected neighbors. MMSPEED is further explored for multimedia-aware service differentiation in the network and MAC layer [31]. In multimedia-aware MMSPEED, routings paths are categorized into two types, namely, near optimum paths, which are dedicated to I-frames, and marginal paths, which are dedicated to P-frames. This differentiated routing is implemented with only two speeds. The higher speed is for I-frame packets, and the intermediate speed is for P-frame packets. Additionally, this differentiation is extended by the MAC layer using IEEE802.11e to maintain two separate queues. This work shows results with improved Peak Signal-to-Noise Ratio (PSNR) or improved video quality for multiple flows. In both works, the number of hops and residual energy metrics are not considered in the routing decision.

RPAR, or the Real-time Power-Aware Routing protocol, allows a tradeoff between communication delay and transmission power [32]. This tradeoff control is achieved by specifying packet deadlines. In RPAR, a packet is forwarded based on a dynamic velocity-assignment policy and a most energy-efficient policy. The velocity-assignment policy dynamically assigns required velocity to a packet based on current network conditions at every node. This dynamic assignment will result in assigning a logical priority to every packet in the queue. The transmission power of a sensor node is increased or decreased based on the velocity requirement. RPAR handles lossy links, bandwidth constraints, and memory constraints, but transmitting a packet at high power levels in RPAR increases interference, resulting in a decrease in throughput. Additionally, power adaption policy degrades performance when a node is congested.

Real-time and Energy Aware Routing (REAR) is an event-driven protocol that uses metadata instead of real data in path exploration [33]. It uses a link-cost evaluation function based on three metrics, namely, distance, remaining energy, and queuing delay of neighboring nodes. It uses an advanced Dijkstra's algorithm to find routes based on a link-cost function. Logical priority is implemented with the help of two queues, one for real-time data and the other for nonreal-time data. A metadata consultation mechanism between neighboring nodes is used to reduce energy consumption and queuing delay at every node. However, the metadata exchange mechanism is not a good option for multimedia streaming applications. In addition, this scheme does not support reliable data transmission.

Another work by Dong at al. makes use of a genetic algorithm to understand the QoS routing for WMSNs [65]. It is based on a cluster network model consisting of functions, namely, encoding, production of the initial population, determination of fitness, method of selection, crossover operation, and mutation operation. For the initial population, it uses a random walk to find a routing path between source and destination. A fitness function depends on three metric parameters, namely, bandwidth, delay, and delay jitter. In this work, the convergence rate is vague with respect to the crossover probability. Since node energy is not considered in routing decision network may survive for less amount of period.

Cluster-based ASARC supports actuating multimedia sensors to maximize event information with a minimum level of redundancy [34]. In the case of an event, a sensor actuation algorithm is used to actuate one or more multimedia sensor nodes from sleep mode. Routing path selection is based on residual power, distance, and routing delay with respect to the neighboring node. It uses a Reed-Solomon encoding scheme at the source throughout data transmission. To improve the data transmission rate, the source adapts a distortion prediction model. Using this model, the source decides which packets to drop to maintain distortion at a minimum level. Additionally, it implements a checkpoint feature in the sensor cluster, which periodically saves machine states and intermediate data. Because of extra overhead in ASARC, complexity level is high, and power consumption is not to the level of expectation.

EEIAMR is a reliable multipath interference-aware routing algorithm that improves energy efficiency [35]. It discovers multiple paths based on the distance between neighboring nodes with respect to the sink, minimum hop count on the path, and residual energy. For the interference-aware feature, the neighboring node with maximum energy and farthest from the preceding node is chosen as the next intermediate node. Out of the multiple paths found, the source selects only one best path to forward the data. A selection of only one path limits the protocol to critical end-to-end delay applications. During data transmission, if the path node fails, then the previous node of the failed path finds an interference-aware alternate path without initiating a new route discovery phase. Less routing overhead reduces energy consumption in EEIAMR, resulting in improved network lifetime, but partial node-disjoint paths may result in energy failure of a common node, disabling these paths. In addition, less number of paths are discovered by EEIAMR.

HLEAR is a Hop and Load-based Energy-Aware Reactive protocol with swarm intelligence [50]. It is based on a routing metric beta (β), which is derived from the hop count, current traffic load, and residual energy of a node. A node with the lowest β value is considered the best intermediate candidate on the path. Additionally, a node with four currently active routes is not permitted to participate in the route discovery process. Similarly, nodes with minimum cut-off residual energy are marked as swap nodes and are not allowed in the route discovery process, preventing the creation of holes near the sink. HLEAR is not scalable because it is based on a table-driven approach.

Another work by Kim et al. based on a heterogeneous hierarchical model uses two paths from the sensing node to the base station [36]. These two paths are the delivery path and the control path. The delivery path is used to send multimedia data from the source node to the base station via relay nodes. The next intermediate relay node is selected based on a cost function, which depends on distance, remaining energy, and bandwidth of a node. A relay node with one existing delivery path is not considered for the establishment of another delivery path. This criterion of only one delivery path through a relay node plays a significant role in the prevention of congestion in the network. However, command paths can be overlapped in one relay node because command data is very small compared with actual data. This protocol also uses security keys to protect against a fraudulent attacker causing an energy collapse of relay nodes. An isolation and recovery step during the establishment of a delivery path affects already-existing delivery paths that simply increase complexity and time. Additionally, the protocol consumes more energy because of the discovery of two different paths.

AMPMCR is an adaptive multipath multiconstraint multitier hierarchical routing protocol [51]. Intercluster routing is based on a cost function that considers three metric parameters, namely, delay, loss rate, and remaining energy. Based on these metric values, paths are classified into delay-sensitive paths, loss-sensitive paths, critical paths, and normal paths. If all three metric values provided by the paths are resourceful, then it is called a normal path. In case the path discovered is not a normal path, multiple paths are discovered. Additionally, depending upon network load, to boost the lifetime of the network, a few nodes in multipath routing are kept in the passive state. Simulation results show that AMPMCR minimizes packet loss rate, delay, and energy consumption. However, during multipath route discovery, it uses flooding, which consumes more energy.

WMSNs routing is also achieved using multiobjective optimization algorithms [69]. Based on different objectives, a diverse set of optimal solutions is produced. Multiobjective routing is based on three metrics, namely, node delay, ETX, and number of hops on a path. It uses a genetic multiobjective evolutionary algorithm, called Strength Pareto Evolutionary Algorithm (SPEA). Here, a breadth-first search algorithm is used to create the initial population. Fitness values are based on ETX and delay, which is assigned to individual initial population samples. Crossover and mutation genetic operators are used to find feasible solutions. SPEA ensures better solutions in early runs, and it finds the path with minimum ETX and delay, satisfying both essential objectives. Because node energy is not considered in routing decision, network lifetime may be shorter.

Maximal Minimal nodal Residual Energy- (MMRE-) AOMDV based Energy Efficient (MAEE) is a multipath, highly reliable protocol designed to transmit images in lossy networks [52]. Multiple routing paths are found based on residual energy, ETX, and buffer size of the node. Images are classified into two types, namely, Overlapping Region (OVR) images and Nonoverlapping Region (NOVR) images. Packets with OVR images are given higher priority over NOVR images. This protocol makes use of good quality links resulting into less packet loss, which increases throughput and decreases delay. However, MAEE is not scalable and is not entirely efficient to deliver images to the destination.

Energy Efficient QoS Assurance Routing (EEQAR) is hierarchical protocol that aims to increase network lifetime [53]. Intracluster routing is based on three metrics, namely, remaining energy, QoS trust value, and data correlation coefficient. After each round, the location of cluster head varies resulting in restructuring of cluster topology. Nodes that are idle are put into sleep mode. For intercluster routing this protocol adapts TPGF [19]. Two types of Transmission Powers are used by the cluster heads, namely, the higher power level for intercluster routing and lower power level for intracluster routing. This protocol does not support packet priority and congestion. Also, contrary to the claim, results related to QoS are not presented and not compared with any previous protocols.

Channel Utilization and Delay Aware Routing (CUDAR) is a multisource protocol that uses cross-layer approach to offer high throughput, better delay, and low jitter in WMSNs [54]. Forwarding node is selected based on cross-layer communication between the network layer and MAC layer. To reduce energy consumption, it uses adaptive channel utilization module in MAC layer. CUDAR uses only three routing metrics to achieve most relevant information about best forwarding node, that is, PST, channel utilization, and remaining energy. Nodes are chosen with lesser PST and contention which further reduces congestion and delay. Results show that throughput gradually increases with increase in the number of source nodes. However, relatively increase in network lifetime is not significant as compared to previous protocols.

3.4. Quartet-Metric Link/Path Cost-Dependent Routing Protocols. Many routing schemes formulate routing decisions based on a combination of four routing metrics. Such schemes which determine link/path cost with the proper blend of four metrics are categorized as quartet-metric link/path cost-dependent routing scheme. Under this category, a comparative summary of routing schemes surveyed is shown in Table 4.

Akkaya and Younis presented energy- and QoS-aware routing support for both real-time and best-effort traffic simultaneously [37]. Path selection is based on four metrics, namely, distance, residual energy, link error rate with respect to the neighboring node, and end-to-end delay of an entire path. It can find multiple paths by using first three metrics along with an extended Dijkstra's algorithm. Further, optimal path satisfying an end-to-end delay constraint is selected. To support both real-time and nonreal-time traffic, a class-based queuing model is adapted. According to this model, every node consists of a classifier and a scheduler. The classifier places every incoming packet in an appropriate queue, and the scheduler decides the priority of every outgoing packet based on bandwidth ratio. This protocol maximizes throughput for real-time traffic and guarantees best-effort data traffic. However, in order to explore multiple paths, complete knowledge of network topology is required at the base station. In addition, link bandwidth is not shared after the initial allotment.

GEAMS is an online geographic energy-aware multipath stream-based routing protocol [38]. The forwarding policy at each node is based on four different metrics, namely, remaining energy, the distance between the current node and its neighbor, current stream history, and a number of hops from source to the current node. It consists of two types of forwarding modes: smart greedy forwarding and walking back forwarding. This protocol being online, every sensor node is regularly updated by its neighboring nodes about distance, link status, and remaining energy. In smart greedy forwarding mode, a list of best neighbors is selected based on an objective function. Based on this function score, packets with small and large hop count are forwarded to the worst neighbor node and the best neighbor node, respectively. Walking back forwarding mode is used recursively in the case of unavailability of the closest neighbor node to the sink. GEAMS is further extended in AGEM, which uses an adaptive greedy-compass forwarding policy to select the best neighbor [39]. AGEM chooses nodes with the smallest angular offset from a virtual line toward the sink that satisfies a minimum number of nodes ($n \geq 2$) to guarantee multipath routing. If the above criteria are not satisfied, then angle (α) is incremented in small steps toward 180°. If $n < 2$ at $\alpha = 180^{\circ}$, then walking back forwarding mode is executed. Both GEAM and AGEM are ideal choices for WMSNs; they ensure load balancing, delay, and packet loss constraint. However, in less dense network scheme performance is not satisfactory and does not consider traffic priority.

S-AOMDV is a multipath video transmission technique which is an extension of previous work [104, 115, 116]. This technique is based on packet priority and path scheduling [55]. Packets are given priority based on the type of frame (I, P, or B frame). Path selection depends on path-score, which is calculated from four metrics, namely, residual energy, free buffer size, hop count, and packet loss rate. At each sensor node, three queues are used separately for each type of frame. When the required transmission rate is greater than the available rate, then the source drops a few packets to maintain distortion at a minimum level. Significant packets are transmitted over more reliable paths, resulting in excellent video quality at the receiver. However, S-AOMDV requires higher bandwidth and consumes more energy in case of multiple sources.

REP is reliable routing based on a self-adaptive power allocation and energy prediction mechanism [56]. Path selection depends upon four metrics, namely, remaining energy of a node, average remaining energy of all nodes on a path, reaching probability, and reliability requirement. The transmission power of a sensor node is varied to eight different levels based on the remaining energy of that node which, in turn, balances network lifetime. In the energy prediction mechanism, every sensor node calculates energy consumption of its own and other nodes. Calculation of energy consumptions of other nodes depends on seven working states, namely, sleep, sense, idle, receive, transmit, process, and access. The entire network is separated into several concentric coronas to ensure that all sensory data reach the sink node. The results show that REP along with energy prediction and power allocation is more reliable and energy efficient. However, at high transmission power levels REP may suffer from intrapath interference. The concept of REP is further explored in ARCH for cluster-based adaptive reliable routing [57]. The cluster structure used is a cellular topology consisting of equal-sized virtual cellular cells. The topology supports multihop routing in single clusters and intercluster, whereas multipath routing is supported only in intercluster. Similar to REP, this technique may also suffer from intrapath interference. The results of ARCH are not compared with any other protocols.

IQAR is an adaptive routing protocol designed to transmit low-resolution images on WMSNs [58]. Based on entropy or edge, every image is assigned a high or low priority before transmission. Next hop selection is based on a cost function, which depends on link quality (PDR), delay, remaining energy, and reliability requirement. The end-to-end delay is maintained with the help of desired delivery speed. Based on average cost and required speed, all neighboring nodes are classified into two categories, namely, high-quality neighbor nodes and low-quality neighbor nodes. From the set of high-quality neighbor nodes, it chooses the next hop node with the highest cost and that meets reliability requirements. With respect to energy, delay, and image quality, IQAR shows better performance than MMSPEED. However, in IQAR, prioritization is limited to only images; that is, prioritization is not applicable for scalar data, audio data, or video data. In addition, relatively IQAR performance is not satisfactory when a number of flows are less.

ACOWMSN is an Ant Colony Optimization based QoS routing algorithm that considers four QoS metrics during the route discovery process, namely, bandwidth, delay, packet loss rate, and remaining energy [59]. Selected link or path should satisfy all four routing constraints. It optimizes the final route based on the hop count of the path. It uses two types of artificial ants, namely, forward ants and backward ants. The source node broadcasts forward ants. Intermediate neighboring nodes that satisfy the requirements of these four-QoS metrics will again broadcast these forward ants. When a forward ant reaches a sink, it converts into a backward ant and returns to the source node in the opposite direction along the same path. A backward ant updates the pheromone concentration value of each node. Though exhibits many properties for WMSNs routing, ACOWMSN generates heavy traffic in the form of ants, which is not suitable for very large networks. However, it is relatively more scalable and reliable than the other ant colony optimization based schemes.

EEQAR is energy-efficient QoS assurance hierarchical routing for WMSNs [60]. The next relay node is selected based on four metrics, namely, remaining energy, trust value, data correlation coefficient, and hop count of the neighboring node to the cluster head. Based on these four parameters, each node stores an optimization factor table. The concept of trust value metric is derived from social network analysis in which trust value is estimated by monitoring directly or indirectly the current and past behavior of neighboring nodes. A data correlation coefficient is used for data fusion to reduce the amount of data transmission. After every round, the cluster structure is modified by giving mobility to the cluster head which avoids creation of network holes and balances energy consumption. EEQAR improves network lifetime over ARCH [57], but its dependence on high transmission power level may cause interference in the nearby nodes.

CR-WMSN is a reactive, cross-layer QoS routing protocol that guarantees end-to-end delay [61]. A selection of the next hop is based on four metrics, namely, PST, hop count, channel utilization, and remaining energy of a node. Channel utilization signifies intensity of contention around the node. During route discovery, CR-WMSN selects nodes with a smaller PST and low contention, which reduces congestion and increases throughput. The length of another path should not be more than three hops longer than the shortest path (other path lengths ≤ shortest path length + 3 hops). This constraint on the length of the path restricts further load balancing and the lifetime of the network. Simulation results show that CR-WMSN guarantees end-to-end delay and higher throughput.

Work by Dong et al. based on the genetic algorithm finds the best routing path from the set of Pareto-optimal routing paths [66]. These paths are found with a multiobjective function that is based on four metrics, namely, bandwidth, delay, jitter, and packet loss rate. A set of Pareto-optimal routing paths is found with the help of a noncontrol sorting method. From this set, the best path is found by using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). In TOPSIS, each path is compared with an ideal best solution and worst solution. Compared with previous schemes using genetic approach, this scheme shows an increase in the probability of finding the best optimal path, though optimal path is completely dependent on the construction of Pareto solution set.

Another routing scheme by Bae et al. provides congestion control, minimizes delay, and maximizes throughput [40]. The optimal path is determined using four metrics, namely, traffic priority, link quality, residual energy, and the distance between nodes. Every node will calculate its priority with respect to sink. Based on this priority and other metrics each node will find two forwarding nodes, namely, main forwarding node and alternate forwarding node. Congestion is identified using buffer occupancy and congestion degree of a node. Alternate node is used when congestion occurs at the main forwarding node. Three types of traffic priorities are defined for packets, that is, green, yellow, and red. The green packet has the highest priority whereas red packet has the lowest priority. Contrary to the claim, results regarding graphs are not shared by the authors. Overhead is more due to two reasons, that is, first, every node that is required to calculate priority with respect to sink and second sharing of buffer and congestion degree information with each other.

Pair-Wise Directional Geographical Routing (PWDGR) solves energy bottleneck problem around sink and source [41]. Next forwarding node is decided based on a number of hops, 1-hop distance, path contract angle, and included angle. Neighbor Nodes selected in the 360° scope around sink node are called as pairwise nodes. All pairwise nodes are used to prolong the network lifetime. Similarly, source neighbor nodes known as source cooperative nodes are selected by considering energy consumption problem in optimized order. Multiple paths in PWDGR help fast bandwidth aggregation, load balancing, and better video quality at the sink. Compared to a dense sensor network, performance of PWDGR diminishes in low-density network. This can be attributed to the availability of very few pairwise nodes in low density network.

3.5. Five and More-Metric Link/Path Cost-Dependent Routing Protocols. These types of QoS routing protocols make a routing decision based on five or more metrics. Such schemes where link/path cost is decided based on five or more metrics are known as five and more-metric link/path cost-dependent routing schemes. Very few such schemes are reported and the same schemes are surveyed in this subsection. Table 5 shows comparative summary of routing schemes under this category.

HQAX is a multitier, hierarchical, soft QoS-aware cross-layer routing protocol [62]. It improves throughput and reduces packet loss for indoor environments. To calculate the cost of the path, it considers physical and MAC layer parameters along with network layer parameters. These parameters of all three layers optimize utilization of resources resulting efficient routing. The link cost function depends on five parameter metrics, namely, delay, SNR, error rate, remaining energy of the sending node, and remaining energy of the receiving node. This link cost function is further normalized using sigmoidal functions [117]. HQAX is independent of the MAC layer and is compatible with existing link and network layers. However, it is not suitable for critical-time applications as it supports only soft QoS-based traffic.

LBA-EA is a load-balanced and energy-aware routing scheme for WMSNs [63]. In this scheme, a new metric known as extended version of the airtime default-link metric is used [70]. This metric consists of two parts, that is, a load-aware airtime factor and an energy-aware factor. An energy-aware factor of a path is computed from residual energy, initial energy, the total number of nodes, and the total number of links along the selected path. Additionally, a load-aware airtime factor is computed from protocol overhead, frame length, link bit rate, link frame error rate, queuing delay, and interflow interference factor. As defined in 802.11s, it uses RM-AODV for path selection [70]. LBA-EA chooses the less congested route, balances traffic load, and considers the lower interflow interference of contending neighbors. The overall performance of the extended metric is better than the default airtime link metric, though LBA-EA causes extra overhead.

POWQR, or the power-controlled QoS routing protocol, uses local information to decide the next forwarding hop [42]. The next hop is decided based on the remaining energy of the node, link quality, distance, delay, and number of hops (levels). Speed is derived by considering both transmitting delay at the sender and queuing delay at the receiver. The forwarding strategy distributes the load over different paths, reducing congestion and improving the lifetime of the network. Reliability of packet transmission is achieved by increasing the transmission power of a node. Simulation results show enhanced performance of POWQR to support reliability, delay, and network lifetime, but it is not scalable.

Inspired by AGEM [39] and based on the QoS routing method [40], Serhan and Diab presented QoS routing protocol that has witnessed an increase in energy efficiency and QoS guarantee for multimedia services [43]. The next forwarding candidate nodes are determined not only by AGEM using four different metrics but also from traffic priority. Traffic priorities (green, yellow, and red) are calculated for every node based on link quality, the residual energy of the neighboring nodes, and hop distance from the neighbor node to the sink. These nodes are sorted for each priority. Additionally, different cost functions are used to calculate the priority for the type of packet, and these packets are routed through different paths. The results presented in this work have been limited to ten nodes in the network and very few packet transmissions from the source to sink.

In this section, from most of the surveyed routing protocols and detailed comparison as mentioned in Tables 1–5, it can be summarized that the number of routing metrics used plays a significant role in the performance of a routing protocol. For example, the single metric-based TPGF [19] is enhanced further with the help of one additional metric in McTPGF [22], MPMP [23], and EA-TPGF [24]. The inclusion of an additional metric in the above three protocols has positive effects on the performances of the routing protocols, that is, in McTPGF [22]; end-to-end delay is much lower than that in TPGF [19]. Additionally, average hop counts in McTPGF are almost the same as in the TPGF. Cross-layer implementation in MPMP [23] guarantees end-to-end transmission delay and maximizes the collection of most significant data at the receiver. EA-TPGF [24] significantly improves the lifetime of the network compared with TPGF [19]. Additionally, including one more composite metric [43] results in a major reduction of the end-to-end delay for high-priority traffic and less energy consumption compared with AGEM [39]. In another example, MMSPEED [30], extended from SPEED [21], shows subtle improvement in the number of flows meeting both timeliness and reliability requirements.

In order to highlight optimum performance of a given protocol, each work has been compared with the previous one. From most of the surveyed papers, higher metrics-based protocols show relatively better performance, for example, TPGF [19] with GEAM [49], SAR [44] with REAR [33], and MMSPEED [30] with IQAR [58]. GEAM [49] achieves excellent load distribution with more balanced energy consumption compared with TPGF [19]. REAR [33] increases the lifetime of the network compared with SAR [44]. IQAR [58] consumes less energy, causes less delay, and has good image quality compared with MMSPEED [30]. In addition, keeping the same number of metrics with appropriate metric permutation also results in optimum performance with respect to the stated objective, for example, REAR [33] and ASARC [34], ARCH [57], and EEQAR [60].

4. Open Issues and Future Directions

WMSN is still an evolving area of study. Despite large amounts of research undertaken in the field of QoS routing protocols in recent years, many key open issues remain that require urgent attention. In this section, related open issues and research directions are outlined for current and future explorations.

4.1. Multiconstraint QoS. Multimedia data traffic has diverse QoS requirements. Thus, there is a need to design a mechanism to deliver multimedia data with a certain level of QoS. These QoS parameters include throughput, bandwidth consumption, energy efficiency, reliability, delay (latency), jitter, mobility, and security. Multiconstraint routing protocol should ensure that delay remains within an acceptable range, and the link bandwidth pertains to the average compression ratio, average jitter, and less energy consumption. For example, in Figure 2, multiconstraint QoS profile emphasizes reliability, throughput, and energy efficiency. Considerable development in multiconstraint-based routing has been achieved to date. Most of this work considers a maximum of three to four constraints for optimizing the performance of routing protocols. A more holistic approach based on multiconstraint QoS is open for exploration in WMSNs [16, 118–121].

4.2. Adapting Green Technology. WMSNs are strictly constrained with regard to memory, processing capability, and particularly energy. Although batteries can provide wireless sensors with energy, it is extremely limited. Network lifetime is directly proportional to the amount of energy consumed for routing the data traffic. In addition, there is a trade-off between energy-efficiency and multimedia QoS guarantee. Hence, it is important to balance energy efficiency and QoS to develop energy-efficient routing techniques in WMSNs [16, 17, 118, 121, 122]. Additionally, efficient data compression techniques with low complexity are required to limit energy and bandwidth consumption. Many works providing bandwidth saving and energy preservation in WMSNs have been reported. However, the problem of achieving efficient image compression and transmission in resource-constrained WMSNs is not completely solved. Several research works surveyed in this paper do not consider an energy constraint in routing. All of these schemes can be further explored to reduce energy consumption. The penetration of WMSNs will benefit largely from adaption of green technology.

4.3. Three-Dimensional Routing. In real applications, sensors are deployed on different floors of buildings, on trees with different heights, covering entire mountain areas, open mines, and so forth. Existing 2D routing techniques perform poorly in practical 3D sensor network deployments [123]. In addition, it is not straightforward to extend existing 2D routing techniques to support 3D space. This survey discovers that a significant amount of work carried out supports only 2D networks and the only exception being TPGF [19] which supports routing in both 2D and 3D spaces. Thus,

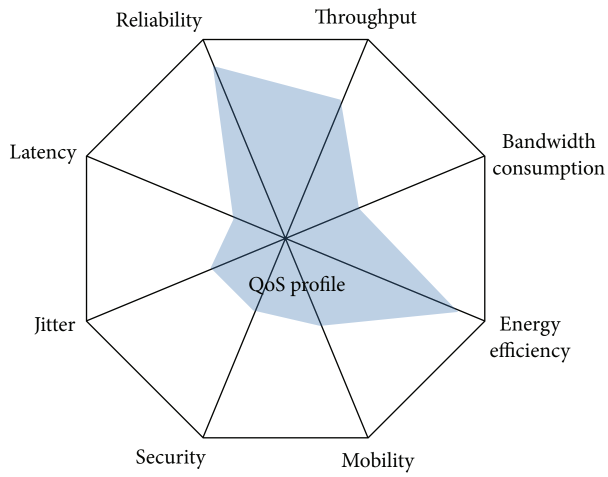
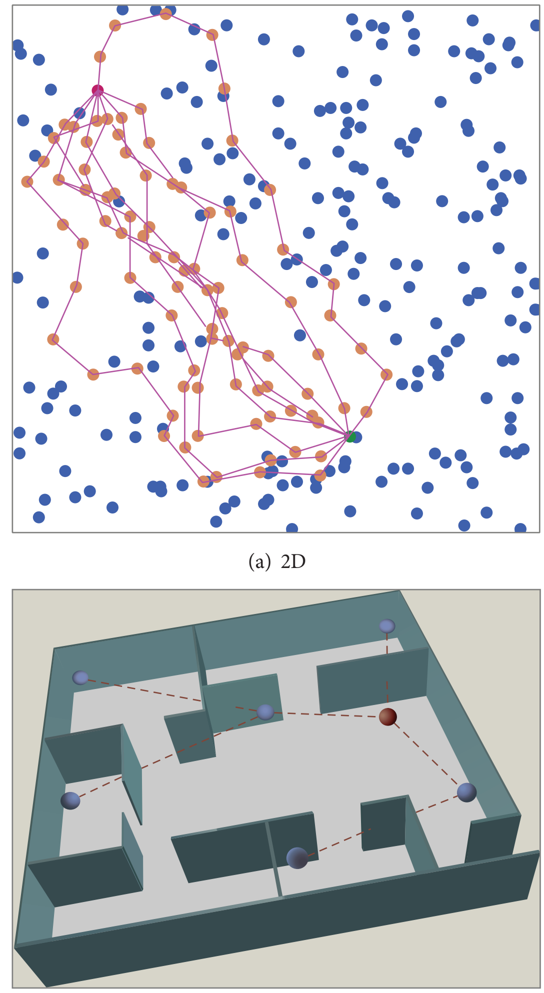


Figure 2: Quality of Service (QoS) parameters in WMSNs.



(a) 2D

(b) 3D

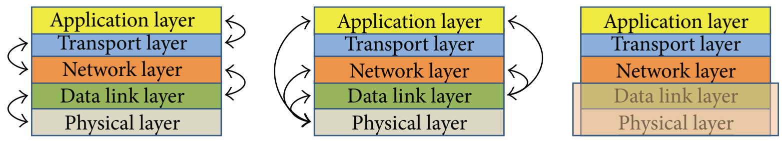
Figure 3: Two-dimensional and three-dimensional space in NetTopo [71] simulator.

QoS routing for practical 3D sensor networks is relatively unexplored. Today few simulation tools like NetTopo [71], Opnet [85], and OMNet++ [89] support 3D along with 2D space. Figure 3 shows simulation scenarios in 2D and 3D space using NetTopo [71] Simulator. Designing new routing protocols based on 3D space is a promising area of research [124, 125].

4.4. Cross-Layer Functionality. In traditional layered approach functionalities and services are divided among layers. Each layer allows interaction or procedure calls between adjacent layers, but it does not allow interaction between nonadjacent layers. As shown in Figure 4(a), each layer works independently, with no sharing of QoS requirements with nonadjacent layers. However, error-prone nature of wireless channel and other factors make the layered approach unsuitable for optimizing overall WMSNs performance. The cross-layer approach shown in Figure 4(b) allows the exchange of information across multiple layers to support optimal performance. It appears to be the most practical approach for guaranteeing QoS in WMSNs. Although little work is performed, the cross-layer approach provides a potential direction for research in WMSNs [16, 17, 120, 121]. To guarantee QoS new protocols can be designed to integrate a minimum of two layers, for example, a combination of the network layer and the transport layer, a combination of the network layer and the data link layer, and a combination of the data link layer and the physical layer as shown in Figure 4(c). Furthermore, one can even explore possibility of integrating three or more layers. In addition, a cross-layer framework for WMSNs can be developed by considering service differentiation, admission control awareness, and rate adaption along with QoS routing [120].

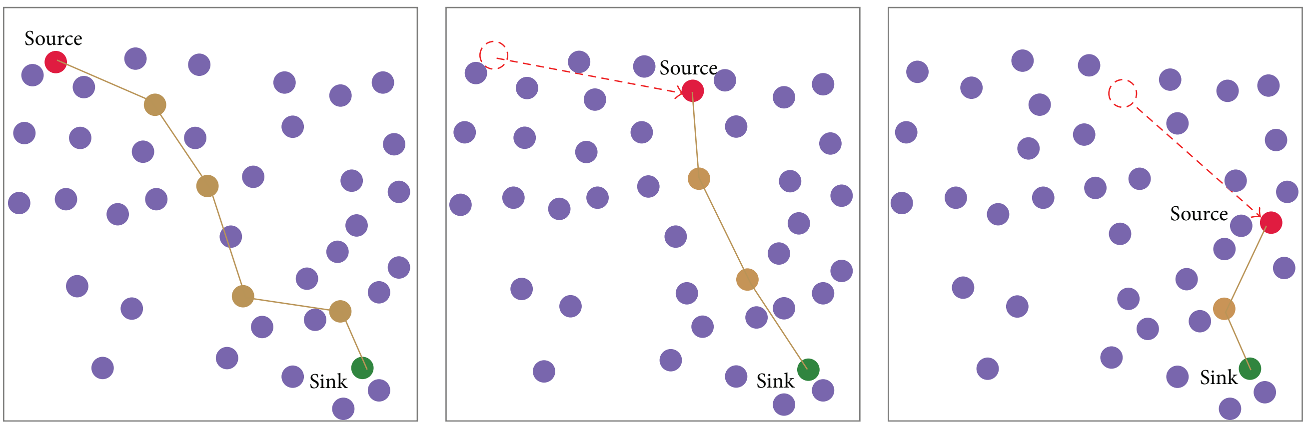
4.5. Support for Node Mobility. In applications like mobile object tracking, border surveillance with Unmanned Aerial Vehicles (UAVs), sensor nodes move to various locations for collecting necessary information. Also, nodes surrounding sink deplete their energy much faster compared to the nodes located far away due to heavy overhead. This shortens network lifetime. Due to the mobility of sensor nodes the network topology becomes highly dynamic, and it generates considerable overhead. In fact, it reduces the number of required nodes with an increase in complexity. Figure 5 shows a simple scenario where source node is mobile and path is explored with TPGF [19]. Due to source mobility, network topology and routing paths are changed (Figures 5(b) and 5(c)). Mobility can be applied to sink, source, and other relay nodes. Node mobility provides greater coverage, helps to mitigate congestion, reduces delay, and increases reliability. However, node mobility poses new challenges with regard to balancing energy efficiency and QoS guarantee. Support for node mobility is relatively unexplored and thus routing with node mobility is an interesting area for future research [16, 17, 118, 122, 126].

4.6. Secure Routing. WMSNs are usually deployed at unattended or in hostile environments. Therefore, they are vulnerable to various security attacks, such as wormhole, sinkhole,



(a) Layered approach (b) Cross-layer approach (c) Cross-layer approach, merging of adjacent layers

Figure 4: Traditional layered and cross-layer approach.



(a) Initial location of source (b) Source moves towards center (c) Source moves towards sink

Figure 5: Source node mobility scenario, change in topology and routing paths.

sybil, spoofed, altered, and selective forwarding attacks [17]. Due to the unreliable wireless channels and unsupervised feature of WMSNs, a malicious adversary may readily launch attacks to compromise the security of the sensor node or network. The constrained capabilities of sensor nodes make it very difficult to implement strong security protocols. A strong security protocol requires more resources that can shorten the lifetime of the sensor node. However, simple security protocol can be easily compromised by an adversary. Due to limited resources available with the sensor nodes, standard security protocols may not be suitable for WMSNs.

Security can be provided with the help of five different services, namely, confidentiality, authentication, integrity, nonrepudiation, and availability. Work done to support extremely simple security features has been reported. Due to limited resources, symmetric cryptography is an ideal choice for scalar-based sensor nodes to implement security. However, in general, symmetric cryptography is not able to support nonrepudiation, authentication, and digital signatures in an effective manner. Additionally, because of the use of simple symmetric keys, nodes can be easily compromised by attack that can disrupt the entire network. For further improvement of secure routing, asymmetric cryptography can be incorporated among a few high-processing multimedia sensor nodes. Therefore, incorporating symmetric and asymmetric encryption techniques and designing mechanisms to prevent different types of attacks and key distribution techniques in resource constraint environment are few promising areas of research in secure routing. QoS guarantee and network security management are two critical aspects that will determine the success of future WMSNs [16, 17, 118, 127].

4.7. Multiple Sources and Multiple Sinks. In large-scale networks, a single sink is placed at a position that may be far away from the source node. Thus, data transmission through multiple intermediate nodes may be expensive in terms of energy and end-to-end delay. In addition, neighboring nodes of sink may deplete energy faster and that may isolate sink from other nodes. Thus, there is a requirement of multiple sink nodes which can be strategically placed within the network. Multiple sink deployment ensures optimum energy consumption with QoS guarantee [128].

With the continuous improvement in the WMSNs hardware and software, the capability to use multiple applications across a single WMSN has increased. Almost all existing QoS routing protocols are designed to route data traffic from a single source to a single sink. Although this is not entirely a new concept, a network with multiple sources and multiple sinks can be required to obtain different event information simultaneously. Designing and exploring a QoS routing protocol for such a robust and complex network can be interesting area of research [16, 118].

4.8. New Class of Algorithms with Appropriate Blend of Routing Metrics. For routing in WMSNs, ACO and game theory based class of algorithms are becoming prevalent. This class of algorithms are mostly multiobjective and adaptive in nature which are suitable for dynamic scenarios. Thus,

Table 6: Comparison of the physical layer standards in WMSNs.

Specifications	UWB	WLAN	Bluetooth	ZigBee
Data rate (max)	250 Mbps	54 Mbps	3 Mbps	250 Kbps
Output power	1 mW	40–200 mW	1–100 mW	1-2 mW
Code efficiency	97.94%	97.18%	94.41%	76.52%
Range	<10 m	30–100 m	1–100 m	10–100 m
Frequency	3.1 GHz–10.6 GHz	2.4 GHz	2.4 GHz	2.4 GHz or 915 MHz or 868 MHz

exploring above class of algorithms can be a new area of research [16, 17]. Also, it is observed from this survey that the proper blend of routing metrics based cost function decides the performance and complexity of a QoS routing protocol. Metric based cost function modeled using more advance mathematical techniques can be developed to offer better routing performance [129]. In addition, WMSNs need to support both scalar as well as multimedia data traffic. Based on the types of application and the type of data traffic, routing should be tailored to guarantee QoS. New protocols for generic routing and adaptive cost functions can be developed to support different types of data traffic [14].

4.9. Adoption of Ultra Wideband (UWB) Technology. Based on modulation schemes and considering bandwidth, physical layer technologies are categorized into three groups: narrow band, spread spectrum, and Ultra-Wideband (UWB) [7, 130]. Also, they are categorized based on standard protocols, namely, IEEE 802.15.4 ZigBee, IEEE 802.15.1 Bluetooth, IEEE 802.11 WiFi, and 802.15.3a UWB which is shown in Table 6. ZigBee is a lightweight, low cost, and low power consumption protocol. It is the most common standard radio protocol used in WSNs. However, ZigBee standard is not suitable for high data rate applications. In addition, Bluetooth and WiFi standard supports higher data rate but with more power consumption. UWB technology supports higher data rate up to 250 Mbps and low power consumption. Thus, it appears that UWB technology can be an ideal choice for short range applications in WMSNs. In addition, with the new characteristics of UWB, location-aware routing protocols can be optimized for better performance. So adoption of UWB technology in WMSNs can be explored further to achieve optimum network performance [7, 120, 130, 131].

4.10. Duty Cycle Based Routing. A sensor node consumes maximum amount of energy when communicating (transmitting and receiving) with other nodes. To conserve energy, sensor nodes should be switched to sleep mode when there is no data to transmit/receive and woken up to active mode whenever required. This active and sleep mode of a sensor node together are referred to as duty cycling. Duty cycle based routing reduces energy consumption, resulting in an increase in network lifetime. It schedules the node radio state depending on network activity to minimize idle listening mode and to favor the sleep mode. Static duty cycle schemes based on fixed duty cycle save less energy and are not suitable for WMSNs. Thus, dynamic, adaptive duty cycle schemes are required which should be based on current traffic load, traffic priority, network topology, residual energy, and sensor density. However, the most challenging task is achieving dynamic duty cycling control due to the volatile nature of the video traffic. A duty cycle makes a huge impact on multipath routing. Work done to support static duty cycle based routing has been reported in WMSNs [72, 73]. Figure 6 shows two simulation scenarios of CKN [72] based TPGF [73] using NetTopo [71] simulator. A number of sleeping nodes (black color) are more in Figure 6(a) compared to Figure 6(b). Due to this reason a number of paths found from source (red color) to sink (green color) are less in Figure 6(a) compared to Figure 6(b). Adaptive duty cycle based routing is relatively unexplored and can be a further area of research [121, 124].

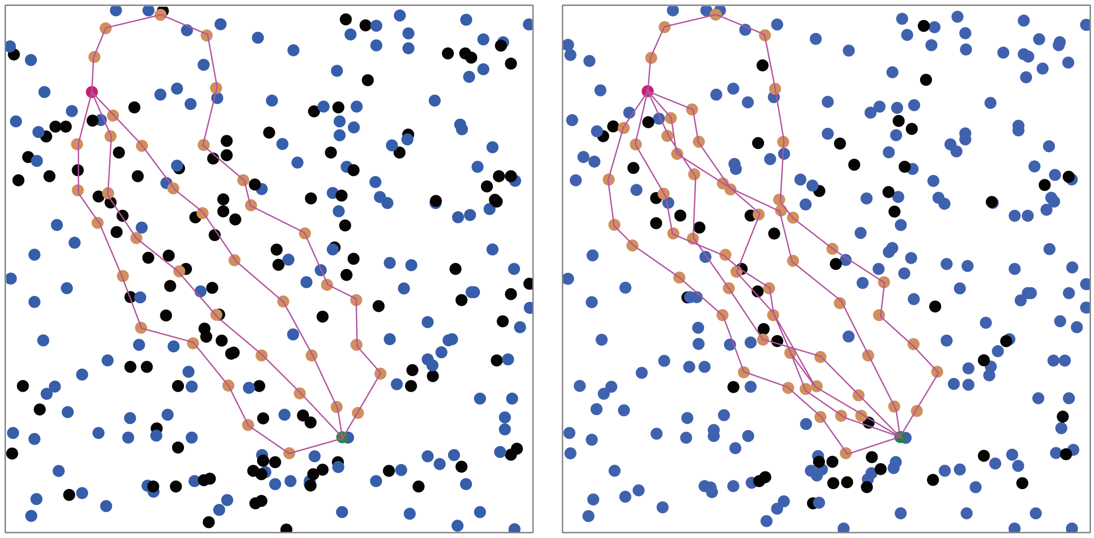
4.11. Internet of Multimedia Things (IoMT). As shown in Figure 7, physical objects or smart things observe and interact with the physical environment and communicate with other things. In addition, these objects need to be controlled remotely with existing network infrastructure. This concept is called Internet of Things (IoT). Internet of Multimedia Things (IoMT) is a specialized subset of IoT, enabling the integration and collaboration of heterogeneous multimedia devices with distinct resource capabilities [132].

In IoMT, the delivery of multimedia data should guarantee QoS. For IoMT new routing metrics should be considered that may be energy efficient and guarantees QoS. Routing protocol for IoMT should be highly flexible and adaptive in nature. Today, there is a need to develop new architecture for IoMT that should take care of bandwidth, complex processing, cloud services, and other issues [16, 17, 132].

5. Conclusions

This paper provides an extensive and novel survey of most of the existing state-of-the-art QoS WMSNs routing protocols. In addition, it provides an overview of the relationship between QoS routing protocols and link/path routing metrics. Furthermore, it emphasizes the importance of blending the number of link/path routing metrics for optimal performance.

Routing protocol plays a important role in guaranteeing QoS in WMSNs. This survey introduces a new taxonomy for the classification of QoS WMSNs routing protocols. Existing QoS WMSNs routing protocols are classified based



(a) CKN [72] based TPGF [73]

(b) CKN [72] based TPGF [73]

Figure 6: Duty cycle based sensor network using NetTopo [71] simulator (active nodes in blue/maroon, sleeping nodes in black, source node in red, and sink node in green color).

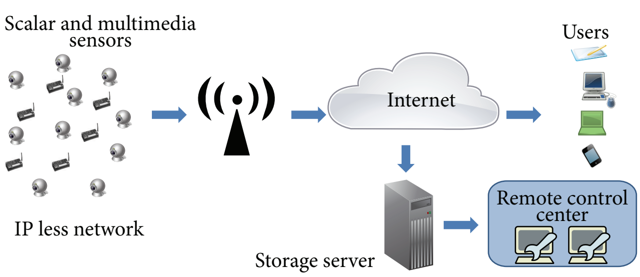


Figure 7: WMSNs architecture for IoMT.

on the number of metrics used to evaluate the cost of a link or a path. An increase in the number of metrics in the routing decision shows significant improvement in the performance of the routing protocol; however, it adds more complexity to the routing. Furthermore, these protocols are surveyed in detail, highlighting different performance issues. Additionally, the merits and demerits of protocols are highlighted and discussed in brief. Summarized comparison of these protocols is presented in Tables 1–5 based on their intrinsic characteristics. It should be noted that every reviewed scheme in this paper has made a significant contribution in QoS routing from different perspectives and in different scenarios. The main objectives of the majority of the protocols in this field are to reduce the average end-to-end delay and extend the lifetime of WMSNs. Also, most of the techniques use distance, delay, and energy based metrics in combination with other metrics. Finally, this paper identifies key open issues and possible future research directions that encourage further investigation in uncharted areas. There is good potential for future research in design and implementation of new efficient QoS routing protocols leading to real, practical WMSNs.

This survey aims to improve the understanding of the current QoS routing techniques based on multiple routing metrics. In addition, it summarizes various routing metrics and their effectiveness in offering QoS guarantee. We hope that this survey will provide researchers and designers a quick insight of work done in the area of WMSNs QoS routing and contribute in the areas listed as potential field of work, thus realizing the dream of designing efficient, real-life practical WMSNs.

Conflict of Interests

The authors declare no conflict of interests.

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