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MEQSA-OLSRv2: A Multicriteria-Based Hybrid Multipath Protocol for Energy-Efficient and QoS-Aware Data Routing in MANET-WSN Convergence Scenarios of IoT

WAHEB A. JABBAR[1], **(Senior Member, IEEE), WASAN KADHIM SAAD**[2], **(Member, IEEE), AND MAHAMOD ISMAIL**[3], **(Senior Member, IEEE)**
[1]Faculty of Engineering Technology, Universiti Malaysia Pahang, Gambang 26300, Malaysia
[2]Engineering Technical College, Al-Furat Al-Awsat Technical University, Najaf 54001, Iraq
[3]Centre of Advanced Electronic and Communication Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia

Corresponding author: Waheb A. Jabbar (waheb@ ieee.org)

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ABSTRACT Convergence of typical wireless networks [mobile ad hoc network (MANET) and wireless sensor network (WSN)] is paving the way toward brand-new cooperative platforms for Internet of Things (IoT) communications. The IoT enables the global connectivity of a wide variety of heterogeneous objects in accordance with their battery capacity, processing capabilities, and mobility to serve people in a collaborative manner automatically and intelligently. In such ubiquitous smart environments, efficient and effective data routing among IoT devices represent a real challenge due to nodes heterogeneity. Thus, this paper proposes a hybrid multipath energy and quality of service (QoS)-aware optimized link state routing protocol version 2 (MEQSA-OLSRv2), which is developed to cope with the challenges presented by limited energy resources, mobility of nodes, and traffic congestion during data transmission in the MANET-WSN convergence scenarios of IoT networks. This protocol uses a node rank according to multicriteria node rank metric (MCNR). This MCNR aggregates multiple parameters related to energy and QoS into a comprehensive metric to dramatically reduce the complexity of multiple constrained considerations and avoid the control overhead caused by separately broadcasting multiple parameters. These metrics are the node's lifetime, residual battery energy, node's idle time, node's speed, and queue length. The MCNR metric is utilized by a new link quality assessment function for multiple-route computation. It is also adopted to select a multipoint relay (MPR) set of nodes by using an energy and QoS-aware MPR selection mechanism for flooding topological information. The simultaneous consideration of energy and QoS parameters can benefit the tradeoff between QoS and energy awareness. The performance of the MEQSA-OLSRv2 is evaluated through EXata-based simulations, and its effectiveness is validated by comparing it with the conventional routing protocols. The MEQSA-OLSRv2 is found to outperform existing schemes even in heavy traffic load and high-mobility scenarios. Furthermore, the MEQSA-OLSRv2 considerably enhances QoS, reduces energy consumption, and decreases the energy cost per packet.

INDEX TERMS MANET, WSN, IoT, convergence scenario, energy efficient, QoS-aware.

I. INTRODUCTION

The current advancement of smart devices with wireless technologies has developed new perspectives in the field of wireless networking and has allowed users to communicate in a peer-to-peer manner irrespective of time and location. A set of mobile and/or stationary autonomous devices with wireless technology support can be interconnected via wireless links to form a temporary dynamic network with or without the aid of any centralized administration or fixed support [1]. These multihop ad hoc wireless networks (MAWNs) (e.g., MANET, WSN, VANET, and WMN) are regarded as key technologies for providing a huge variety of Internet of Things (IoT)

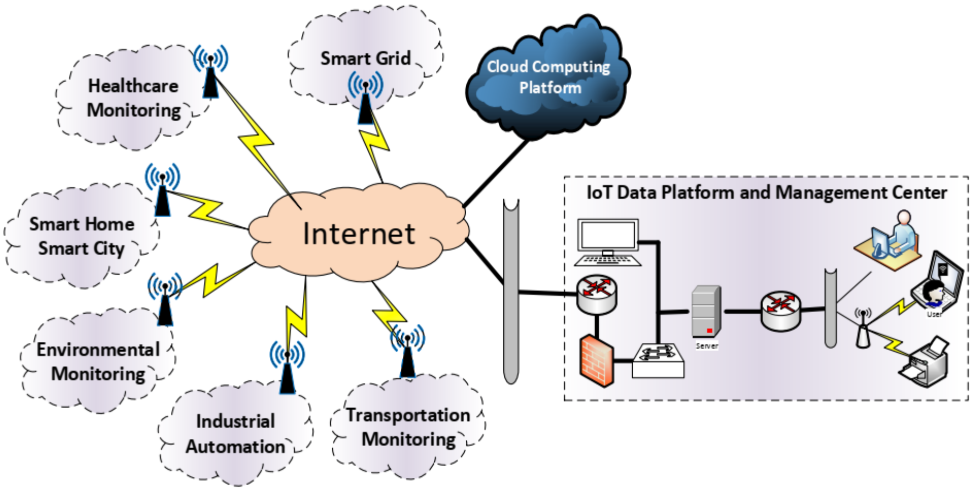

FIGURE 1. Example of IoT-based scenario architecture.

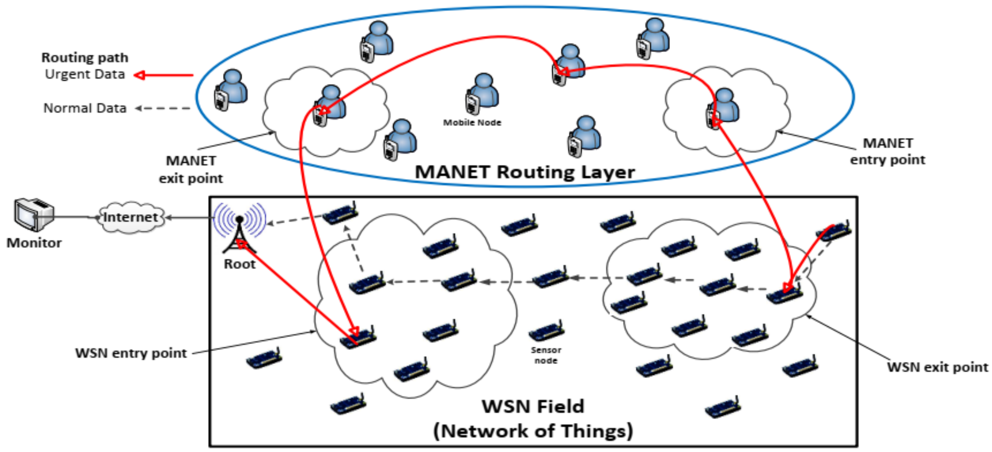

FIGURE 2. A simple MANET-WSN convergence scenario in the IoT environment.

applications and services (Fig. 1) to improve life quality [2]–[4]. One of the core advantages of multihop wireless communication is its capability to extend connectivity in a way that allows two nodes without a direct connection to communicate using a routing protocol via intermediate nodes.

The IoT as an emergence technology represents an innovative solution to enable the connection of billions of physical devices in the digital world by utilizing diverse networks with heterogeneous objects in terms of energy resources, processing capabilities, mobility, and communication technologies. In a smart environment, the IoT interacts with wireless sensor networks (WSNs) and mobile ad hoc network (MANETs), thereby creating convergence scenarios that open new ways for providing applications and rendering them attractive to users [5]. Such MANET-WSN convergence scenarios allow great mobility and flexibility for users and reduce the cost of network deployment. As shown in Fig. 2, MANET-WSN convergence scenario composes two types of wireless networks. First, WSN or network of things which consists of a huge number of low-cost and easy-deployable sensors, typically for monitoring environment. Second, a well-known MANET, which allows people with smart devices (nodes) to freely and dynamically form a self-configuring, self-organizing and infrastructure-less wireless network to send, receive, and share data in a restricted zone.

The convergence scenario opens brand-new opportunities in the infrastructure of Smart City and IoT in monitoring wide-scale urban. A variety of nodes (sensors, smart phones, smart meters, laptops, etc.) with different capabilities and different deployment nature (stationary and/or mobile) will connect together to create a smart interactive environment. Most of nodes in WSN scenarios are fixed nodes with low energy resources and low data rates. These nodes sense data from the surrounding environment and send it via multiple hopes to Sink node (Root), which in turn update the collected data to the Server. In contrast, most MANET's nodes are mobile with higher processing capabilities and energy reserves. Indeed, MANET-WSN convergence paves the way towards brand-new platforms for IoT communication to overcome limitations of both typical paradigms of WSN and MANET when deployed separately. Fig. 2 describes the routing of urban data in MANET-WSN convergence scenario by harvesting the monitored information from a huge number of collaborating sensors. Unlike typical scenarios, data can be forwarded from the field sensor to the server via intermediate WSN and/or MANET nodes. In case of urgent data (e.g., disaster and rescue management, city surveillance, and home security) where effective data collection is critical, data will be routed via MANET's nodes due to their superiority in terms of energy and processing capabilities compared to typical sensors. Thus, more efficient paths will be selected for data routing to ensure the successful transmission of data to the server and overcome technical issues of typical WSN limitations (limited-energy, delay, low data rate, etc.).

In the MANET-WSN convergence deployments, MANET overlays has been integrated and opportunistically exploited for collaboratively formed on-top of WSNs, to boost the harvesting of data in a wide range of IoT applications in various domains. MANET overlays are utilized to dynamically speed-up the forwarding of urgent sensed data over lower latency and higher reliability MANET routes. Despite the considerable flexibility presented by non-direct communication wireless networks, they open new challenging issues that are related to energy efficiency and quality of service (QoS) [6]. Among these constraints, the most difficult problem is to find and sustain reliable paths for efficiently routing packets from an originator to a destination. This difficulty stems from the low reliability of wireless media, the modest processing capabilities of nodes, and the dynamic topology of networks.

A. RESEARCH MOTIVATION

Prior to explain the importance of efficient data routing in IoT environment, let us start with this question "Why MANET-WSN convergence scenarios?". As aforementioned, MANET-WSN convergence deployment enables a brand-new Device-to-Device (D2D) cooperative networks [7] for communication in IoT environment, hence overcome limitations of individual operation of typical WSNs and MANETs. At the same time, such cooperative communication represents a key feature in the next generation of mobile communication networks (5G) [8]. In such convergence environment, nodes heterogeneity will be a key player in data sensing and transmitting between source-destination pairs.

For example, let us consider a flood monitoring system targeted at the monitoring of water level using WSN nodes disseminated on river sides for continuously collecting data about changes in river level and send early alerts to users in case of flood occurs. When high level flood is detected (e.g., warning or dangerous situation), the system triggers an alert to population or agencies to take prevent actions, this warning messages must be sent to the server faster than normal readings of water level. This preference is not applicable in typical WSN, where packet latency totally depends on number of hops and the status of sensor (transmit, receive, idle, or sleep). In MANET-WSN scenarios, the latency of urgent data can be reduced by exploiting overlays MANET nodes. Thus, alleviates two main limitations of WSN, low data rate and low battery capacity. In practical, even nodes in MANETs have some energy constraints but most nodes are mobile and can transmit data with a higher bandwidth and lower latency. Consequently, both MANET and WSN can mutually gain benefits from each other in convergence scenarios.

Data communications in IoT is becoming an active research field with great prospects for the future. Previously, IoT applications were focused on data sensing environments, particularly sensor and actuator networks, in which IoT sensors with limited battery capacity and computing capabilities communicate with one another over wireless channels [9]. The energy efficiency in the IoT networking paradigm has been paving the way for an emerging area called green IoT [10]. Most IoT devices are supposed to be battery operated and disconnected from the mains. Moreover, they are equipped with additional sensors and wireless communication capabilities and thus require additional energy [11]. The IoT network becomes congested with billions of devices, and the energy demand greatly increases [12]. The battery replacement of these devices is not always feasible due to areas of deployment. Therefore, the communication protocol stack must become increasingly efficient and require a low energy consumption [13]. By contrast, as the IoT paradigm gains proliferation, the need to meet the provisions of QoS for real-time IoT applications and multimedia services is growing as well. These applications have strict QoS requirements, such as delay, bandwidth, data delivery, jitter, and overhead [14].

B. PROBLEM STATEMENT

The routing protocol in the IoT network architecture must be reliable enough to provide effective and efficient communication and data transmission among IoT objects for the precise implementation of IoT systems. Most existing routing protocols have a single path and primarily focus on the sensor networking paradigm of ad hoc networks; thus, they are not robust enough to support IoT applications, especially with a heavy traffic load. Multipath routing that aggregates multiple constraints into a single comprehensive metric is important to achieve reliable data forwarding in the IoT [15], [16]. Figure 3 shows that the IoT networking paradigm with large-scale sensors is facing THREE (3) major challenges related to data routing. The figure also demonstrates the suggested solutions that have led to the proposal of the multipath energy and QoS-aware optimized link state routing protocol version 2 (MEQSA-OLSRv2). We have addressed these challenges with the proposed solutions as follows.

(i) High-reliability data transmission cannot be guaranteed by lower layers (PHY and MAC layers); it needs to be realized

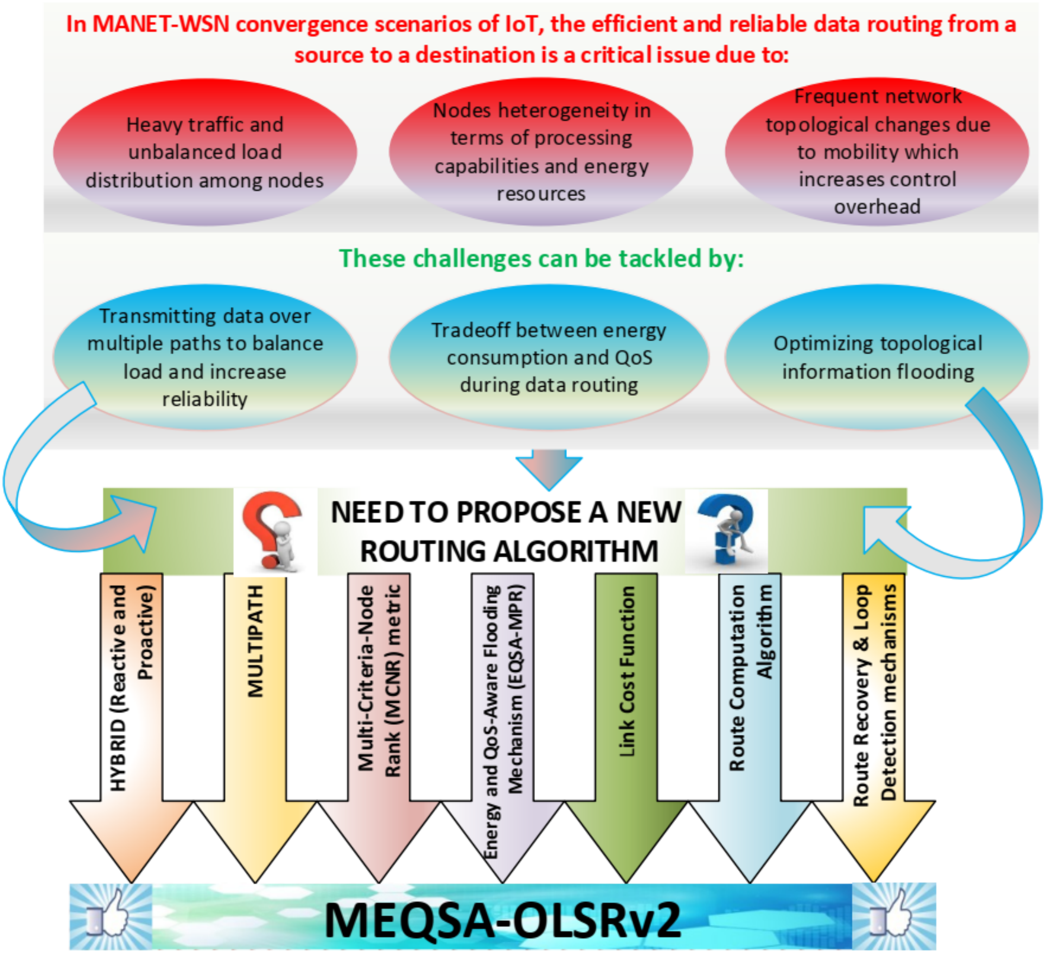

FIGURE 3. Challenges and suggested solutions.

by the network layer via a routing protocol. A hybrid multipath routing protocol that involves proactive and reactive routing for transmitting datagrams is an effective approach to increase communication reliability. Multiple paths can avoid the occurrence of failures in a single path, benefit the load balancing among nodes, and increase throughput.

(ii) The routing protocol should be robust enough, and each node's load must be fully addressed. Nodes have limited energy resources and processing capabilities. Thus, the energy consumption for data forwarding and the number of tasks per node should be minimized to avoid the depletion of the nodes' resources.

(iii) QoS constraints are essential to support multimedia communications in the IoT. Thus, the third challenge is how to maintain QoS performance through the routing protocol in real-time applications of the IoT. Computing multiple paths on the basis of multicriteria metrics to rank link quality can improve the delivery ratio of data and decrease latency because the shortest path is not always the best option.

Thus far, no reported study has explored the tradeoff between QoS awareness and energy consumption during data routing in IoT applications. In addition, QoS constraints in the conventional energy-efficient routing protocols in the context of the IoT have not been studied extensively in the literature yet [17]. Nevertheless, numerous studies have addressed energy and/or QoS issues for single path routing and do not benefit from the multipath concept. Although several multipath approaches for routing data in WSNs and MANETs are widely available, these routing protocols particularly emphasis on ad hoc and sensor networking scenarios. Hence, they are not responsive and robust enough to support IoT applications, especially in heterogeneous scenarios with mobility and heavy traffic load. Moreover, most existing energy-efficient multipath and/or QoS-aware routing schemes are either reactive or proactive and only utilize one QoS metric and not multicriteria metrics. Furthermore, energy constraints are not considered together with QoS awareness [18], [19]. In our previous works, we proposed two routing schemes, namely, MBQA-OLSR and MBMA-OLSR, on the basis of the conventional multipath OLSRv2 (MP-OLSRv2) [20] to address multipath routing together with energy efficiency and QoS issues [14], [21].

MBQA-OLSR focuses on the remaining battery energy and data traffic congestion during route computation while ignoring each node's mobility and the generated overhead. Thus, the MBQA-OLSR scheme is more suitable for static scenarios with heavy traffic load. By contrast, MBMA-OLSR considers each node's mobility with its energy resources and performs well in high-mobility scenarios, but it does not consider the congestion degree of the network. Thus, the MBMA-OLSR does not function well in heavy traffic situations.

C. RESEARCH CONTRIBUTIONS

With the intention to tackle all these challenges, we propose a new hybrid multipath routing algorithm on the basis of multicriteria metrics to provide a tradeoff between energy efficiency and QoS in IoT networks, thus paving the way for efficient and green IoT communication. This study proposes an extension for our previous schemes (MBQA-OLSR and MBMA-OLSR), namely, MEQSA-OLSRv2, which can increase the energy efficiency and reliability of data forwarding in highly dense networks in heavy traffic load and high mobility scenarios by transmitting data packets over multiple disjoint paths on the basis of link quality. This scheme utilizes the multipath concepts of the MP-OLSRv2 routing protocol with consideration of the multicriteria node rank (MCNR) metric, which comprises several node metrics related to energy, congestion level, node's activity status and mobility during multiple route computation. In addition, this scheme has the capability to avoid the selection of nodes on the basis of the same node rank metric for flooding topological information. The main contributions of this work are listed as follows:

(i) This study investigates the performance of existing multipath routing algorithms (MP-OLSRv2, multipath queue-based OLSRv2 [MPQ-OLSRv2], MBQA-OLSR, and MBMA-OLSR) on the basis of energy and QoS performance metrics under various IoT simulation scenarios.

(ii) This study develops a hybrid multipath routing algorithm for energy-efficient and reliable data transmission in IoT applications. This scheme uses a node rank metric based on multiple criteria (energy and QoS) to assess link quality and select the best routes to the destination. This study also puts forward an optimizing mechanism (EQSA multipoint relay [MPR]) for selecting MPRs on the basis of the MCNR for flooding topological information.

(iii) This study evaluates and validates the proposed scheme performance through a network simulation model using the EXata network simulator [22].

The remainder of the paper is organized as follows. In Section II, we present a brief background on the conventional and benchmark protocols and highlight our previous schemes along with related studies that considered energy and QoS during data routing. In Section III, we detail the proposed MEQSA-OLSRv2 with its features, structure, models, and functionalities. Section IV introduces simulation design and evaluation criteria. In Section V, we present the simulation results and performance of the proposed scheme in comparison with the benchmarks. Finally, in Section VI, we provide the concluding remarks and future work. For readability and the clarity of presentation, we first define the useful terms and notations used in this paper in Table 1.

II. BACKGROUD & RELATED WORK

A. OLSR-BASED CONVENTIONAL ROUTING PROTOCOLS: AN OVERVIEW

In the last decade, OLSR has been the leading and most widely used proactive routing protocol in MANETs. The first version of OLSR (OLSRv1) has been standardized as RFC 3626 [23]. OLSRv1 was originally developed for routing in MANETs, and it works in a proactive manner in which topology information is exchanged between nodes on a periodic basis. The core optimization of OLSR is to minimize control traffic by selecting a small number of nodes, known as MPRs, which represent an improved flooding mechanism for topological information. The IETF has exerted efforts to standardize the conventional OLSRv2 [24], a successor of OLSR. OLSRv2 holds the same basic mechanisms and algorithms as OLSR. In addition, OLSRv2 provides a flexible signaling framework and some simplifications of the messages exchanged between nodes. OLSRv2 also accommodates IPv4 and IPv6 addresses in a compact fashion. Currently, a large and active community is focused on OLSR, thereby standardizing OLSRv2.

The conventional MP-OLSRv2 was proposed in [25] and [26] as a multipath extension to OLSRv2. The standardization process of MP-OLSRv2 is currently in progress. The conventional MP-OLSRv2 is a hybrid multipath routing protocol that involves proactive and reactive routing concepts for data transmission. In this protocol, the multipath Dijkstra algorithm is utilized to discover several alternative routes proactively between source–destination pairs. However, this proactive behavior is changed to reactive behavior for on-demand route computation. MP-OLSRv2 has two main phases, namely, topology sensing and route computation, which are used to maintain several paths for the same source–destination pair. Furthermore, MP-OLSRv2 has two auxiliary phases, namely, route recovery and loop detection, for improving the performance of the OLSRv2 component; hence, it is regarded as one of the most efficient routing protocols. MP-OLSRv2 supports the source routing concept with multiple description coding for data transfer and uses two incremental cost functions for the link cost between nodes to generate multiple node-disjoint or link-disjoint paths.

MPQ-OLSRv2 is a modified version of the conventional MP-OLSRv2 [27]. MPQ-OLSRv2 uses the queue length metric to evaluate the link quality for computing multiple routes. MPQ-OLSRv2 utilizes a linear weight function to define the link cost between two nodes in accordance with the queue length. This link cost is normalized into integer values between 0 and 255 to avoid the overflow of 1-byte space. This space is specified to attach the queue length information to the

HELLO and topology control (TC) messages such that other nodes in the network can be aware of the queue length in the local node. Then, the cost based on the queue length is used as the initial cost of the links in the multipath Dijkstra algorithm. This modified scheme keeps all other functionalities of the conventional MP-OLSRv2.

B. MBQA-OLSR and MBMA-OLSR

Previously, we developed two energy-efficient and QoS-aware schemes (MBQA-OLSR and MBMA-OLSR) for multipath routing in MAWNs [14], [21]. The proposed schemes emerge as solutions to reduce energy consumption and prolong network lifetime by enhancing the QoS. This goal can be achieved by considering some node-related metrics, which reflect the status of nodes in terms of its energy resources, congestion level, and mobility. These metrics help to derive routing decisions on the basis of link quality. In addition, these metrics are used to select a set of nodes, namely, MPR nodes, to enhance the flooding of topological information, which minimizes control traffic. In the MBQA-OLSR and MBMA-OLSR schemes, the modified main and auxiliary functionalities of MP-OLSRv2 contribute effectively to the reduction of energy consumption and the improvement of the QoS. MBQA-OLSR is preferred in low mobility or static networks, whereas MBMA-OLSR considers mobility and is thus preferred in high mobility scenarios.

MBQA-OLSR is a multipath battery and load-aware routing scheme that uses the advantage of the multipath Dijkstra algorithm in MP-OLSRv2 to balance the load among nodes in different paths. MBQA-OLSR utilizes the energy-aware EA-MPR selection mechanism for selecting the MPR set on the basis of the lifetime and duration of idle time for each node to optimize the topological information flooding in accordance with energy resources and the status of nodes. A new MCNR metric used in the MBQA-OLSR scheme assesses the link quality of the path between the source and the destination in accordance with the status of nodes, including residual battery, idle time, and queue length, as a measure of the battery energy level and traffic load at the node. MBQA-OLSR selects the nodes with sufficient remaining battery energy, long duration of idle time, and low congestion degree to construct reliable multipath between source–destination pairs by using a new link cost function. However, this scheme is only suitable for static scenarios in which nodes do not change locations. By contrast, in mobile scenarios, this scheme generates a considerable amount of control overhead. Further detail on the implementation and performance evaluation of MBQA-OLSR can be found in [14].

The MBMA-OLSR scheme was developed for energy-efficient and mobility-aware routing in MAWNs. This scheme selects the nodes with the highest energy level and lowest speed as MPR nodes to flood topological information to the medium by using a new EMA-MPR mechanism. Moreover, the information about the status of nodes in terms of battery energy and mobility is used by the MCNR metric in this scheme to select the nodes with the highest rank for constructing multiple routes to a target destination. Similar to that in MBQA-OLSR, the link cost function in MBMA-OLSR is used to estimate the link quality among nodes. By contrast, MBMA-OLSR does not perform well in scenarios with static nodes, such as mobile scenarios. This scheme ignores the status of nodes in terms of congestion level and transmission activity. The structure and performance analysis of MBMA-OLSR can be found in [21].

C. RELATED WORKS

Despite the active research on IoT issues, especially over the last five years, data routing in MANET-WSN convergence scenarios for IoT applications remains a vastly unexplored field with only a handful of related studies. Energy-efficient, QoS-aware, and multipath routing schemes are widely utilized for MANET and WSN networks in the literature. To the best of our knowledge, a good number of studies are based on the OLSR routing protocol and consider different metrics to make routing decisions or select MPR nodes. Some of these studies considered metrics that are based on energy and/or QoS to modify MPR selection or route computation separately or simultaneously. On the basis of the modified OLSR functionalities, we classified these works into three main categories. The first category emphases on energy-based metrics to enhance the energy efficiency of OLSR [28]–[36]. The second category considers QoS-based metrics to assess link quality or select the MPR set [37]–[42]. The third category focuses on multipath OLSR solutions [43]–[51]. According to that classification and for the sake of brevity, the OLSR-related studies have been reviewed and compared in Table 2.

In summary, all relevant studies are based on OLSRv1 [23] or its multipath extension MP-OLSR [52]. Most of these studies do not benefit from the multipath concept, which enables load distribution among different paths. Although some researchers addressed energy and/or QoS issues individually, others combined some metrics but modified one of the OLSR functionalities, namely, route computation or MPR mechanism. Only a handful of studies considered nodes' mobility during route discovery and/or MPR selection. In other words, none of the previous studies considered energy, QoS constraints, and mobility simultaneously with the multipath concept to select MPR sets and compute multiple routes to target destinations. Although some researchers in the literature suggested multi-objective routing metrics, they did not combine multiple metrics into a single metric, such as our MCNR metric, to simplify information exchange throughout the network and reduce overhead. To the best of our knowledge, none of these previously mentioned researchers fully addressed energy efficiency together with the QoS requirement in MPR and path selection for OLSRv2 or the conventional MP-OLSRv2. Consequently, the work reported in this paper concentrated explicitly on the evaluation of protocols with the simultaneous consideration of multipath routing solutions, together with energy efficiency and QoS

TABLE 1. Summary of notations and terminology.

Term/Symbol	Description	*Term/Symbol*	Description
OLSR	Optimized Link State Routing Protocol (v1) RFC3626	*Link cost*	A value representing link or/and node ranks of a path. It is used to compare multiple paths.
OLSRv2	A routing process based on [RFC7181], without multipath extension	*Link Cost Function*	An exponential function to assess the quality of links and determines the initial link cost based on the MCNR metric of both nodes for each link
MP-OLSRv2	A multipath routing process based on [RFC 8218]as an extension to [RFC7181]	*Residual battery (RB)*	It specifies the amount of remaining energy charge at an instant in time of the attached battery to the node.
MPQ-OLSRv2	An extension to [RFC7181]	*Drain rate (DR)*	It specifies the amount of energy being spent by the node over time, due to the node's activities
MBQA-OLSR	A battery and queue-aware multipath routing process based on this specification as an extension to [RFC 8218].	*Node's lifetime (LT)*	Is defined as the estimated service life of a battery-operated node with a given time-varying load. In other definition, it corresponds to the period of time since a node becomes active until the node is said to be dead, i.e., from a network perspective, the node ceases to exist
MBMA-OLSR	A battery and mobility-aware multipath routing process based on this specification as an extension to [RFC 8218].	*Idle mode*	When a node is not receiving or transmitting, the node is still listening to the shared medium (overhearing) and is said to be in Idle mode
MEQSA-OLSRv2	A multipath energy and QoS-aware routing process based on this specification as an extension to [MBQA-OLSR and MBMA-OLSR].	*Network lifetime*	Is associated to the duration of time until the first node in a network fails due to the exhausted battery
MCNR	A Multi-Criteria Node Rank metric, which comprises metrics related to energy and QoS	*Queue length (QL)*	It specifies the number of bytes in data packets that need to be buffered in queues temporarily by the Network Layer before passing them to the Data Link Layer
EA-MPR	An Energy-Aware Multi-Point Relay selection mechanism to select the MPR set based on the lifetime and the duration of idle time for each node to optimize the topological information flooding according to energy resources and node's status	*Energy cost*	The cost associated to the node or to the association between two nodes which consider the energy parameters
EMA-MPR	An Energy and Mobility-Aware Multi-Point Relay selection mechanism to select the MPR set based on the lifetime, residual battery and the speed nodes to optimize the topological information flooding according to energy resources and node's mobility	S_{max}	Is the maximum speed of node that has been set to the mobility model
EQSA-MPR	An Energy and QoS-Aware Multi-Point Relay selection mechanism to select the MPR set based on MCNR metric for each node to optimize the topological information flooding according to multiple matrics	S_{mob}	Is the instantaneous speed of a node that can be extracted from mobility model
Optimal path	Is defined as a path that minimizes (or maximizes, respectively) the Rank value between any given pair of source-destination pairs, as well as its sub-paths (links)		
f_p	Arcs incremental cost function to use different arcs	P_{idle}	Node's power in idle state
f_e	Arcs incremental cost function to avoid vertices	P_{sleep}	Node's power in sleep state
NR_i	Rank of node *i*	t_{trans}	Transmit state time duration
W_i	Willingness of node *i* to work as MPR	t_{rec}	Receive state time duration
MPR	Multi-Point Relay	t_{idle}	Idle state time duration
$NR_{mc}(i)$	*MCNR* value of node *i*	t_{sleep}	Sleep state time duration
LT_i	Node *i* Lifetime	$T_{total}(i)$	Total service time of node *i*
RB_i	Node *i* Residual battery	P_{CO}	Power consumption of Circuit over whole signal path
NR_{max}	Maximum node rank	P_t	Power of signal transmission (PHY layer)
NR_{min}	Minimum MCNR-based node rank	α	Energy power amplifier inefficiency coefficient
$L_{cost}(i, j)$	Cost of link between nodes *i* and *j* based on MCNR	E_{Trans}	Radio transceivers energy consumption
$NR_{mc}(i, j)$	Link's rank based on ranks of nodes *i* and *j*.	E_{DC}	Energy consumption of the processor
LT_{max}	Maximum node's lifetime	E_{CPU}	Energy consumed by the DC-DC converter
MAX_LT_{th}	Maximum node's lifetime threshold	E_{Bat}	Battery efficiency losses
MIN_LT_{th}	Minimum node's lifetime threshold	DR_i	Drain rate of node *i*
NR_{RB}	Residual battery-based node rank	T	Service time duration
RB_{max}	Maximum battery capacity	*PDR*	Packet delivery ratio
NR_{mob}	Mobility-based node rank	t_f	Time of first packet received
S_{max}	Maximum speed in RWP model	p	Total number of packets received
S_{mob}	Instant speed of node's mobility	$Delay(j)$	Total transmission delays of a packet
V	Voltage of power supply of the radio	*Avg. EED*	Average End-to-End Delay
E_{trans}	Node's energy consumption in transmit state	*Avg.* T_Q	Average time in FIFO queue
E_{rec}	Node's energy consumption in receive state	PD_{FIFO}	FIFO total packets dropped
E_{idle}	Node's energy consumption in idle state	PD_{RL}	Packet drops due to retransmissions limit
E_{sleep}	Node's energy consumption in sleep state	*Avg.* E_{cons}	Average energy consumption
$E_{total}(i)$	Total consumed energy by node *i*	*ECP*	Energy cost per packet
P_{trans}	Consumed power by node in transmit state	*Avg. RBE*	Average remaining battery energy
P_{rec}	Node's power in receive state	*NoDN*	Number of Dead Nodes

awareness, in convergence scenarios. Energy resources, mobility, and congestion are considered as QoS constraints.

Reference [54] proposed a component-based design of the Trustful Space–Time Protocol as an IoT protocol to avoid a massive implementation of the cross-layer approach and highlight the close interactions among MAC, router, location, and time synchronization components. Reference [55] introduced survivable path routing for congestion- and interference-aware energy-efficient routing in WSNs with high traffic load, such as the typical scenario in IoT applications for remote healthcare monitoring. Reference [56] presented an adaptive distributed routing method with cooperative transmission to solve the influence of the mobility problem on data transmission in flying ad hoc

TABLE 2. Summary of OLSR-based routing protocols.

Category	Routing scheme	Considered metrics: Energy awareness	QoS	Mobility	Routing mechanism	Data transmission path	Modified functionality: MPR Selection	Route computation	Complexity
Energy-based OLSR	De Rango, et al. [28]	Yes	No	No	Proactive	Single	Yes	No	Low
	Ghanem, et al. [29]	Yes	No	No	Proactive	Single	Yes	No	Low
	Kots and Kumar [30]	Yes	Yes	Yes	Proactive	Single	Yes	No	High
	Fatima and Najib [31]	Yes	No	Yes	Proactive	Single	Yes	No	High
	Guo, et al. [32]	Yes	No	No	Proactive	Single	No	Yes	Medium
	Kunz and Alhalimi [33]	Yes	No	No	Proactive	Single	No	Yes	Low
	Benslimane, et al. [34]	Yes	No	No	Proactive	Single	Yes	Yes	Low
	Mahfoudh and Minet [35].	Yes	No	No	Proactive	Single/Alternate	Yes	Yes	High
	Kunz [36]	Yes	No	No	Proactive	Single	Yes	Yes	Low
QoS-based OLSR	Ge, et al. [37]	No	Yes	No	Proactive	Single	Yes	Yes	High
	Nguyen and Minet [38]	No	Yes	No	Proactive	Single	Yes	Yes	Medium
	Nguyen, et al. [39]	No	Yes	No	Proactive	Single	Yes	Yes	High
	Badis and Al Agha [40]	No	Yes	No	Proactive	Single	Yes	Yes	High
	Munaretto and Fonseca [41]	No	Yes	No	Proactive	Single	Yes	Yes	High
	Fatima and Najib [42]	No	Yes	Yes	Proactive	Single	Yes	No	Medium
	Guo, et al. [32]	Yes	Yes	Yes	Proactive	Single	No	Yes	Low
Multipath-based OLSR	**MP-OLSRv2**, Yi, et al. [25]	No	No	No	Hybrid	Multipath	No	No	Low
	MPQ-OLSRv2, Yi [27]	No	Yes	No	Hybrid	Multipath	No	Yes	Low
	Badis and Al Agha [43]	No	Yes	No	Proactive	Multipath	No	Yes	High
	Doghri, et al. [44]	No	Yes	Yes	Hybrid	Multipath	No	No	Medium
	Szwabe, et al. [45],	No	No	No	Proactive	Multipath	No	Yes	Low
	Huang, et al. [46]	Yes	No	No	Hybrid	Multipath	No	Yes	High
	Xuekang, et al. [47]	No	Yes	No	Hybrid	Multipath	No	Yes	High
	Joshi and Rege [48],	Yes	No	No	Hybrid	Multipath	Yes	Yes	Medium
	Le and Pujolle [49]	No	Yes	No	Hybrid	Multipath	No	Yes	High
	Boushaba, et al. [50]	No	Yes	No	Hybrid	Multipath	No	Yes	High
	Anuradha and Anandha [51]	Yes	Yes	No	Hybrid	Multipath	No	Yes	Low
	MBQA-OLSR [14, 69]	Yes	Yes	No	Hybrid	Multipath	Yes	Yes	Low
	MBMA-OLSR [21]	Yes	No	Yes	Hybrid	Multipath	Yes	Yes	Low
Proposed MEQSA-OLSRv2		Yes	Yes	Yes	Hybrid	Multipath	Yes	Yes	Low

networks as an important part of IoT communication services. Reference [57] aimed to increase network reliability and decrease excessive packet retransmissions for WSN-based smart grid applications by proposing a dynamic cluster-based energy-efficient and QoS-aware routing protocol. Reference [58] targeted the constituent phases of cluster-based energy-aware routing while considering all the steps from node deployment to network architecture and from data sensing to data routing to prolong network lifetime and minimize battery utilization.

Reference [59] proposed a hybrid control channel-based cognitive AODV routing protocol with directional antennas to discover the channel route from the LLN boarder router to the destination that is connected within the cognitive radio networks to transmit the constrained IoT data opportunistically. This opportunistic routing concept may offer an effective solution with the cooperation of the relay nodes for forward data packets to the surface sink in underwater acoustic sensor networks, as in [60]. The authors addressed the energy consumption problem and proposed an energy-efficient cooperative opportunistic routing protocol.

In [61], the energy consumption optimization in MANET was highlighted by applying the fitness function technique and proposing AOMDV with the fitness function as a multipath reactive routing protocol. Reference [62] proposed a new energy-efficient region-based routing protocol, which only requires a subset of nodes for route discovery and thus achieves energy saving during data delivery without compromising reliability. In [63], a leader-based approach using local information from neighbor nodes for routing in mobile WSNs was presented to cope with the connectivity changes due to the mobility of sensors or sink nodes. Reference [64] aimed to achieve high efficiency and intended security that is suitable for WSN-based IoT networks by proposing an energy-aware trust derivation scheme using the game theoretic approach, which can manage overhead while maintaining the adequate security of WSNs.

In terms of convergence paradigm, References [2] and [65] proposed an original solution for fasten the delivery of urgent sensed data by integrating and exploiting MANET overlays with WSN to boost urban data harvesting in IoT. Their proposed paradigm showed promising results toward the full utilization of MANET and WSN convergence deployment in the IoT aiming at supporting fast data collection in urban areas. In both references, authors focused on the data type which categorized into urgent and normal data. In [66], authors investigated some key challenges from a technical perspectives for the convergence of cellular networks and WSNs. Authors suggested the using of terminals in cellular network as a sensor and gateway for WSN at the same time in the converged networks. Authors claimed that simulation results showed a better throughput, delay, and network lifetime of WSN when it interacted with mobile cellular network. Another convergence networking paradigm for IoT applications by exploiting the existing technology of network communication was introduced in [67]. Authors proposed a model that covered several aspects such as spectrum distribution, deployment of nodes, mobility and routing of MANET and IoT applications implementation. A smart city scenario with nine zones, which includes MANET and WSN nodes was considered. The mentioned study focused more on number of gateways in the entire model.

The focus of most previous researches was on either MANETs or WSNs as a typical scenario, thereby neglecting the MANET-WSN convergence scenario, which combines both types of nodes in terms of battery capacity and mobility. In addition, a few studies focused more on developing new paradigms for cooperative networks for IoT applications by using the existing wireless technologies. However, they were not focusing on the impact of routing protocols and their performances in the developed approaches. In the current study, we focus on these convergence scenarios as good examples for real IoT applications. In our new scheme, multiple parameters are considered at the same time as one parameter. This single metric is utilized to optimize two main phases of routing, namely, topology sensing and multi-route computation. To the best of our knowledge, this study is the first to consider energy and QoS simultaneously along with nodes' mobility in MANET-WSN convergence scenarios with heterogeneous nodes on the basis of energy resources, mobility, and types of traffic connections (point to point [P2P] and multipoint-to-point [MP2P]). In other words, we propose a routing solution for IoT networks by using a combination of MANET and WSN routing protocol principles.

III. PROPOSED PROTOCOL: MEQSA-OLSRV2

A. PROTOCOL STRUCTURE AND MAIN FEATURES

The adopted methodology in this research is implemented in four phases to achieve the aims. In Phase I, a literature review of the key issues of routing in the IoT scenario is conducted, followed by a performance evaluation of our previous routing algorithms (MBQA-OLSR and MBMA-OLSR) and several existing schemes to identify their limitations in the MANET-WSN convergence scenarios in Phase II. Accordingly, a new algorithm (MEQSA-OLSRv2) is developed in Phase III with integration and implementation by using the GUI-based EXata simulator. Finally, performance validation is conducted using network simulation in Phase IV. The conceptual framework in Figure 4 describes the methodology adopted for this work, including the systematically organized stages of research in conjunction with the detailed implementation features of the proposed scheme. Furthermore, this framework clarifies the structural components of the proposed techniques and their integration to achieve the research aim. In addition to the new EQSA-MPR selection mechanism and MCNR metric estimation algorithm, which are amended for MEQSA-OLSRv2, several structural components and functional modules (Figure 4) are dedicated to find efficient multipaths.

This section describes the developed MEQSA-OLSRv2 routing protocol from an operational perspective. The developed scheme is based on our two existing schemes, namely, MBQA-OLSR and MBMA-OLSR. Conceptual aspect validation, confirmation of adopted methods and systems, and comprehensive performance evaluation can be found in [14], [21], [68]–[71]. The MEQSA-OLSRv2 routing scheme suggests appropriate modifications to reduce energy consumption and improve QoS performance of the conventional routing protocol in heterogeneous networks. MEQSA-OLSRv2 retains and takes advantages of some functionalities in our pervious schemes, such as the hybrid and multipath concept of routing, but modifies others, including MCNR metric estimation and willingness setting mechanism. Figure 4 presents the mean and detailed features of MEQSA-OLSRv2.

The proposed MEQSA-OLSRv2 routing protocol modifies two main mechanisms in the previous approaches, namely, MCNR calculation and willingness setting mechanism. To combine the best features of MBQA-OLSR and MBMA-OLSR, this protocol integrates all parameters that are considered in both schemes, namely, (i) node's lifetime, (ii) residual battery energy, (iii) node's idle time, (iv) node's speed, and (v) queue length, into a single node rank metric. Unlike the previous schemes, MEQSA-OLSRv2 uses this single metric for multi-route computation and MPR selection by using the EQSA-MPR mechanism. Similar to conventional schemes, the MEQSA-OLSRv2 scheme retains the HELLO and TC message structures for the topology sensing process and multipath Dijkstra algorithm.

Simplicity and applicability are key features in routing algorithm design. Therefore, prior to developing our new routing scheme, we conducted a comprehensive survey for a huge variety (more than 110 studies) of existing routing algorithms as presented in [5]. According to the results of the conducted literature, we selected one of the most recent and reliable multipath protocols that developed by experts from IETF MANET working group, MP-OLSRv2 [RFC 8218] as our base work due to its simplicity and applicability (It uses the well-known Dijkstra algorithm). There are three implementations of MP-OLSRv2, specified in Yi and Parrein [72] standardization draft, for both testbed and simulation use as follows:

(i) *Multi-path extension based on nOLSRv2*: The implementation is conducted by University of Nantes, France, and it is based on Niigata University's nOLSRv2 implementation [73]. It is known as MP-OLSRv2 [25], and it can be used for QualNet simulations, and be exported to run in testbed. The proposed schemes in the current thesis are based on this conventional MP-OLSRv2 implementation using EXata simulator.

(ii) *Multi-path extension based on OLSRd*: The implementation is conducted under SEREADMO (Securite des

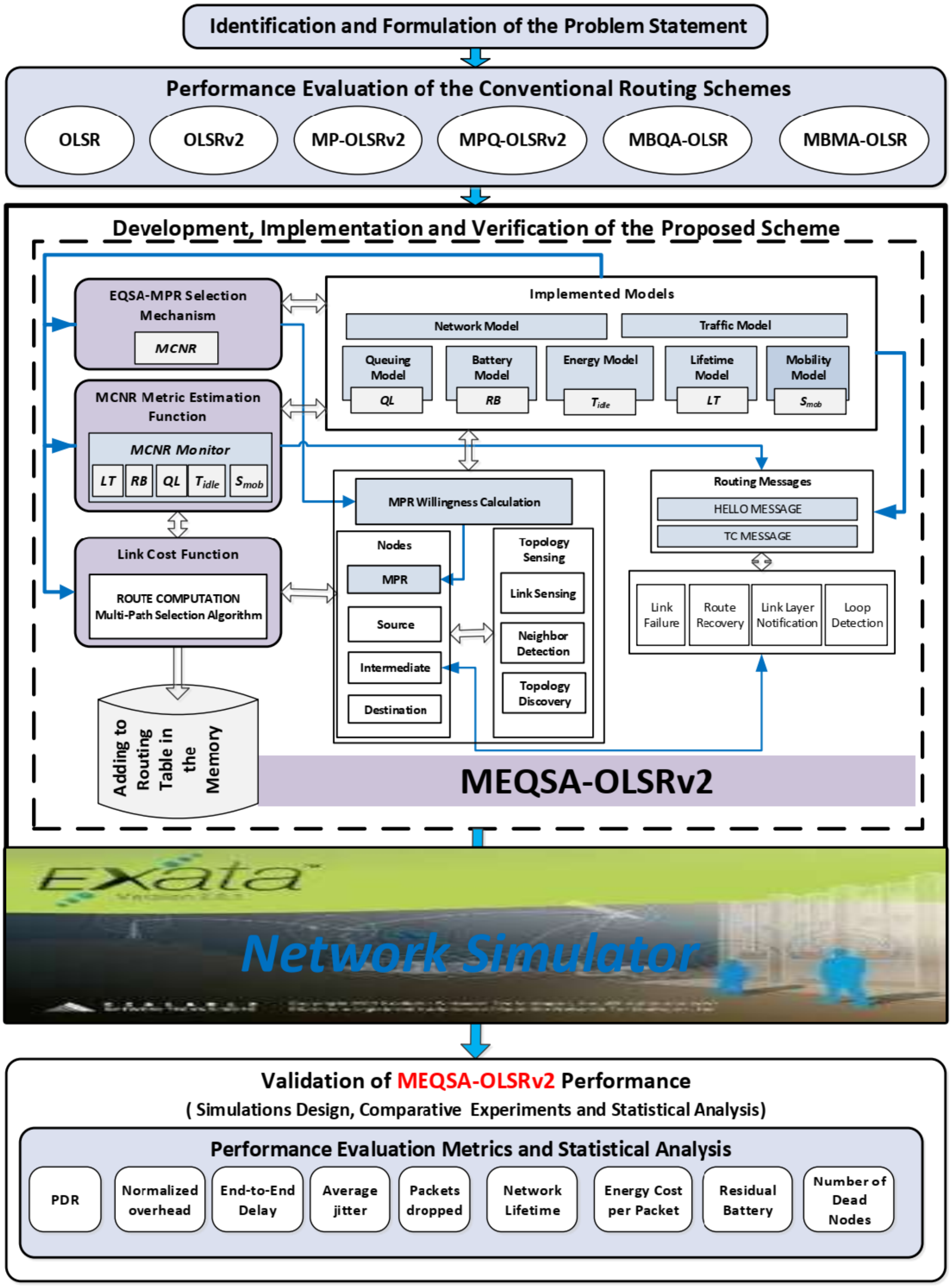

FIGURE 4. Conceptual framework and MEQSA-OLSRv2 structure, functionalities and processing model.

Reseaux Ad Hoc & Mojette) project [74] and supported by French research agency (RNRT2803). It is based on OLSRd implementation [75]. The implementation is for testing the specification in the field. Implementation experience and test data can be found in Yi *et al*. [25].

(iii) *Multi-path extension based on umOLSR*: The implementation is conducted by University of Nantes, France, and is based on um-OLSR implementation [76], which is an implementation of the standardized version of Clausen and Jacquet [77]. This implementation is only for Network Simulator version 2 (NS2). This implementation is known as MP-OLSR [52].

Our algorithm, MEQSA-OLSRv2, keeps the simplicity and applicability of the conventional MP-OLSRv2, by using the same multipath Dijkstra algorithm to compute

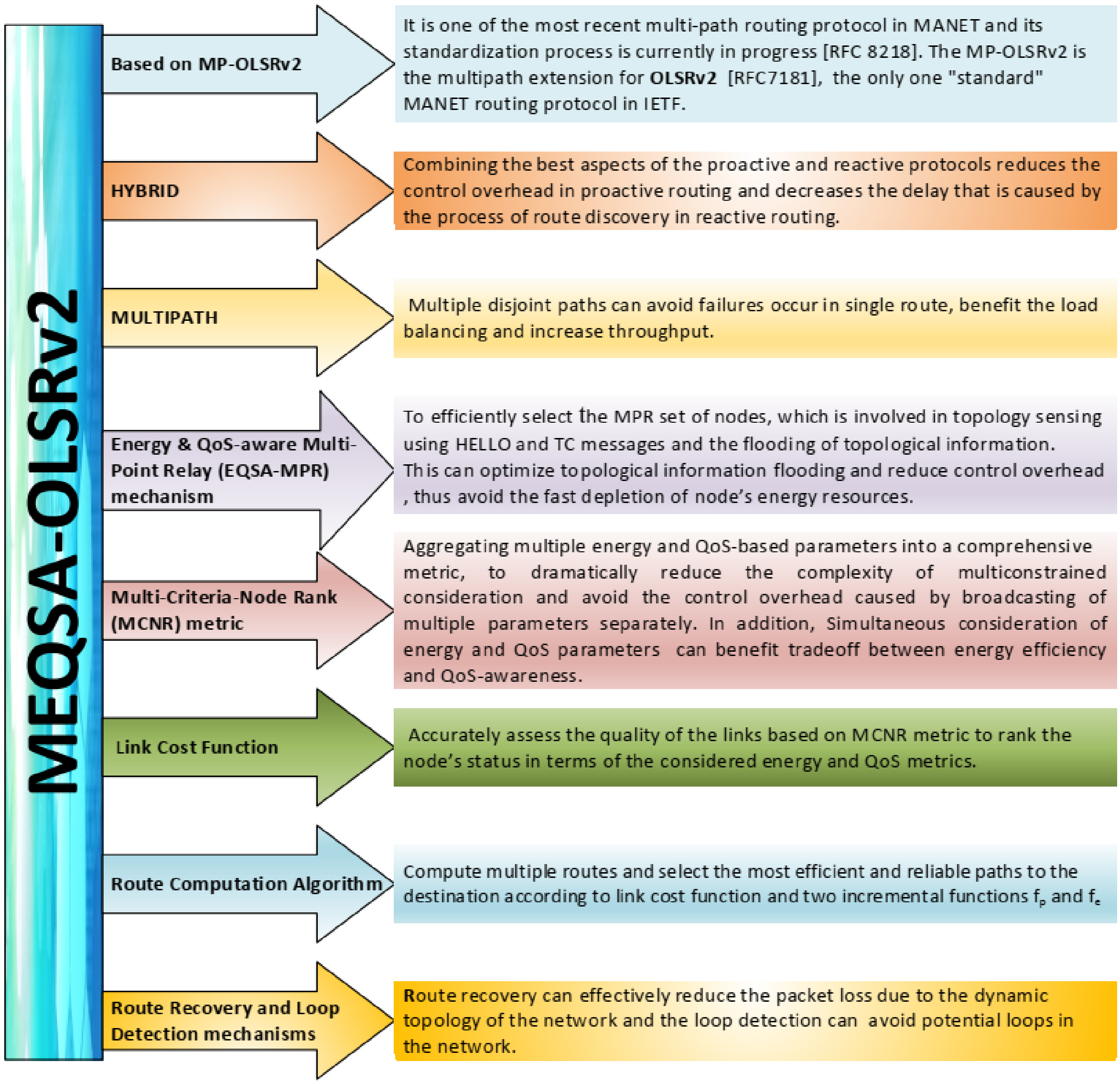

FIGURE 5. Detailed features of MEQSA-OLSRv2.

multiple paths. Compared to MP-OLSRv2, this extension does not introduce any new message type, thus not increasing the algorithm complexity. MEQSA-OLSRv2 only integrated one type–length–value (*TLV*) for the node rank information in the existing HELLO and TC messages.

This new TLV composes of multiple parameters into one value to avoid the repetition of broadcasting several parameters as in the existing schemes with multiple consideration, hence our scheme decrees total overhead as we will see in the results section. As an extension of MP-OLSRv2 and OLSRv2, this algorithm is applicable to ad hoc networks for which MP-OLSRv2 and OLSRv2 are applicable. It supports operation on single or multiple interfaces to find multiple disjoint paths from a source node to a destination node. MEQSA-OLSRv2 is designed for networks with heterogeneous nodes and support dynamic topology and fixed deployment to avoid link failure of single route algorithm. It also balances load and provides higher aggregated throughput. In addition, MEQSA-OLSRv2 has the same parameters and constants defined in [RFC 8218], Therefore, we can ensure that our proposed scheme does not add any complexity to the conventional MP-OLSRv2, which had already implemented in a real test bed by University of Nantes, France, as stated in [26]. In terms of the considered parameters which related to energy and QoS, it will be extracted from the attached models for each node, like energy model, battery model, lifetime model, etc. as stated in the following subsections.

B. IMPLEMENTED MODELS

In MAWNs, each node has several models to set and measure different parameters required for performing various tasks (send, receive, and relay). Each model is responsible for extracting instantaneous parameter values that correspond to its related metric (e.g., energy consumption, delay, number of packets, and speed). Then, these parameter values are used by the MEQSA-OLSRv2 routing protocol to find optimal paths to the target destination. In the current work, simulation scenarios are created by defining the network topology and number of nodes with an implemented MEQSA-OLSRv2 routing protocol. Prior to discussing the design components of the MEQSA-OLSRv2 routing protocol, we define the implemented models of MEQSA-OLSRv2 and briefly describe the following concepts related to the proposed modifications as follows.

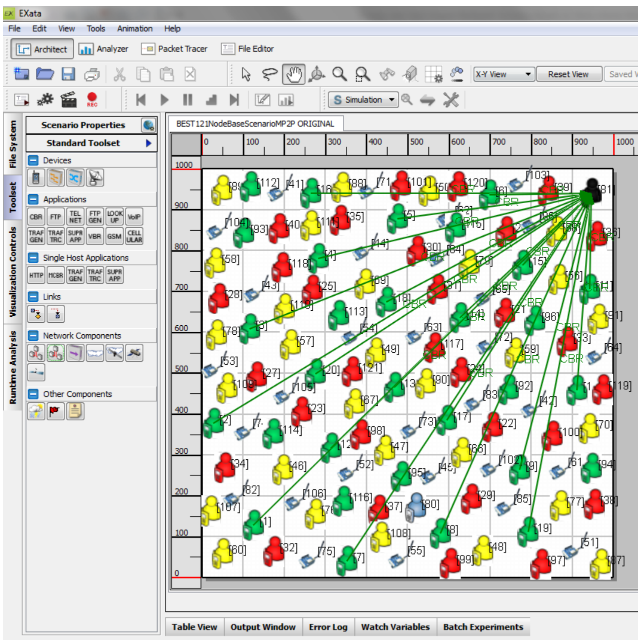

FIGURE 6. Network topology in MP2P deployment scenario.

1) NETWORK MODEL

Wireless ad hoc networks can be modeled by a graph $G(V, E)$, which consists of two sets, namely, V (nodes) and E(arcs). The arc models the range of wireless radio between pairs of devices. If nodes υ_1 *and* $v_2 \in V$ are neighbor nodes within the communication range of each other, then they can communicate directly. However, if both nodes (υ_1, v_2) are far from each other due to their mobility, then they utilize the intermediate nodes between them to communicate using the routing protocol. In scenarios with mobility nodes, the network topology changes frequently. Figure 6 shows a network topology for a selected MP2P scenario, as shown in EXata-GUI. Numerous parameters should be configured

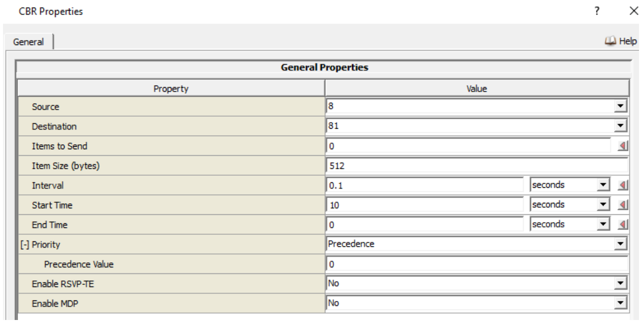

FIGURE 7. Configured parameters of the CBR data traffic generator.

in the network model starting from the physical layer to the application layer.

2) TRAFFIC MODEL

The type of traffic pattern greatly influences the routing protocol performance in wireless networks. The traffic model controls the type, size, and rate of data packets between source destination pairs. Thus, the traffic model exerts a serious effect on nodes, network congestion levels, and hence the energy consumption. The well-known constant bitrate (CBR) data flow as a UDP application generates traffic patterns at a constant rate to transmit data packets with a fixed size from an originator to a destination. Two different scenarios based on CBR flows are deployed in this work: MP2P and P2P traffic. Various traffic-related parameters, such as number of traffic flows, number and size of packets, and start/end time of sending data, can be configured in the traffic model to analyze the performance of the MEQSA-OLSRv2 routing protocol (Figure 7). Several performance statistics can be obtained from this model, and they include the number of packets sent, number of packets received, data delivery ratio, and end-to-end delay.

3) MOBILITY MODEL

In wireless networks, a node's mobility can be modeled by two main parameters, namely, speed and pause time. Mobility in any wireless network scenario causes topological changes, increases routing overhead, and links failure rates. The random waypoint model (RWP) is commonly used for node mobility modeling in network simulations due to its simplicity. The maximum and minimum speeds of each node can be configured along with its pause time duration to simulate real deployment scenarios with high-, medium-, and low-speed nodes. In some scenarios, the nodes are deployed without any mobility models to simulate static scenarios. The instantaneous speed of a node, which varies between minimum and maximum speeds, is considered in MEQSA-OLSRv2 during the estimation of the MCNR metric for ranking the nodes participating in forwarding data packets and flooding control traffic. Figure 8 shows the parameters of

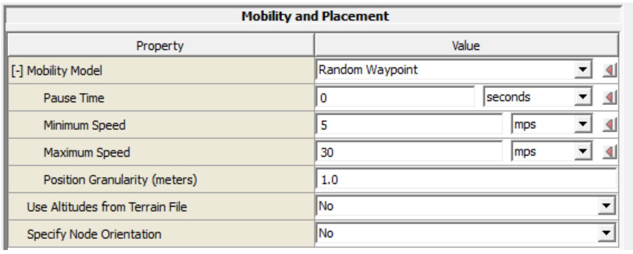

FIGURE 8. Configured parameters of the RWP model.

the RWP model that should be configured before starting the simulation.

4) QUEUING MODEL

This model is one of models involved in the architecture of MEQSA-OLSRv2. During simulations, the queue length exerts a significant effect on the average time delay. The main function of this model is to buffer data packets in queues by network layer prior to passing them to the lower layers to overcome the limited capacity of the data link layer. First in, first out (FIFO) is a basic type of priority queue that allocates packets in accordance with their priorities in proper queues. The queuing model returns an instantaneous queue length (QL) value as the number of bytes in the queue. Such value is used by MEQSA-OLSRv2 to measure the congestion degree of nodes. Figure 9 illustrates the various parameters of the queue model in the GUI of EXata. Some performance statistics, such as peak queue size, average time in queue, and total packets dropped in queue, can be extracted from this model.

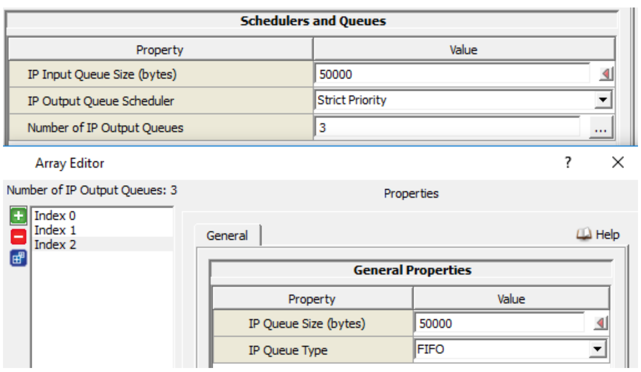

FIGURE 9. Configured parameters of the queue model.

5) ENERGY CONSUMPTION MODEL

This model is regarded as a core model in energy-aware routing protocols such as MEQSA-OLSRv2. The type and configuration of this model play a crucial rule in energy consumption estimation during routing. The main components of radio models that deplete energy are the transmitter and receiver. The node has four states with definite energy: transmit, receive, idle, and sleep. Similar to previous schemes, MEQSA-OLSRv2 utilizes a generic radio energy model to estimate the consumed energy for each state of node.

$$E_{trans} = P_{trans} \times t_{trans} \tag{1}$$

$$E_{rec} = P_{rec} \times t_{rec} \tag{2}$$

$$E_{idle} = P_{idle} \times t_{idle} \tag{3}$$

$$E_{sleep} = P_{sleep} \times t_{sleep}, \tag{4}$$

where E_{trans}, E_{rec}, E_{idle}, and E_{sleep} are energy consumptions in the transmit, receive, idle, and sleep states, respectively. t_{trans}, t_{rec}, t_{idle}, and t_{sleep} denote the node's state times. P_{rec}, P_{idle}, and P_{sleep} represent the circuitry power consumptions for each state; it can be configured in the generic energy model. However, P_{trans} involves a transmission signal power from the PHY layer (P_t) and circuit power consumption over the entire signal path (P_{CO}).

$$P_{trans} = \alpha V P_t + P_{CO}, \tag{5}$$

where α is the inefficiency coefficient of the energy power amplifier and V indicates the voltage of the radio's hardware in volts. Figure 10 illustrates the configured parameters of the used generic energy model.

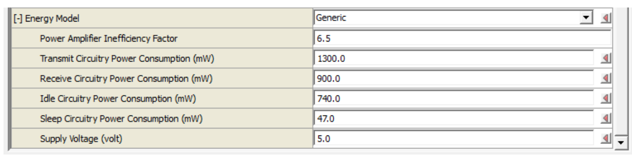

FIGURE 10. Configured parameters of the generic energy model.

Typically, nodes are forced into sleep mode in wireless networks by the MAC protocol. Consequently, the energy consumed in sleep mode E_{sleep} is neglected. Accordingly, the total energy consumption (E_{total}) for a node i to transmit and receive a packet of k bit size is

$$E_{total}(i) = E_{trans} + E_{rec} + E_{idle} \tag{6}$$

6) BATTERY MODEL

The battery provides the voltage and current for the hardware components of nodes (e.g., radio interfaces, CPU, and sensing core). The total energy consumption per cycle is as follows:

$$E_{Cycle} = E_{Trans} + E_{CPU} + E_{DC} + E_{Bat}, \tag{7}$$

where E_{Trans}, E_{CPU}, and E_{DC} are the energy consumptions of radio transceivers, processor, and DC-DC converter, respectively; and E_{Bat} denotes the battery efficiency loss.

In MEQSA-OLSRv2, a simple linear battery model is attached to each node to estimate its residual battery (RB). Figure 11 presents two key configurable parameters: (i) battery charge monitoring interval and (ii) full battery capacity. The proposed scheme uses the instantaneous residual battery level of nodes to estimate their lifetime.

Battery Model		
Property	Value	
[-] Battery Model	Linear Model	
Battery Charge Monitoring Interval	1	seconds
Full Battery Capacity (mA.h)	18.2	

FIGURE 11. **Configured parameters of the linear battery model.**

The number of dead nodes and the average residual battery energy are among the metrics that can be obtained from this model in our scheme.

7) NODE LIFETIME MODEL

This model is derived from the generic energy and linear battery models. The long lifetime of a node indicates a long network lifetime. The drain rate of the node's battery is a function of its load. Accordingly, if nodes have equal battery capacity, then the node with the highest drain rate dies first. The node's drain rate (DR_i) in mAhr/s at an instant t can be calculated as follows:

$$DR_i(t) = \frac{3600 \times E_{total}(t)}{V \times T}, \tag{8}$$

where T is the service time in s and E_{total} and V represent the total consumed energy in mWh and the voltage in volts in accordance with the generic energy model, respectively.

At an instance of time t, the lifetime (LT_i) for each node, where i is the ratio between the residual battery (RB_i) according to the linear battery model and the drain rate of the node i (DR_i) as obtained from Equation (8), is as follows:

$$LT_i(t) = \frac{RB_i(t)}{DR_i(t)} \tag{9}$$

C. PROTOCOL FUNCTIONALITIES

We evaluate the performance of our previous schemes (MBQA-OLSR and MBMA-OLSR) designed to enable scalable, energy-efficient, and load- and mobility-aware routing in MANETs. At the same time, we propose the MEQSA-OLSRv2 approach, which is an extension of previous schemes with additional components to make it adaptable to different topologies, traffic load, and network heterogeneity. This section presents these proposed modifications to combine the best aspects of MBQA-OLSR and MBMA-OLSR. The details of the common structure components and functionalities that MEQSA-OLSRv2 retains from existing schemes are not be reported in this paper for brevity. Further details about the non-modified mechanisms, components, and functionalities can be found in [14] and [21].

1) MCNR METRIC

MEQSA-OLSRv2 applies the MCNR metric to assess link quality prior to selecting paths for data routing in wireless deployment scenarios. This multi-criteria metric aggregates five parameters on the basis of energy and QoS into a single metric (lifetime, residual battery, queue length, idle time, and node speed). Thus, the MCNR metric ranks the status of nodes on the basis of their activity, energy resources, congestion degree, and mobility. This metric is then used by a link assessment function to select the most optimal paths to the destination. MEQSA-OLSRv2 depends on several models, namely, lifetime, energy, battery, queue, and mobility models, to extract the parameters required to estimate the MCNR metric. The MCNR metric is estimated locally at each node and broadcasted periodically to its neighbors as a single metric value to avoid the control overhead caused by separately broadcasting multiple metrics. A high MCNR metric value of a node means a high chance to be selected for building routes (data forwarding) and joining the MPR set (control traffic flooding). The instantaneous MCNR metric value for each node i at an instance of time t can be estimated as follows:

Node's Lifetime ($LT_i(t)$): This metric is a good indicator of the node's drain rate and is obtained from the node's lifetime model.

Idle Time-based Node Rank (NRT_{idle}): This metric can be estimated from the generic energy model and declares the time of a node's idle state as a percentage of the total period of time (T_{total}) for the node's activities (transmit, receive, idle, and sleep). This metric can be estimated as

$$T_{total}(i) = t_{trans} + t_{rec} + t_{idle} + t_{sleep} \tag{10}$$

$$T_{idle}(i) = 100 \times \frac{t_{idle}}{T_{total}(i)}\% \tag{11}$$

$$NRT_{idle}(i) = NR_{max} \times \frac{T_{idle}(i)}{MT_{idle}} \tag{12}$$

where t_{trans}, t_{rec}, t_{idle}, and t_{sleep} are the time durations spent by node i in different states, T_{idle} represents the percentage of time duration that node i has been in idle mode, and MT_{idle} denotes the maximum duration of T_{idle}.

Residual Battery-based Node Rank (NR_{RB}) : This metric declares the status of the node's battery as a percentage of its total capacity. It can be extracted from the linear battery model as

$$NR_{RB}(i) = NR_{max} \times \frac{RB_i}{RB_{max}} \tag{13}$$

where RB_i represents the instant residual battery of node i, RB_{max} denotes the full battery capacity, and NR_{max} indicates the maximum value for the MCNR node's rank metric.

Queue Length-based Node Rank NR_{QL}: This metric is a measurement of the congestion level at each node, with the lowest value being the preferred one. Among existing schemes, only the proposed MBQA-OLSR scheme considers this metric in MCNR estimation.

$$NR_{QL}(i) = NR_{max} \times \left(1 - \frac{QL_i}{QL_{max}}\right) \tag{14}$$

where QL_i is the number of bytes in the FIFO queue of node i and QL_{max} refers to the maximum queue length size (bytes).

Mobility-based Node Rank (NR_{mob}): Similar to MBMA-OLSR, the proposed MEQSA-OLSRv2 considers the node's mobility for MCNR metric estimation. This value is attained

Algorithm 1 MCNR Estimation in MEQSA-OLSRv2

```
RB(i) ← residual battery of node i
T_idle(i) ← idle time duration of node i
QL(i) ← length of queue at node i
S_mob(i) ← Speed of node i
LT(i) ← lifetime of node i, i∋ V
NR_i ← NR_mc of node i
Get LT(i), RB(i), S_mob(i), T_idle(i), QL(i) of node i
 if (LT(i) ≤ MIN_LT_th) then
     NR_i = 0
     else if (S_max== 0) then
     NR_i= NR_mc(i)        // Case 1 as Equation (16)
     else
     NR_i= NR_mc(i)        // Case 2 as Equation (17)
   end if
return NR_i
```

from the RWP mobility model on the basis of the instantaneous node's speed $S_{mob}(i)$ as follows:

$$NR_{mob}\,(i) = \frac{1}{S_{mob}(i)} \tag{15}$$

$NR_{mob}(i)$ is used together with other metrics to estimate the MCNR value ($NR(i)$) of node i as stated in Algorithm 1. The value of $NR(i)$ is estimated continuously and independently, consistent with the normalized weighted additive utility function, which is based on the normalizing criteria values and uses weights of importance ranging from "0" to "1". Two cases are available to estimate the value of the MCNR metric as stated in Algorithm 1. In the first case, if the node is static (no mobility $S_{mob} = 0$) and the node's lifetime is greater than the minimum threshold value, then Equation (16) is used; otherwise, $NR(i)$ is set to "0".

$$NR_{mc}\,(i) = w_1 \times NR_{RB}(i) + w_2 \times NRT_{idle}(i) + w_3 \times NR_{QL}(i) \tag{16}$$

where w_1, w_2, and w_3 are the normalized weight factors of the node ranks. The normalized weight factors with their sum, which is equal to "1", indicate the importance of the components of the MCNR metric. Equal weights can be assigned for the different metrics in accordance with the additive combination rule. In the second case, if the node is a mobile node with a speed S_{mob} not equal to zero, then Equation (17) is used only if the node's lifetime is greater than the minimum threshold value; otherwise, $NR(i)$ is set to "0".

$$NR_{mc}\,(i) = [w_1 \times NR_{RB}(i) + w_2 \times NRT_{idle}(i) + w_3 \times NR_{QL}(i)]/S_{mob}(i) \tag{17}$$

Similar to the approach in conventional schemes, the node's MCNR metric value is measured and monitored periodically to be broadcasted via HELLO and TC messages to the medium in the topology sensing phase.

2) EQSA-MPR SELECTION MECHANISM

The second core contribution of MEQSA-OLSRv2 is optimizing control traffic generated during the topology sensing phase. This condition has been achieved using the *EQSA-MPR*selection mechanism, which modifies the setting of the willingness concept in the original MPR selection mechanism. *EQSA-MPR*can select a small set of nodes with the highest MCNR value to flood TC messages to the entire network instead of involving all nodes in such process, thereby reducing control traffic and energy consumption. The node's willingness represents a numerical value for five willingness levels: WILL_NEVER "0", WILL_LOW "1", WILL_DEFAULT "7", WILL_HIGH "14", and WILL_ALWAYS "15". In MEQSA-OLSRv2, these levels are graded on the basis of the estimated MCNR value to reflect a node's willingness to be selected as an MPR. Algorithm 2 describes the new willingness setting algorithm for the *EQSA-MPR*selection mechanism. A multicriteria metric is used while selecting the MPR node. As previously mentioned, the MCNR metric aggregates five parameters (LT, T_{idle}, RB, QL, and S_{mob}) related to energy and QoS into a single metric.

In contrast to the willingness setting mechanisms of MBQA-OLSR and MBMA-OLSR, the EQSA-MPR mechanism in MEQSA-OLSRv2 involves nodes that announce their own willingness on the basis of their MCNR metric value. The nodes, which have an estimated NR_{mc} metric lower than the minimum NR threshold value (NR_{min}), are set to the lowest willingness value (*WILL_NEVER*) and never participate in flooding TC messages due to their critical status in terms of various metrics. The nodes with a NR_{mc} metric value higher than 75% of the NR maximum threshold value (NR_{max}) are set to the highest willingness value (*WILL_ALWAYS*) and become the best candidates to be selected as MPRs. Other nodes are provided a willingness value on the basis of their ranks as stated in Algorithm 2. Then, every node broadcasts its own willingness value to its neighbors through HELLO and TC messages. Each node elects its MPR set (M) among its one-hop neighbor nodes x on the basis of their willingness $W(x)$, reachability $R(x, M)$, and degree $D(x)$ [24].

The topology sensing phase (link sensing, neighbor detection, and topology discovery), which aims at increasing the awareness of nodes about network topology benefits from MPRs, is set to forward HELLO and TC messages, similar to what is done under conventional schemes. The structure of these messages is not changed in MEQSA-OLSRv2 because we already included the information about MCNR in our previous schemes by adding an additional type–length–value (*TLV*) for the node rank information (Figure 12). These modifications let nodes know their MCNR metric values. MEQSA-OLSRv2 sends out HELLO and TC messages periodically for topology sensing as a proactive scheme. However, MEQSA-OLSRv2 does not always keep a routing table, and it utilizes an on-demand (reactive) scheme to compute multiple routes only when data packets need to be sent out.

Algorithm 2 EQSA-MPR Willingness Setting

Require: Node Rank > NR_{min}

Ensure Acceptable node lifetime && Higher Residual Battery && Lower Speed && Lower traffic && Lower idle time of nodes

NR_{max} ← the maximum node's rank of node
NR_{min} ← the minimum node's rank of node
$NR_{mc}(i)$ ← the instantaneous node's rank of node i
W_i ← *willingness of node* $i \ni V$
Get $NR_{mc}(i)$ *of node i*
  if $NR_{mc}\ (i) < NR_{min}$ **then**
    $W_{\mathrm{i}} = WILL\_NEVER$ //0
  else if $NR_{mc}(i) \geq 0.75 \times NR_{max}$ **then**
    $W_{\mathrm{i}} = WILL\_ALWAYS$ //15
  else if $0.50 * NR_{max} \leq NR_{mc}(i) < 0.75 \times NR_{max}$ **then**
    $W_{\mathrm{i}} = WILL\_HIGH$ //14
  else if $0.25 * NR_{max} \leq NR_{mc}(i) < 0.50 \times NR_{max}$ **then**
    $W_{\mathrm{i}} = WILL\_DEFAULT$ //7
  else
    $W_{\mathrm{i}} = WILL\_LOW$ //1
  end if
return W_{i}

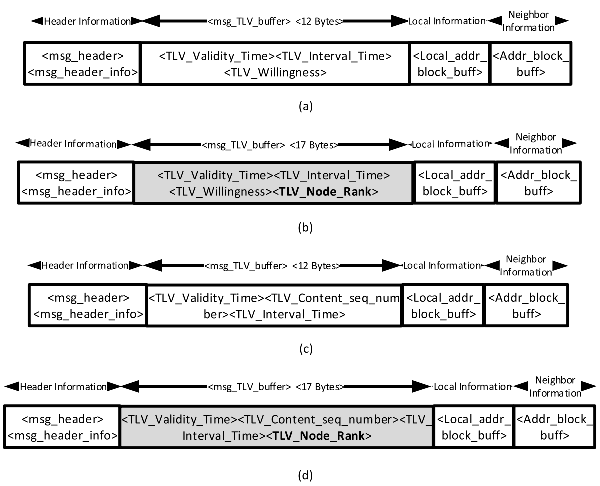

FIGURE 12. Type-Length-Value (TLV) added to HELLO and TC messages in MEQSA-OLSRv2.

Such scheme is expected to avoid the heavy computation of multiple routes for every possible destination just like MP-OLSRv2. The multipath Dijkstra algorithm of conventional schemes is used to compute the multiple routes to the destinations. For a detailed description of topology sensing and route computation algorithm, the reader can refer to [14] and [21].

3) LINK COST FUNCTION

Most existing routing protocols (e.g., MP-OLSRv2, OLSRv2, OLSR, AODV, and DYMO) are based on the hop

Algorithm 3 Link Cost Calculation

$G(V, E)$ ← *graph of V node set* and *E link set*
$NR_{mc}(i)$ ← *MCNR* metric value for node, $i \ni V$
$NR_{mc}(j)$ ← *MCNR* metric value for node, $j \ni V$
$NR_{mc}(i, j)$ ← *rank of the link,* $L(i, j)$ between nodes i and j; $L(i, j) \ni E$
$L_{cost}(i, j)$ ← *cost of link* $L(i, j)$ based on the *MCNR* metric of i and j
Get $NR_{mc}(i)$, $NR_{mc}(j)$ for each link $L(i, j)$ in E
  if $NR_{mc}(i) \geq NR_{min}$ **&&** $NR_{mc}(j) \geq NR_{min}$ **then**
    Calculate $NR_{mc}(i, j)$ Equation (18)
    Calculate $L_{cost}(i, j)$ Equation (19)
  else
    $L_{cost}(i, j) = MAX\_L_{cost}$
  end if
return $L_{cost}(i, j)$

count metric in which all link costs are treated equally. However, this measurement does not ensure link quality. In fact, in high data traffic networks, nodes may become congested easily due to unstable links. Link instability causes the retransmission of packets in the MAC layer, which significantly increases transmission delay. Therefore, we examine related works [14], [21] to improve the link quality assessment function by considering some QoS and energy-based metrics. MBQA-OLSR and MBMA-OLSR can offer improved performance in certain scenarios, but the benefit is not remarkable in heterogeneous networks, especially in MANET-WSN convergence scenarios (nodes with different battery capacities and speeds). Therefore, we propose to use the MCNR metric for routing path computation. The MCNR metric can faithfully reflect link quality on the basis of the utilized multiple parameters from different layers (PHY, MAC, and network). This metric depends on cross-layer interaction, which increases the accuracy of link quality assessment. For MEQSA-OLSRv2, Algorithm 3 is adopted to estimate the cost of links for each pair of nodes i and j according to their MCNR values by an equal ratio to give both nodes the same priority. Upon receipt of the HELLO or TC message, the MCNR value is extracted from *TLV_Node_Rank*. A linear function is used to define the average link rank $NR_{mc}\ (i, j)$ between two nodes.

$$NR_{mc}\ (i, j) = \frac{NR_{mc}\ (i) + NR_{mc}(j)}{2} \tag{18}$$

where $NR_{mc}(i)$ and $NR_{mc}(j)$ are the normalized values of *MCNR* rank for nodes i and j, respectively.

On the basis of the estimated value of the link's rank, $NR_{mc}(i, j)$, the cost of links (L_{cost}) between nodes i and j can be calculated as

$$L_{cost}\ (i, j) = 1 + k \times \frac{NR_{max}}{NR_{mc}\ (i, j)} \tag{19}$$

where k indicates the slope coefficient to determine the influence of the MCNR node's metric on link cost, $NR_{mc}(i,\ j)$

denotes the rank of the link between i and j nodes, and NR_{max} represents the maximum node rank.

For example, if $NR_{mc}(i)$ and $NR_{mc}(j)$ have maximum values, NR_{max}, then the link cost is minimum, i.e., "$1 + k$"; if nodes i and j have zero MCNR metric values, then the link cost becomes infinite. According to the new link quality assessment function, the link's initial cost is inversely proportional to MCNR metric value nodes at both ends of the link. In other words, the optimal path from the source to the destination is the path with the highest node rank metric and lowest link cost.

IV. SIMULATION ENVIRONMENT

This section introduces the simulation results and discusses the performance of the MEQSA-OLSRv2 routing scheme in two different scenarios. The obtained results are compared with those of several conventional schemes on the basis of selected performance criteria. In this section, we first describe the experimental setup and simulation environment. Then, we highlight the considered performance evaluation metrics. Finally, we discuss and analyze the simulation results of MEQSA-OLSRv2 in comparison with conventional routing schemes under the same conditions.

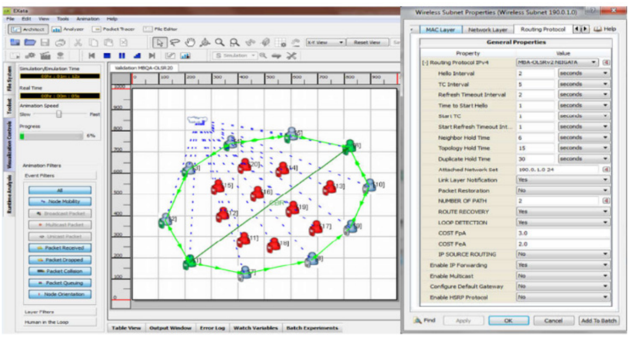

FIGURE 13. MEQSA-OLSRv2 GUI-based EXata simulation model operation.

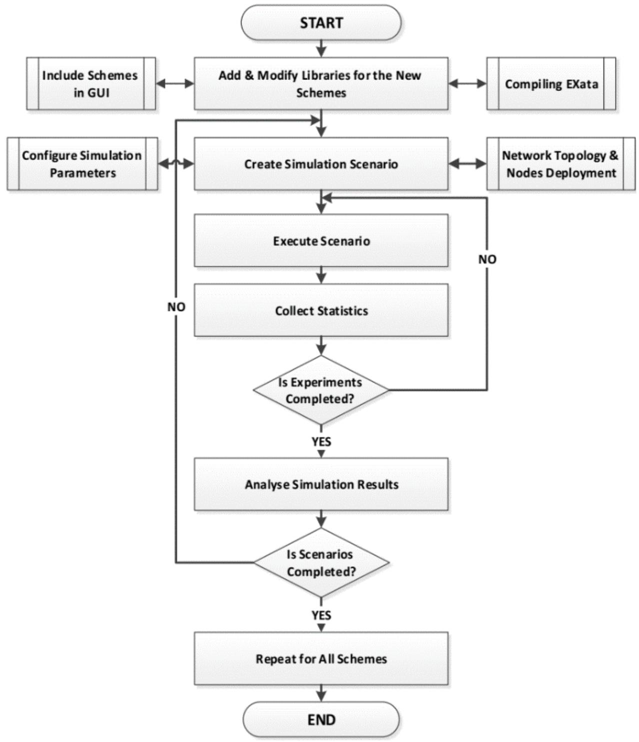

FIGURE 14. EXata simulation procedures.

A. SIMULATION SETTINGS

The performance of MEQSA-OLSRv2 and different versions of OLSRv2 with multipath extensions is evaluated by simulations on the EXata network simulator. The EXata can run on cluster, multi-core, and multi-processor systems to model large networks with high fidelity. This simulator uses a highly detailed standard-based implementation of protocol models. The EXata also includes advanced models for wireless environments to ensure an accurate modeling of real-world networks. Although simulating real wireless networks is an approximation of real network behavior due to the fidelity of their lower layers to reality, these networks do offer a baseline for comparative performance analysis and general best-scenario results, i.e., real-network performance will not be better than simulation results. In addition, the network simulator allows running numerous experiments for different scenarios with different protocols under identical parameters and conditions in all layers. Figure 13 demonstrates the developed GUI-based EXata simulation model for validating the proposed protocol with an operational example, whereas Figure 14 presents the flow chart for evaluating the performance of all schemes.

Some of the considered protocols in this work are already implemented in the EXata simulator. Nevertheless, we have implemented other schemes, including MP-OLSRv2, MPQ-OLSRv2, MBQA-OLSR, MBMA-OLSR, and MEQSA-OLSRv2. For consistency, we do not discuss the verification and validation of all these schemes. Further details can be found in our published papers as previously mentioned.

Simulations are conducted using the distributed coordination function (DCF) of IEEE 802.11 for wireless LAN as the MAC layer protocol to notify the network layer about link breakage. The two-ray ground propagation model is used as a path loss model with a channel frequency of 2.4 GHz and constant shadowing model with 4.0 shadowing mean. In the physical layer network, the transmission power is set to 15 dBm, and the generic energy model is used. The radio transmission range is approximately 270 m as a result of the selected Wi-Fi parameter setting. The radio type in our simulations is an 802.11b data link layer with an omnidirectional antenna model and 11 Mbps data rate. According to [78], and for the sake of implementation simplicity, we assumed all nodes (WSN and MANET) are provided with IEEE 802.11b wireless interfaces. Although various radio technologies are available in IoT networks, such as 802.15.4, Bluetooth, and low-power Wi-Fi, the 802.11b radio supports the basic DCF distributed mechanism for channel access.

Thus, the general behavior of the protocols under evaluation can be inferred from simulations using 802.11b radio and MAC protocol [78], especially for our schemes which were implemented in the Application Layer. The simulation topology of the scenarios represents a square field measuring 1000 m by 1000 m. Depending on the scenarios, CBR flows with source–destination pair are generated. Each CBR flow starts 10 s after the commencement of the simulation to provide adequate time for exchanging routing messages and sending 10 packets of 512-byte size per second for a period of 100 s from the source to the destination. Table 2 lists the other detailed parameters of the simulation.

B. DESIGN OF SIMULATION SCENARIOS

The performance of the proposed scheme in the converged MANET and WSN scenarios was evaluated by extensive simulations and compared with the several conventional schemes. As mentioned earlier, in a converged network of IoT, both WSN and MANET can benefit from each other. However, MANET nodes play a vital function in such convergence scenarios due to their inherent properties such as communication interferences, mobility support and processing capabilities. These features make MANET nodes superior compared to WSN nodes.

Therefore, the design and implementation of simulation scenarios focused more on the behavior and natures of nodes in the real MANET-WSN convergence scenarios. From this point of perspective, the heterogeneity of nodes in the designed scenarios was a key player to simulate the converged IoT network. For example, fixed nodes with low battery resources were considered as sensors in a WSN, whereas mobile nodes with high battery capacity represented MANET. In such convergence scenario of IoT, nodes of MANET can move around the WSN network and gather data from different fixed sensors, and forward data to the Internet gateway over multiple intermediate nodes.

Taking into account the diversity of traffic in the convergence MANET and WSN networks, two scenarios were designed in this study: (i) MP2P traffic scenario and (ii) P2P traffic scenario. The traffic type in first scenario is similar to typical WSN with sensor-to-root traffic, like reporting of periodic sensors readings. In such scenario all sensors generate data traffic and send to the same destination which is a single, stationary router in the network. Comparably, with MP2P scenario, the second P2P scenario was particularly designed to prove the effectiveness of the developed protocol in routing urgent data through MANET overlays. However, energy resources of nodes in this scenario were limited to prove the ability of MEQSA-OLSRv2 to saving energy and prolong nodes lifetime. Both converged scenarios were designed to show how our scheme can survive WSN nodes and transmit data efficiently from WSN to the Internet by involving MANET nodes. It should be clarified that these two scenarios are not the end of our performance analysis of the developed scheme because there are challenges are not considered in this study, Thus, more specific IoT scenarios need further investigation and evaluation, and they will be our future work. Following is more details about other parameters that considered for each simulation scenario.

TABLE 3. Simulation parameters.

Parameter	Values
Routing protocol	MEQSA-OLSRv2, MBQA-OLSR, MBMA-OLSR, MP-OLSRv2 ,MPQ-OLSRv2, OLSRv2, OLSR
No. of paths in multipath schemes	2
Incremental cost functions	$f_{p(c)}= 3c$ $f_{e(c)}= 2c$ where c: initial link cost
Link layer notification	Yes
Simulation time	110 sec
No. of Nodes	**P2P**:50; **MP2P**:40, 50, 60, 70, 80, 90,100, 110 and 120
No. of Flows	**P2P**: 25,and **MP2P**:20
Packet size	512
Applications traffic	CBR
Traffic start-end	10 sec - 110 sec
Mobility/ Full battery capacity	**P2P** RWP, Min speed 0, Max speed 30 m/ s, pause time 10 sec, 3.3 mAh **MP2P** GROUP 1 = Static, 18.2 mAh GROUP 2 = Static, 5 mAh GROUP 3 = RWP [5-30] mps, Pause: 0 Sec, 15 mAh GROUP 4 = RWP [5-30] mps, Pause: 0 Sec, 5 mAh
Transport protocol	UDP
Network protocol	IPv4
Energy model	Generic: P_{trans} = 1300 mW P_{rec} = 900 mW P_{Idle} = 740 mW P_{Sleep} = 47 mW Supply voltage 5.0 Volts
Transmission signal power	P_t = 15 dBm
Battery model	Linear Battery Model
Priority input queue size	50000
Mac protocol	IEEE 802.11
Physical layer model	PHY 802.11b
Wireless channel frequency	2.4 GHz
Path loss model	Two Ray
Shadowing model	Constant
Shadowing mean	4.0 dB
Data rate	11 Mbps

1) MP2P TRAFFIC SCENARIOS

This scenario is designed to reflect the real deployment of the convergence scenario for mobile and static nodes with different speeds and heterogeneous energy resources. In each of the MP2P scenarios based on network size, nodes are distributed into four groups on the basis of their speeds and battery capacities (Table 3). In this scenario, n nodes are spread out randomly on a scenario terrain (n is the number of nodes in the network varying from 40 to 120 with the gradual addition of 10 nodes). Another static single "root" in the network acts as a sink for all data flows, thereby resulting in $(n + 1)$ routers as the total number of nodes in different scenarios based on network size. Twenty static routers generate CBR traffic flows to the "sink." To avoid the termination of a simulation due to battery exhaustion at the sources or the sink node, all originators and the sink node were configured to have the maximum power resource of 18.2 (mA.h). Ten simulation iterations are run for each scenario (with different seeds), i.e., each point of data in the results represents an average of 200 CBR flows.

2) P2P TRAFFIC SCENARIO

In this scenario, 50 mobile nodes are placed and randomly distributed and 25 concurrent CBR traffic flows are generated. Each CBR connects a random originator router to another random destination router. Ten simulation iterations (10 different seeds) are run for each scenario, i.e., each data point in the results represents an average of 250 CBR flows. All nodes are provided with a linear battery model with an equal full battery capacity of 3.3 mA.h. We deliberately set a relatively low initial node battery energy value to generate scenarios where nodes deplete their battery and die. We assume that idle energy consumption is addressed with any of the existing complementary schemes. Thus, to emphasize the possible gains due to enhanced scheme, we ignored idle energy consumption in this scenario similar to [28]. The network topology may therefore undergo random change because the movement of nodes is random in accordance with the utilized RWP model. In mobility-based scenarios, we changed the speeds of nodes as 5, 10, 15, 20, 25, and 30 m/s, whereas the minimum speed is set to zero, and the pause time duration is set to 10 s.

C. EVALUATION CRITERIA

The objective of the experiments with the EXata network simulator is to validate the effectiveness of the MEQSA-OLSRv2 routing protocol and the benchmarks on the basis of the following adopted metrics.

1) PACKET DELIVERY RATIO (PDR)

This metric refers to the ratio of the number of data packets successfully delivered to the destination over the total number of packets sent by originators. It also illustrates the reliability of the routing protocol. Most IoT applications require more than 80% PDR to ensure the reliable data transmission between nodes.

$$PDR = 100 \times \frac{Total\ Packets\ Received}{Total\ Packets\ Sent}\% \tag{20}$$

2) THROUGHPUT

This metric is defined as the total number of bits successfully received at the server within a definite time duration. The throughput at the receiver can be calculated as follows:

$$Throughput = \frac{TotalBytes\ Received \times 8}{(t - t_f)}, \tag{21}$$

where t_f is the time of the first packet received and t represents either the time of the last packet received if the session is complete or the simulation time if the session is incomplete; the times are in seconds.

3) AVERAGE END-TO-END DELAY (AVG. EED)

This metric indicates the average time duration over all surviving data packets that are transmitted from the source to the destination. This value includes all possible delays caused by buffering, queuing, retransmissions, propagation, and transfer through a channel.

$$Avg.EED = \frac{1}{p}\sum_{j=1}^{p} Delay(j) \tag{22}$$

where p is the total number of packets received and $Delay(j)$ denotes the total transmission delays of a packet, which refers to the difference between the time of the packet being received at the destination and the time of the packet being transmitted at the source. All times are in seconds.

4) NORMALIZED ROUTING CONTROL OVERHEAD

This metric presents the ratio of the number of bytes of control messages (HELLO and TC) to the number of data bytes successfully received at destination nodes.

5) PEAK FIFO QUEUE SIZE

This metric is known as the maximum length of the FIFO queue in bytes during packet buffering in the network layer.

6) FIFO TOTAL PACKETS DROPPED (PD_{FIFO})

This metric refers to the total number of packets dropped due to the full queue.

7) PACKET DROPS DUE TO RETRANSMISSION LIMIT (PD_{RL})

This metric represents the packets not rescheduled after exceeding the maximum number of unsuccessfully delivered fragments.

8) AVERAGE REMAINING BATTERY ENERGY (AVG. RBE)

This metric specifies the average remaining charge of all batteries attached to nodes at the end of the simulation time; it can be calculated as follows:

$$Avg.RBE = \frac{1}{n}\sum_{i=1}^{n} RB(i) \tag{23}$$

where RB is the residual battery energy of node i at the end of the simulation and n denotes the total number of nodes in the network.

9) AVERAGE ENERGY CONSUMPTION (AVG. E_{cons})

This metric is defined as the average consumed energy in mWh of all nodes at the end of the simulation. The average consumption energy of the nodes changes according to the node's state (i.e., transmit, receive, or idle). This metric is calculated as follows. Let n be the total number of nodes in the network, and let the total consumed energy $E_{total}(i)$ for each node i be calculated as shown earlier.

$$Avg.E_{cons} = \frac{1}{n}\sum_{i=1}^{n} E_{total}(i) \tag{24}$$

10) ENERGY COST PER PACKET (ECP)

This metric indicates the ratio between the total energy consumption over the total number of successfully delivered data packets to the destinations and is calculated as:

$$ECP = \frac{Total\ Energy\ Consumption}{Total\ Packets\ Delivered} \tag{25}$$

11) NUMBER OF DEAD NODES

This metric presents the total number of dead nodes at the end of the simulation time.

V. PERFORMANCE ANALYSIS

In order to evaluate the performance of MEQSA-OLSRv2 in MANET-WSN convergence scenarios, this section presents a set of EXata simulations, comparing MEQSA-OLSRv2, MBQA-OLSR, MBMA-OLSR, MP-OLSRv2, MPQ-OLSRv2, OLSRv2, OLSR, DYMO and AODV, with the aforementioned simulation parameters.

A. MP2P TRAFFIC SCENARIOS

The network size is one of the major parameters in simulation studies of the routing protocol evaluation in ad hoc networks. In the current reported work, the number of nodes was selected as a parameter to evaluate the developed scheme in the first scenario. As the network size increases, the protocol scalability can be tested. Several QoS-aware metrics are evaluated to prove the QoS awareness of the proposed scheme.

In MP2P scenarios, the PDR of MEQSA-OLSRv2 decreases slightly as the network size increases, as shown in Figure 15(a). Unlike other figures, this figure includes plots for AODV and DYMO as representatives for reactive routing protocols to compare the gain in performance obtained due to the hybrid nature of MEQSA-OLSRv2. MEQSA-OLSRv2 effectively increases the PDR and outperforms all schemes regardless of network size. MEQSA-OLSRv2 maintains a PDR greater than 83% as the expected level of QoS for reliable data delivery in IoT applications. This result could be attributed to the capability of the developed scheme in selecting the most reliable paths to the destination in accordance with the node's MCNR metric with simultaneous consideration of multiple metrics during route computation. In other words, MEQSA-OLSRv2 selects nodes with high residual energy, low congestion level, long idle time, and stability (less mobility), thereby keeping a higher PDR and lower delay than other multipath schemes.

The four single path protocols, namely, AODV, DYMO, OLSR, and OLSRv2, achieve the lowest PDR in most scenarios, thereby causing a huge increase in their average end-to-end delay. Thus, we exclude their plots from Figure 15(b) for graph clarity. MEQSA-OLSRv2 adopts the benefits of the EQSA-MPR mechanism to add the most stable nodes to the MPR set for control traffic optimization. Moreover, it reuses the existing routing information to achieve a low normalized overhead and minimal collisions, as shown in Figure 15(c). For readability, we report only the curves

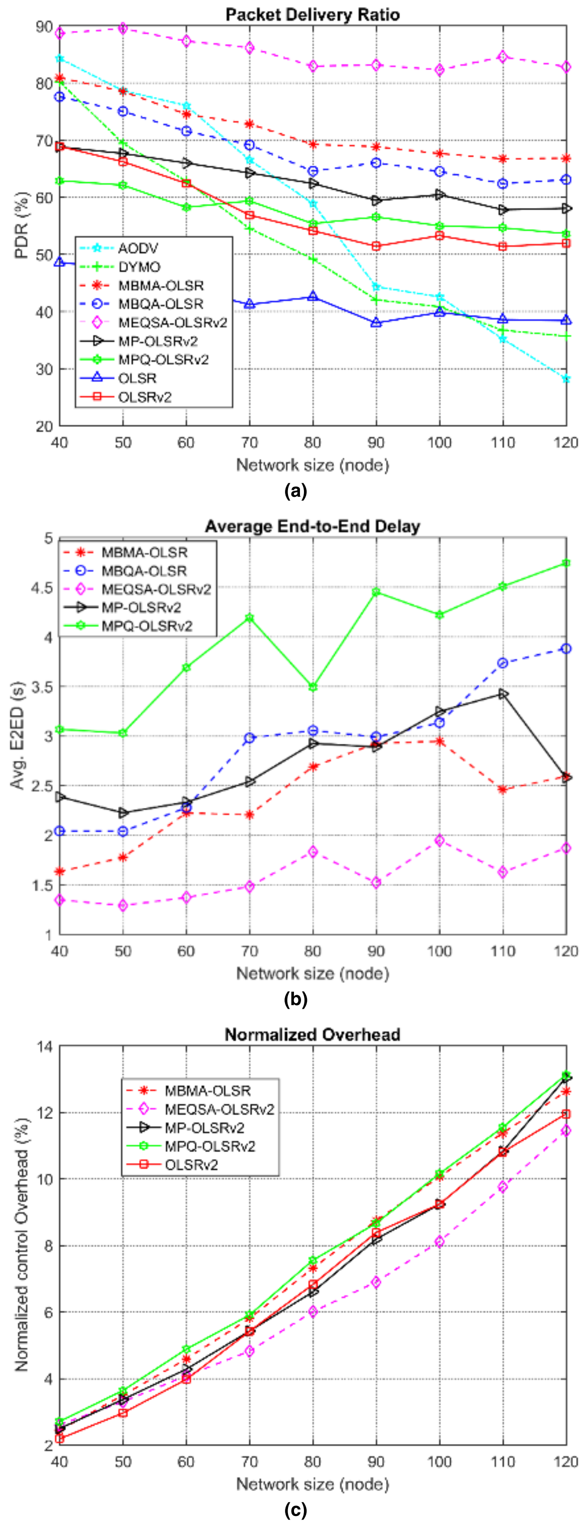

FIGURE 15. MP2P Simulation Results: (a) Packet delivery ratio (b) Average end-to-end delay (c) Normalised overhead.

relative to OLSRv2-based schemes. We also exclude the plots of MBQA-OSR because it has a considerably higher overhead than other schemes.

As a result of considering packet queue length during route computation and MPR selection, MEQSA-OLSRv2 can

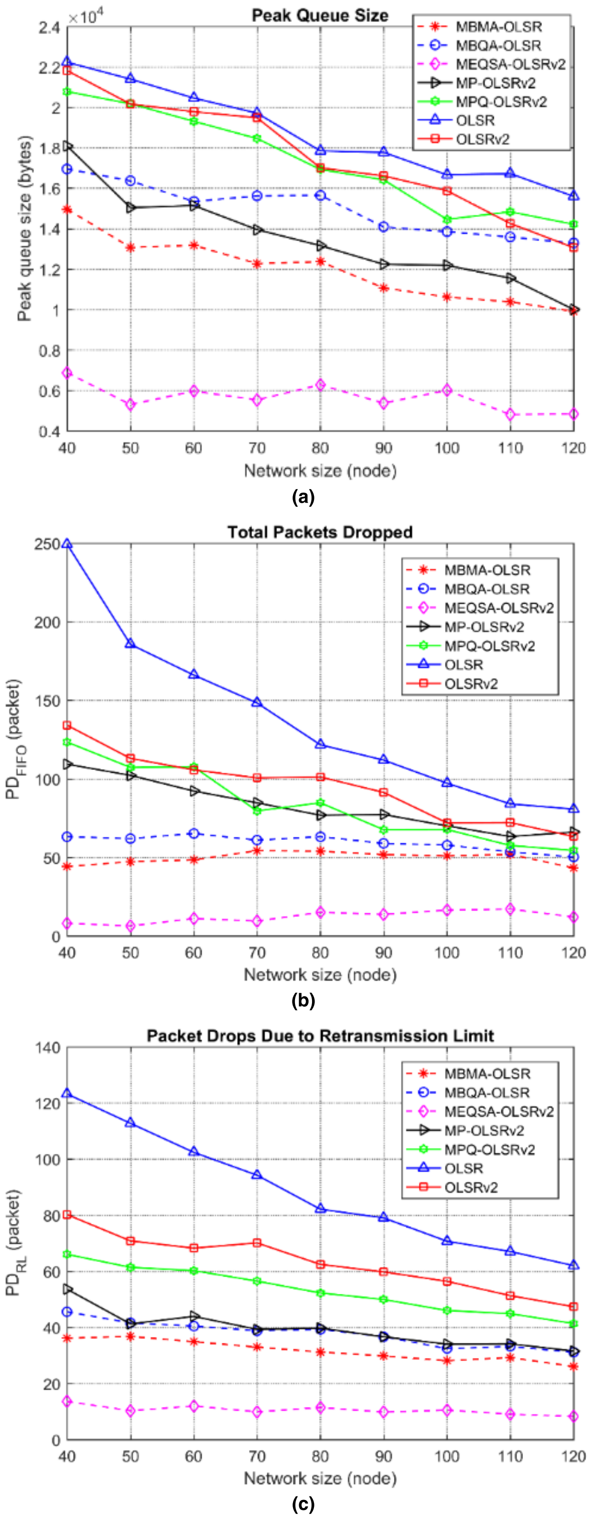

FIGURE 16. **MP2P Simulation Results: (a) Peak queue size (b) Packets dropped in FIFO (c) Packet drops due to retransmission limit in 802.11 DCF.**

significantly reduce the peak queue size, thereby reducing the average time in queue and the number of dropped packets in FIFO queue as illustrated in Figures 16(a) and (b). These metrics are good indicators for the behavior of routing protocols based on network congestion. Mobility in these scenarios provides MBMA-OLSR a privilege over other schemes, although MEQSA-OLSRv2 still presents the best performance. This condition is due to their consideration of node speed during multiple route selection. The integration of mobility awareness techniques in the MEQSA-OLSRv2 and MBMA-OLSR routing schemes has a significant influence on decreasing the number of packet drops due to the retransmission limit in the MAC layer, as displayed in Figure 16(c). MEQSA-OLSRv2 maintains the lowest number of packets dropped by minimizing the number of packet retransmission trials and decreasing the link failure occurrence due to high-speed nodes.

To study the influence of the proposed protocol on energy saving during the route process, we evaluate several energy-based performance metrics. In these scenarios, the cost per packet (energy efficiency), average residual battery energy, and percentage of time in idle mode are compared for different approaches. The energy per packet indicates the total energy consumption, total number of data packets received, and total overhead in the network. This metric is the best to evaluate the energy efficiency of routing protocols. The protocol that consumes the least amount of energy for transmitting additional data packets is regarded as the energy-efficient protocol. Figure 17(a) reveals that the proposed MEQSA-OLSRv2 achieves the lowest energy cost per packet in all scenarios regardless of the number of nodes. This result can be explained by the fact that MEQSA-OLSRv2 reduces energy consumption and increases the number of successfully transmitted packets by utilizing the new energy-aware techniques, which do not exist in other schemes.

Although the average residual energy of MEQSA-OLSRv2 seems to be the lowest in Figure 17(b), it is still reasonable according to the number of successfully transmitted packets and relative to other multipath and single-path protocols. Our previous schemes, namely, MBQA-OLSR and MBMA-OLSR, still perform better than the conventional schemes in terms of energy efficiency. In idle state, nodes consume energy for hearing the medium without forwarding packets to destinations; thus, the energy consumed in idle time is considered to be energy loss. With its consideration of idle time during route computation, our scheme achieves the shortest period in idle state, as shown in Figure 17(c). This result means that most nodes with the new scheme, relative to other schemes, will be involved for most of the time in transmitting and receiving packets, thereby enhancing energy utilization during data routing.

B. P2P TRAFFIC SCENARIO

To evaluate the performance of MEQSA-OLSRv2 in typical MANET scenarios, we conduct simulations with P2P CBR traffic. These scenarios evaluate and compare the performance of MEQSA-OLSRv2 and other schemes on the basis of mobile node speed, which is one of the main parameters in evaluation studies of routing protocols in mobile networks. The effectiveness of implementing mobility awareness

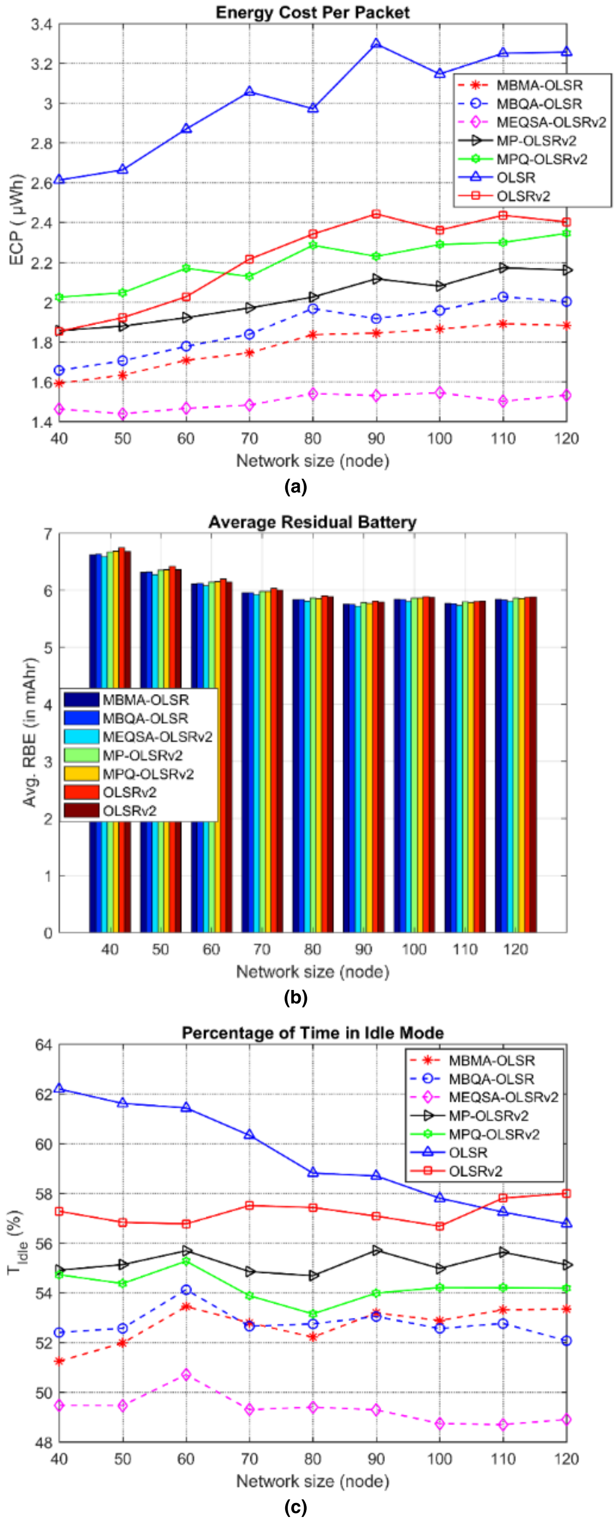

FIGURE 17. **MP2P Simulation Results: (a) Energy cost per packet (b) Average remaining battery (c) Node's idle time.**

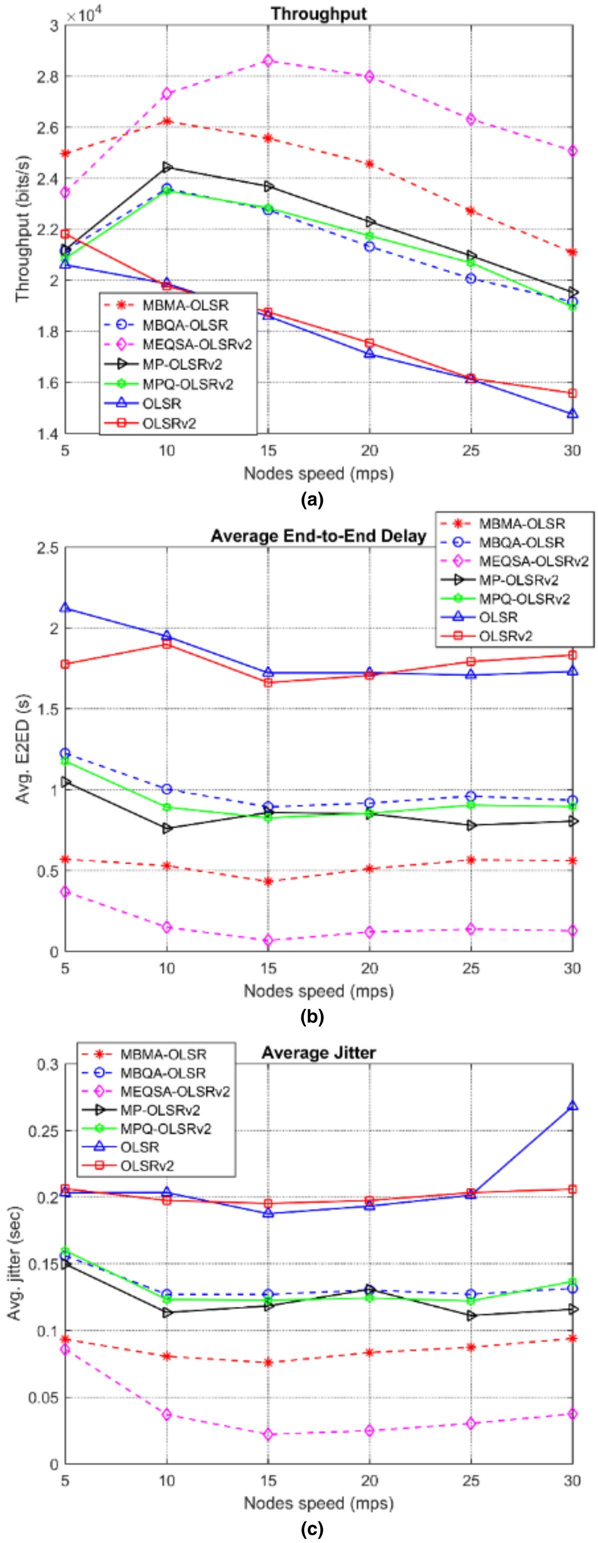

FIGURE 18. **P2P Simulation Results: (a) Throughput (b) Average end-to-end delay (c) Average jitter.**

techniques in the proposed extensions is evaluated in these P2P scenarios. The maximum speed in the RWP model is used to specify the maximum way point speed of nodes and is changed from 5 m/s to 30 m/s. Several QoS and energy-based metrics are compared for the protocols under evaluation.

Figures 18 and 19 illustrate some important QoS metrics for routing protocol evaluation. Figures 18(a), (b), and (c) compare the throughput, average delay, and average jitter, respectively. The PDR is not presented as it is identical

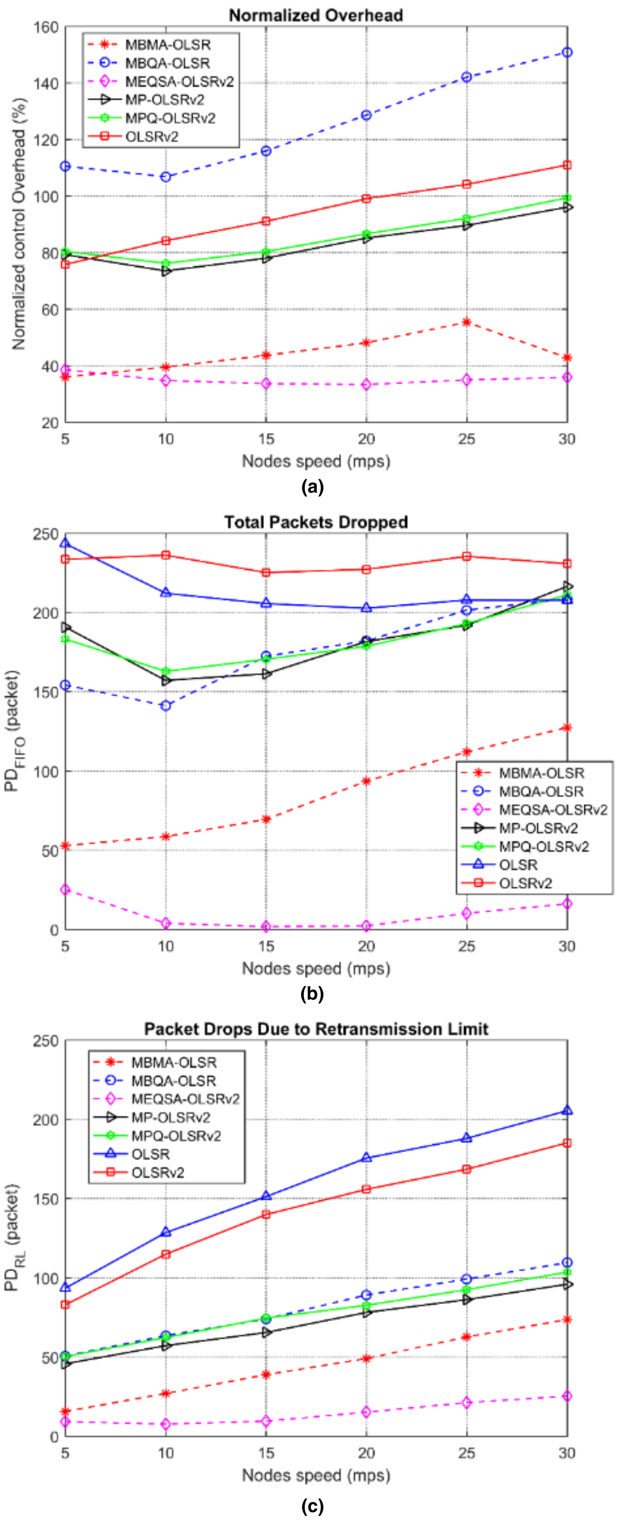

FIGURE 19. P2P Simulation Results: (a) Normalized overhead (b) Packets dropped in FIFO (c) Packet drops due to retransmission limit in 802.11 DCF.

to the throughput and MEQSA-OLSRv2 has the highest PDR in these scenarios. MEQSA-OLSRv2 yields the highest throughput and shorter delays and jitter than others, especially in high-mobility scenarios starting from 10 m/s. This result is attributed to the absence of mobility awareness support in all schemes except MBMA-OLSR to select the best routes especially in the case of link failure due to the mobility of nodes. MEQSA-OLSRv2 keeps paths for a long time because it selects high-reliability paths, thereby decreasing the time delay of data transmission, as shown in Figure 18(b). Thus, we can notice the superiority of MEQSA-OLSRv2 in all situations. As average jitter depends on the average end-to-end delay, the behavior of all protocols in terms of average jitter is consistent with their behavior in terms of average end-to-end delay, as shown in Figure 18(c).

Figure 19 presents the overhead and total packets dropped in FIFO queue and due to retransmission limit. Under high-mobility scenarios, additional routing overhead will be generated due to the re-initiation of topology sensing and route discovery, consequently generating further control overhead. In low-mobility scenarios, routes become stable. Thus, the need to reinitiate the route discovery process is often diminished. The use of the EQSA-MPR mechanism to select nodes with low speed, low traffic, and high residual energy to act as MPR nodes to limit the number of control traffic reduces the protocol overhead in MEQSA-OLSRv2 compared with other protocols.

Figure 19(a) shows that MEQSA-OLSRv2 yields the lowest normalized overhead. This result is almost the same in all cases because MEQSA-OLSRv2 always selects the most stable nodes for broadcasting topological information to the entire network at the start of topology sensing. This condition limits the rebroadcasting process and reduces the overhead. MBMA-OLSR achieves the second best protocol in terms of overhead because it also considers the node's mobility. Regarding the total packets dropped either in FIFO queue or due to the retransmission limit, MEQSA-OLSRv2 outperforms all schemes and achieves zero packets dropped in some scenarios, as illustrated in Figures 19(b) and (c). This result is because MEQSA-OLSRv2 decreases the probability of link failure, and thus, no data packets are sent in unreliable routes. MEQSA-OLSRv2 avoids the selection of nodes that may change their positions due to high mobility or become exhausted due to their limited energy resources for constructing multiple paths for data transmission, in addition to its capability to force lazy nodes to be involved in data forwarding. For the same reasons, an increase in node speed exerts a slight influence on the performance of the proposed scheme.

Figures 20(a), (b), and (c) illustrate the influences of varying speeds of nodes on the number of dead nodes, energy cost per packet, and average residual battery, respectively. These figures show that MEQSA-OLSRv2 can also considerably reduce the number of dead nodes, reduce the energy cost per packet, and increase the average residual battery energy in common MANET scenarios (e.g., P2P scenario). It is particularly efficient in heterogeneous scenarios and if most of nodes are sending data packets to a few root destinations in the network (e.g., MP2P scenario). MEQSA-OLSRv2 reduces energy consumption and enhances energy

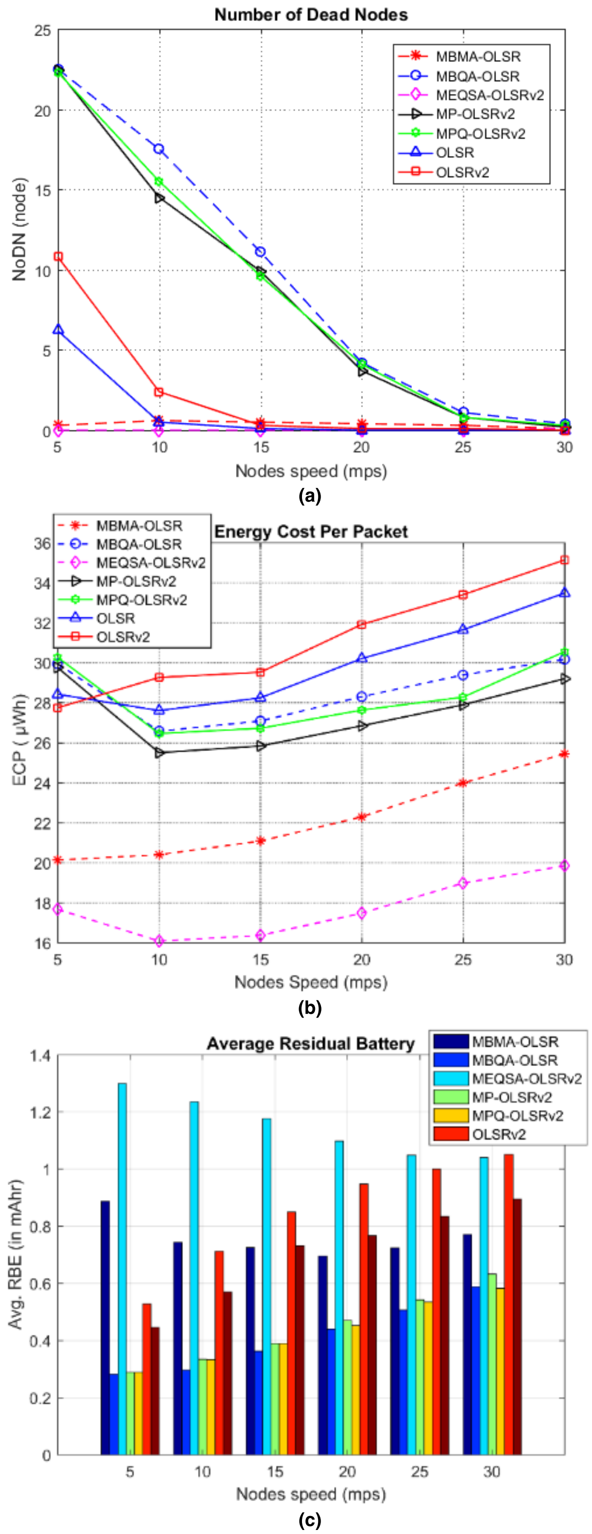

FIGURE 20. **P2P Simulation Results: (a) Number of dead (b) Energy cost per packet (c) Average remaining battery.**

efficiency without ignoring other QoS performance metrics, such as PDR, end-to-end delay, and normalized overhead. Thus, the proposed scheme is highly recommended to be exclusive in MANET-WSN convergence scenarios.

Figure 20(a) shows that no MEQSA-OLSRv2 router is dead in all cases regardless of node speed. MEQSA-OLSRv2 routers with a low battery energy level must hold back and never show their willingness to contribute as MPRs; in this way, their lifetime can be prolonged. Although dead nodes with a single-path protocol (OLSR and OLSRv2) are few, this case is due to the limited number of data packets transmitted in all cases. MBMA-OLSR remains the second best scheme in terms of energy efficiency, followed by MEQSA-OLSRv2.

Figure 20(b) presents the superiority of MEQSA-OLSRv2 in terms of decreasing the energy cost per packet. This result is because MEQSA-OLSRv2 benefits from its simultaneous consideration of energy, mobility, and QoS metrics during topology sensing (via MPRs) and multiple route computation. In scenarios with mobile nodes, each node moves, and its path randomly changes with time, which imposes further complexity on topology sensing and route computation phases. Furthermore, MPR nodes consume more energy than other nodes because they have to forward data and control packets from their selectors to the entire network. Therefore, MEQSA-OLSRv2 adopts the advantages of its new extensions to select the most reliable nodes and thereby contribute as MPRs for topological information flooding and data packet forwarding to destinations via the most stable routes. Thus, this process reduces the energy cost per packet and increases the node's lifetime.

Accordingly, the average residual battery energy for MEQSA-OLSRv2 routers is the highest in all cases, as shown in Figure 20(c). This result is because the EQSA-MPR mechanism utilized by the proposed scheme to select and optimize the nodes acting as MPRs has a huge influence on saving total energy consumption. In MEQSA-OLSRv2, little energy is consumed during the route computation and flooding of topological information because it selects the nodes with low speed and high residual battery to exchange control messages and forward data packets to the destination. As a result, a balance in consumed energy and an increase in battery energy saving occur. As previously mentioned, single-path schemes consume little energy because they transmit a limited number of packets to destinations (lowest PDR, highest delay, and highest energy cost per packet).

VI. CONCLUSION

We performed a network performance evaluation of several OLSR-based routing protocols including single path and multipath approaches in MANET-WSN convergence scenarios under a series of simulations by considering energy consumption and QoS metrics. On top of the outcome of the evaluation of the existing schemes, we proposed an improved hybrid multipath routing approach called MEQSA-OLSRv2 to make routing in convergence scenarios (P2P and MP2P) highly efficient. In contrast to existing algorithms, the MEQSA-OLSRv2 approach aggregated multiple criteria (related to energy and QoS) into a single metric for making a routing decision (and MPR selection). The acquired results showed that MEQSA-OLSRv2 can significantly improve QoS and energy awareness in typical MANET (P2P) and common WSN (MP2P) scenarios as well. This improvement in energy efficiency was not compromising other QoS metrics (PDR, throughput, and delay) as in conventional schemes (MBMA-OLSR, MBQA-OLSR, MP-OLSRv2, and MPQ-OLSRv2). This method inherited the main characteristic of MP-OLSRv2 and our previous extensions (MBMA-OLSR and MBQA-OLSR) and retained them as hybrid multipath routing protocols for MANETs. However, at the same time, this process enabled energy and QoS awareness during its two main phases, namely, topology sensing and route computation, rendering it an attractive protocol for data acquisition in convergence network deployments. MEQSA-OLSRv2 achieved load balancing through multiple paths similar to MP-OLSRv2, coped with link failure due to the node's mobility like MBMA-OLSR, and dealt with heavy traffic load and congested routes same as MBQA-OLSR. Thus, MEQSA-OLSRv2 avoided the selection of nodes with high mobility, low battery energy, and high congestion in the MPR set and multiple paths. Furthermore, MEQSA-OLSRv2 showed capability to force idle nodes in data transmitting and topology sensing activities instead of having them consume energy for nothing. The effectiveness of the proposed extensions was proved through extensive simulations of the two common scenarios. MEQSA-OLSRv2, was compared to several conventional schemes and achieved the best performance in terms of PDR, throughput, and end-to-end delay. It also decreased energy cost per packet, prolonged node lifetime, and reduced control overhead.

By providing multiple disjoint paths with energy and QoS awareness, MEQSA-OLSRv2 became further resilient to routing failures, especially in high-traffic scenarios. Although conducting simulation deployments and running codes and simulations have proven the effectiveness of MEQSA-OLSRv2 in certain networks, further experiments and experiences are still needed to enhance the protocol performance and understand the effects of the protocol specified in this paper. The MEQSA-OLSRv2 scheme can be further tested in other popular multi-hop wireless networks scenarios, including pure MANET, typical WSN, and MANET-IoT scenarios. The proposed scheme in this work was not implemented in a real testbed that could evaluate its performance in a real network deployment scenario. The performance evaluation and validation of MEQSA-OLSRv2 were conducted using the developed simulation model, which also has limitations because input values and parameters are based on assumptions or previous studies.

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WAHEB A. JABBAR received the B.Sc. degree in electrical engineering from the University of Basrah, Iraq, in 2001, and the M.Eng. degree in communication and computer and the Ph.D. degree in electrical, electronics, and system engineering from the Universiti Kebangsaan Malaysia, Bangi, Malaysia, in 2011 and 2015, respectively. He joined the Faculty of Engineering Technology, Universiti Malaysia Pahang, Malaysia, in 2016, where he is currently a Senior Lecturer of electrical engineering technology. His research interests include routing protocols in ad hoc networks, mobile communications, and wireless networking. He also has a keen interest in Internet of Things, smart city, and advanced electronics and automation.

WASAN KADHIM SAAD received the B.Sc. degree in electrical and electronic engineering/electronic and communication and the M.Sc. degree in satellite communication engineering from the University of Technology, Baghdad, Iraq, 1997 and 2005, respectively, and the Ph.D. degree in electrical, electronic and system engineering from the University Kebangsaan Malaysia, Faculty of Engineering and Build Environment, Malaysia, 2017. She is currently a Senior Lecturer with the Engineering Technical College, Al-Furat Al-Awsat Technical University, Najaf, Iraq. Her main research interests are wireless communications, cognitive radio network, and image processing.

MAHAMOD ISMAIL received the B.Sc. degree in electrical and electronics from the University of Strathclyde, U.K., in 1985, the M.Sc. degree in communications engineering and digital electronics from the Institute of Science and Technology, The University of Manchester, Manchester, U.K., in 1987, and the Ph.D. degree from the University of Bradford, U.K., in 1996. He joined the Department of Electrical, Electronics and Systems Engineering, Faculty of Engineering and Built Environments, Universiti Kebangsaan Malaysia, in 1985, where he is currently a Professor in communications engineering. His research interests include mobile, wireless networking, and radio resource management for the next generation wireless communication.