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RESEARCH ARTICLE

Energy-Efficient Multi-Rate Opportunistic Routing in Wireless Mesh Networks

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ABSTRACT Opportunistic or anypath routing protocols are focused on improving the performance of traditional routing in wireless mesh networks. They do so by leveraging the broadcast nature of the wireless medium and the spatial diversity of the network. Using a set of neighboring nodes, instead of a single specific node, as the next hop forwarder is a crucial aspect of opportunistic routing protocols, and the selection of the forwarder set plays a vital role in their performance. However, most opportunistic routing protocols consider a single transmission rate and power for the nodes, which limits their potential. To address this limitation, this paper proposes a multi-rate and multi-power opportunistic routing protocol called Energy-efficient Multi-rate Opportunistic Routing (EMOR). EMOR considers multiple transmission rates and power for each node, and in addition to selecting the forwarder set, it should select the transmission rate and power to reach this set in each node. Using different transmission rates and power levels can enhance EMOR's ability to effectively utilize the spatial diversity of the network. To prioritize the forwarder set, EMOR uses a transmission energy-based routing metric called Expected Opportunistic Transmission Energy (EOTE). EMOR also employs a distributed polynomial algorithm, Multi-rate Multi-power Opportunistic Bellman-Ford (MMOBF), to select the forwarder set, transmission rate, and transmission power in each node, minimizing the cost from the node to the destinations. The simulation results show that EMOR significantly outperforms the multi-rate opportunistic routing and multi-power opportunistic routing in terms of performance metrics such as packet delivery ratio, delay, and energy consumption.

INDEX TERMS Anypath routing, multi-rate, multi-power, opportunistic routing, transmission power control, wireless mesh networks.

I. INTRODUCTION

Wireless mesh networks have gained popularity in various Internet of Things (IoT) applications due to their scalability and reliability [1]. However, the variability of wireless link quality and the constraints of nodes, such as energy and bandwidth, pose significant challenges for routing in wireless mesh networks [2], [3].

In traditional routing [4], [5], each node selects one of its neighbors as the next hop and uses unicast to transmit the packets to this neighbor. Traditional routing retransmits the packet if it is not received in the next hop, even if some neighbors have received it. Packet retransmission wastes energy and bandwidth. Therefore, traditional routing cannot be suitable for wireless mesh networks. Unlike traditional routing, in opportunistic routing (OR) [6], [7], each node selects a subset of its neighbors, the forwarder set, and uses broadcast to transmit the packet to these neighbors. OR retransmits the packet if none of the nodes in the forwarder set have received it. OR mitigates the impact of the variability of wireless link quality by taking advantage of the broadcast nature of wireless media and the spatial diversity of wireless mesh networks. Adopting OR can improve the reliability and throughput of the wireless mesh network.

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Wireless devices typically support multiple transmission rates and power levels in their physical layer [7], [8].

Various routing protocols adopt different transmission rates or power levels as part of their approaches, and Opportunistic Routing (OR) protocols are no exception. Many routing protocols opt for higher transmission rates or lower transmission power levels to achieve reduced delay and energy consumption. However, these approaches may not always deliver the intended benefits and could potentially lead to network partitioning. The nature of Opportunistic Routing, which enhances the reliability of wireless mesh networks, presents an opportunity for synergy with the use of diverse transmission rates and power levels. Employing such variations can lead to improved reliability and also contribute to network efficiency.

The OR protocols presented so far can be categorized into three groups based on their approach to multiple transmission rates or power levels: single-rate and single-power OR, multi-rate OR, and multi-power OR. Single-rate and single-power OR protocols [6], [9], [10], [11] are designed assuming that each node operates at a single transmission rate and power level and usually use routing metrics based on transmission count. On the other hand, multi-rate OR protocols [7], [12], [13] are designed assuming multiple transmission rates and single transmission power levels for each node and usually use routing metrics based on transmission time. Lastly, Multi-power OR protocols [8], [14], [15] are designed assuming multiple transmission power levels and a single transmission rate for each node and usually use routing metrics based on transmission energy. Before discussing the challenges of each category, it is necessary to discuss the effect of changing transmission rate and power level on the performance of OR.

Increasing the transmission rate in a wireless link reduces the transmission time, thus reducing the energy consumption in the transmitter and receiver(s). On the contrary, decreasing the transmission rate increases energy consumption. Decreasing the transmission power level in a wireless link reduces the energy consumption in the transmitter. On the contrary, increasing the transmission power level increases energy consumption.

On the other hand, increasing the transmission rate or decreasing the transmission power level in a wireless link increases the probability of packet retransmission. On the contrary, decreasing the transmission rate or increasing the transmission power level reduces the probability of packet retransmission. Since packet retransmission wastes energy and bandwidth, a higher transmission rate or a lower transmission power level does not continuously improve performance in terms of delay and energy consumption.

Increasing the transmission rate or decreasing the transmission power level in a wireless link reduces the transmission range. On the contrary, decreasing the transmission rate or increasing the transmission power level increases the transmission range. Reducing the transmission range reduces the number of nodes contributing to the forwarder set, which reduces spatial diversity. Furthermore, reducing the transmission range reduces the number of nodes that can hear the transmission, which reduces energy consumption because the nodes that cannot hear the transmission consume no energy to receive the transmitted packet. Increasing the transmission range increases spatial diversity and energy consumption.

As explained, changing the transmission rate or power level in a wireless link has a contradictory effect on the performance metrics of OR, such as packet delivery ratio, delay, and energy consumption. Therefore, finding the optimal point in the compromise between transmission rate and power level is one of the critical challenges in designing a multi-rate and multi-power OR protocol.

Single-rate and single-power OR protocols are often limited to employing low transmission rates and high transmission power levels to maintain network connectivity. Unfortunately, this constraint increases both delay and energy consumption within the network. In multi-rate OR protocols, nodes are required to choose the transmission rate and the forwarder set. However, these protocols encounter challenges due to the conflicting impacts of changing the transmission rate. Typically, the transmission power level of each node is set to the maximum, leading to high energy consumption. On the other hand, in multi-power OR protocols, nodes are responsible for selecting the transmission power level and the forwarder set. These protocols also face challenges related to the contradictory effects of changing the transmission power level. Commonly, the transmission rate of each node is usually set to the minimum, resulting in increased delay and energy consumption.

Single-rate and single-power OR, multi-rate OR, and multi-power OR protocols face limitations in fully leveraging the advantages of selecting both appropriate transmission power and rate in diverse network conditions. These protocols may not be able to optimize their performance effectively across various scenarios due to their fixed configurations, thereby missing out on potential improvements in terms of energy efficiency, delay, and overall network performance. In this paper, we introduce a multi-rate and multi-power OR protocol called Energy-efficient Multi-rate OR (EMOR). EMOR enables the nodes to select different transmission rates and power levels. EMOR uses a transmission energy-based routing metric called Expected Opportunistic Transmission Energy (EOTE) to prioritize the forwarder set. The EOTE represents the energy required to successfully receive the transmitted packet at a specific transmission rate and power level by at least one node in the forwarder set. EMOR solves the problem of finding the forwarder set, transmission rate, and transmission power level from each node to a specific destination so that the cost of each node to that destination is minimized. We call this problem the shortest multi-rate and multi-power hyperpath and propose the Multi-rate and Multi-power Opportunistic Bellman-Ford (MMOBF) algorithm to address it. MMOBF is a generalization of the Multi-rate Anypath Bellman-Ford (MABF) algorithm [13] and inherits its properties, including polynomial running time and optimality.

Paper Contributions:

The main contributions of this paper are as follows:

- We present EMOR, a multi-rate and multi-power Opportunistic Routing (OR) protocol. EMOR allows nodes to select different transmission rates and power levels, aiming to optimize energy consumption while maintaining network connectivity.
- We introduce the EOTE routing metric to prioritize the forwarder set. EOTE quantifies the energy required for successful packet reception at a specific transmission rate and power level by at least one node in the forwarder set.
- We address the challenge of finding the shortest multi-rate and multi-power hyperpath by proposing the MMOBF algorithm, which efficiently solves this problem.

The rest of this paper is organized as follows: Section II discusses related work involving multiple transmission rates or power levels. Section III presents the main concepts used by the EMOR protocol. The general structure of the EMOR protocol is described in Section IV. Section V evaluates the performance of the EMOR protocol compared to state-of-the-art protocols. Finally, Section VI provides the conclusion for this paper.

II. RELATED WORK

In this section, the related works are reviewed. Most OR protocols are designed with the assumption of using a single transmission rate and power level for each node. In Subsection A, some single-rate and single-power OR protocols are reviewed, and their routing metric and forwarder set selection methods are discussed. In Subsections B and C, some multi-rate and multi-power OR protocols are reviewed, respectively.

A. SINGLE-RATE AND SINGLE-POWER OR PROTOCOLS

Zeng et al. [9] have proposed the Geographical OR (GOR) protocol. This protocol uses the Expected One-hop Throughput (EOT) routing metric and a timer-based coordination method. EOT is a local metric that considers the trade-off between one-step progress and delay caused by transmission. Using a heuristic algorithm with exponential running time, the authors select the forwarder set that optimizes the routing metric locally.

Biswas and Morris [6] have proposed the first link-state-aware OR protocol called Extremely OR (ExOR), which integrates routing and media access control. This protocol uses the Expected Transmission count (ETX) routing metric to prioritize the nodes in the forwarder set and a timer-based coordination method to avoid sending duplicate packets in the network.

Chachulski et al. [10] have proposed the Mac-independent OR & Encoding (MORE) protocol, which makes OR independent of media access control. This protocol uses the ETX routing metric and network coding coordination method.

OR protocols can use traditional routing metrics or OR metrics. If traditional routing metrics are used, the cost from each node to the destination is equivalent to the cost of a route from that node to the destination, which contradicts the opportunistic nature of OR. Therefore, it cannot be an appropriate metric to represent the cost from each node to the destination in OR. On the other hand, if opportunistic metrics are used, the cost from each node to the destination is the weighted sum of the cost of each possible path from that node to the destination.

ETX is a traditional routing metric incompatible with the opportunistic nature of OR. Zhong et al. [16] have proposed the first OR metric called Expected Anypath transmission (EAX). Their motivation is to reduce the size of the forwarder set to reduce the overhead of coordination protocol. The authors first select the forwarder set using the same ExOR method and then filter the selected forwarder set using a heuristic algorithm based on the EAX metric.

The above protocols and many works in OR use a single transmission rate and power level and do not have an optimal method to select the forwarder set. Forwarder set selection is usually based on a non-optimal heuristic so that if a neighbor has a lower expected number of transmissions to the destination, it will be included in the forwarder set.

Dubois-Ferriere et al. [11] have proposed an OR protocol called Least-Cost Anypath Routing (LCAR). This protocol uses a routing metric based on the number of transmissions called the Expected Anypath Transmission Count (EATX), a generalization of the ETX metric. By generalizing the well-known Belman-Ford algorithm for anypath routing, the authors propose an algorithm with exponential running time to find the shortest anypath and prove its optimality.

Hao et al. [17] have proposed an OR protocol based on the Markov decision process (MDP-OR). The authors use a finite-state MDP problem to model the packet forwarding process. Then, an optimal forwarding strategy is obtained by solving the MDP problem to minimize the expected number of transmissions. Furthermore, the EAX metric is used to select the candidate forwarder set, which can significantly reduce the feasible optimal solution space.

Pai et al. [18] have suggested the Power and Load-Aware Enhanced OR (PLAEOR) protocol based on the opportunistic gradient forwarding strategy. This protocol considers the remaining power, transfer energy, and expected packet delay to select the optimum routes. Moreover, the Multichannel Cooperative Neighbor Discovery (MCND) protocol is introduced to avoid the broadcast storm of control packets in the network. MCND finds the collaborative neighboring nodes to transmit the path information packets via the optimum routes. Therefore, frequent transmission and reception of control packets are prevented from reducing the overhead and power depletion of the nodes.

Naderi and Ghanbari [19] have proposed an Adaptive Prioritizing candidate Forwarder Set scheme (APFS) to address the challenging vehicular environments. In this scheme, the potential candidate forwarding sets are computed, from the one-hop and the two-hop neighbors, based on a simple linear positional estimation model. These sets are obtained by making a trade-off between network stability, delay, and good-put.

These OR protocols overlook the potential benefits of adopting different transmission rates and power levels for each node, even when achieving the same packet delivery ratio can be accomplished with lower transmission power levels or higher transmission rates. Consequently, this lack of consideration results in increased energy consumption and unnecessary interference in the network.

B. MULTI-RATE OR PROTOCOLS

Recently, multiple transmission rates have been considered in OR. Zeng et al. [12] have proposed the Multi-Rate Geographic OR (MGOR) protocol, which is a generalization of the GOR. This protocol uses the Opportunistic Effective One-hop Throughput (OEOT) routing metric, a generalization of the EOT metric. OEOT considers the trade-off between one-step progress and delay caused by transmission at different transmission rates. Using a heuristic algorithm, the authors select the transmission rate and the forwarder set in such a way as to optimize the routing metric locally.

Laufer et al. [7], [13] have proposed an OR protocol called Multi-rate Anypath Routing (MAR), which integrates OR and multiple transmission rates. This protocol uses a routing metric based on transmission time called Expected Anypath Transmission Time (EATT), a generalization of the Expected Transmission Time (ETT) metric. The authors propose two algorithms with polynomial running times to find the shortest multi-rate path and prove their optimality.

These OR protocols do not consider different transmission power levels for each node, even when the same transmission rate and packet delivery ratio can be achieved by lower transmission power levels. Therefore, energy consumption and unnecessary interference increase in the network.

C. MULTI-POWER OR PROTOCOLS

Mao et al. [14] have proposed an Energy-Efficient OR (EEOR) protocol for wireless sensor networks that integrates OR and multiple transmission power levels. This protocol uses a routing metric based on the transmission energy but does not specify how to calculate the transmission energy. Using an optimal algorithm, the authors select the transmission power level and the forwarder set to minimize the energy consumption for each node.

Coutinho et al. [8] have proposed a Transmission power Control-based OR (TCOR) protocol for wireless sensor networks. TCOR reduces the energy consumption of each node by dynamically selecting the transmission power level while maintaining network reliability. This protocol uses a transmission energy-based routing metric that considers the effect of multiple transmission power levels on the packet delivery probability to the forwarder set.

Zhao et al. [15] have proposed a Reliable and Energy-efficient OR (REOR) protocol. This protocol uses a new routing metric to measure the transmission cost and also selects the transmission power level and forwarder set at each node. REOR significantly reduces the death of nodes and ensures continuous network connectivity with a dynamic workload-sharing method.

Xian et al. [20] have proposed a Novel Energy-Efficient OR (NEOR) protocol for marine wireless sensor networks (MWSNs) based on compressed sensing combined with power control. In this paper, the authors introduce the compressed sensing theory to reduce the amount of data. Besides, an adaptive power control mechanism is presented to determine appropriate power levels for the nodes. NEOR determines the candidate sets that minimize the network energy consumption in variable transmission power levels and prioritizes the candidate nodes. It considers the mobility of nodes, packet advancement, communication link quality, and the remaining energy of nodes in this process.

Li et al. [21] have introduced an efficient and reliable transmission power control-based OR (ERTO) to enhance packet delivery probability (Psc), while simultaneously reducing energy consumption and network interference. They considered Psc, expected energy consumption, and the relationship between transmission power and node degree to optimize both the transmission power and forwarding node degree, which are conflicting objectives. To address this, they formulated a multi-objective optimization problem and derived a Pareto optimal solution. Consequently, during the routing process, the nodes calculate the optimal transmission power and forwarding node degree to achieve improved performance.

Ren and Yao [22] have presented an OR protocol named ORDPD designed specifically for energy-harvesting wireless sensor networks with dynamic transmission power and duty cycle. In ORDPD, the transmission power of sensor nodes is adjusted at the end of each time slot based on the predicted available energy. Additionally, if sensor nodes receive packets from other nodes outside their current transmission range, both the transmission power and duty cycle are adjusted in subsequent time slots. ORDPD incorporates an improved transmission model and information exchange mechanism, enabling dynamic updates of relay sets and forwarding paths to enhance overall efficiency and adaptability.

These OR protocols primarily focus on reducing energy consumption and prolonging network lifetime by adjusting the transmission power level of nodes. However, they overlook the potential impact of different transmission rates, which can have a more significant effect on lowering energy consumption in the network. Considering transmission rates alongside transmission power levels could lead to more effective energy-saving strategies.

III. PRELIMINARIES

A. SYSTEM MODEL AND ASSUMPTIONS

To illustrate the relationship between a node and its forwarder set in OR, we use a directed hypergraph to model the wireless mesh network. A hypergraph is a pair $(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes, and $\mathcal{E}$ is the set of hyperlinks. A directed hyperlink is an ordered pair (i, F_i) where $i \in V$ is a node and $F_i \subseteq V$ is the set of its forwarders. A directed hypergraph is a hypergraph with directed hyperlinks.

We consider a wireless mesh network where each node $i \in V$ can select its transmission rate from the set $R = \{r_1, r_2, \ldots, r_{|R|}\}$, and its power level from the set $P_{tx} = \{p_{tx1}, p_{tx2}, \ldots, p_{tx|P_{tx}|}\}$. Since the number of neighbors for each node $i \in V$ depends on its selected transmission rate and power level, we define $N_i^{r,p_{tx}}$ as the set of neighbors of node i when the packet is transmitted by node i at transmission rate r and transmission power level p_{tx}. For each hyperlink $(i, F_i) \in \mathcal{E}$, we have a packet delivery probability $p_{i,F_i}^{r,p_{tx}}$ and a cost $d_{i,F_i}^{r,p_{tx}}$ for each transmission rate $r \in R$ and transmission power level $p_{tx} \in P_{tx}$.

$p_{i,F_i}^{r,p_{tx}}$ is the packet delivery probability of the hyperlink (i, F_i) at transmission rate r and transmission power level p_{tx}. By assuming the independent packet delivery probability of neighboring links, $p_{i,F_i}^{r,p_{tx}}$ is simplified to

$$p_{i,F_i}^{r,p_{tx}} = 1 - \prod_{j \in F_i} \left(1 - p_{i,j}^{r,p_{tx}}\right), \tag{1}$$

where $p_{i,j}^{r,p_{tx}}$ is the packet delivery probability of the link (i, j) when the packet is transmitted by node i at transmission rate r and transmission power level p_{tx}. $p_{i,F_i}^{r,p_{tx}}$ is the probability that the packet transmitted by node i at transmission rate r and transmission power level p_{tx} is successfully received by at least one node in the forwarder set F_i.

B. COST OF THE MULTI-RATE AND MULTI-POWER HYPERPATH FROM NODE i TO DESTINATION d THROUGH THE FORWARD SET F_i AND AT THE TRANSMISSION RATE r AND TRANSMISSION POWER LEVEL p_{tx}

In energy-efficient multi-rate OR, there are multiple paths between each pair of nodes, and each node has the potential to use different transmission rates or power levels. We call the set of all possible paths between each pair of nodes a multi-rate and multi-power hyperpath, wherein each node may use a different transmission rate or power level.

$D_{i,F_i,d}^{r,p_{tx}}$ is the cost of the multi-rate and multi-power hyperpath from node i to destination d through the forwarder set F_i at transmission rate r and transmission power level p_{tx} and is defined as

$$D_{i,F_i,d}^{r,p_{tx}} = d_{i,F_i}^{r,p_{tx}} + D_{F_i,d}^{r,p_{tx}}, \tag{2}$$

where $d_{i,F_i}^{r,p_{tx}}$ is the hyperlink cost from node i to the forwarder set F_i when the packet is transmitted by node i at transmission rate r and transmission power level p_{tx}. $D_{F_i,d}^{r,p_{tx}}$ is the remaining cost from the forwarder set F_i to destination d when the packet is transmitted by node i at transmission rate r and transmission power level p_{tx}. Since both the hyperlink cost and the remaining cost depend on the transmission rate and power level of node i, the cost of multi-rate and multi-power hyperpath from node i to destination d varies for each forwarder set $F_i \subseteq V$, transmission rate $r \in R$, and transmission power level $p_{tx} \in P_{tx}$.

We introduce the expected opportunistic transmission energy (EOTE) routing metric and define the cost $d_{i,F_i}^{r,p_{tx}}$ based on it. $d_{i,F_i}^{r,p_{tx}}$ is the cost of hyperlink (i, F_i) at transmission rate r and transmission power level p_{tx} and is defined as

$$d_{i,F_i}^{r,p_{tx}} = \left(\frac{1}{p_{i,F_i}^{r,p_{tx}}} \times \frac{s}{r}\right) \times \left(W_{tx}^{r,p_{tx}} + \left|N_i^{r,p_{tx}}\right| \times W_{rx}^{r}\right), \tag{3}$$

where $p_{i,F_i}^{r,p_{tx}}$ is the packet delivery probability of the hyperlink defined in (1), s is the maximum packet size, $W_{tx}^{r,p_{tx}}$ is the power consumption of the transmitter in the transmitting mode at transmission rate r and transmission power level p_{tx}, W_{rx}^{r} is the power consumption of the receiver in the receiving mode at transmission rate r, and $N_i^{r,p_{tx}}$ is the set of neighbors of node i when the packet is transmitted by node i at transmission rate r and transmission power level p_{tx}. The cost $d_{i,F_i}^{r,p_{tx}}$ is the energy required to successfully receive the packet transmitted by node i at transmission rate r and transmission power level p_{tx} by at least one node in the forwarder set F_i.

The power consumption of the transmitter in transmitting mode and the receiver in reception mode is not significantly affected by the transmission rate and can be ignored. Moreover, the effect of the transmission power level on the power consumption of the transmitter in transmitting mode can also be neglected. This is because the change in power consumption $W_{tx}^{p_{tx}}$ resulting from changing the transmission power level p_{tx} is negligible compared to $\left|N_i^{r,p_{tx}}\right| \times W_{rx}$. Consequently, reducing the transmission power level to minimize energy consumption in the transmitter does not yield substantial practical benefits, as the conserved energy constitutes a negligible fraction of the total energy consumed [23], [24], [25]. Therefore, $d_{i,F_i}^{r,p_{tx}}$ is simplified to

$$d_{i,F_i}^{r,p_{tx}} = \left(\frac{1}{p_{i,F_i}^{r,p_{tx}}} \times \frac{s}{r}\right) \times \left(W_{tx} + \left|N_i^{r,p_{tx}}\right| \times W_{rx}\right), \tag{4}$$

where W_{tx} is the maximum power consumption of the transmitter in transmitting mode, and W_{rx} is the maximum power consumption of the receiver in reception mode.

The remaining cost $D_{F_i,d}^{r,p_{tx}}$ is the weighted average cost from each node $j \in F_i$ to destination d and can be expressed as

$$D_{F_i,d}^{r,p_{tx}} = \sum_{j \in F_i} w_{i,j}^{r,p_{tx}} \times D_{j,d}, \; with \sum_{j \in F_i} w_{i,j}^{r,p_{tx}} = 1, \tag{5}$$

where $w_{i,j}^{r,p_{tx}}$ is normalized of the probability that node j is the forwarder of the packet transmitted by node i at transmission rate r and transmission power level p_{tx}, and $D_{j,d}$ is the cost of the shortest multi-rate and multi-power hyperpath from node j to destination d. By assuming the independent packet delivery probability of neighboring links, $w_{i,j}^{r,p_{tx}}$ is simplified to

$$w_{i,j}^{r,p_{tx}} = \frac{p_{i,j}^{r,p_{tx}} \prod_{k=1}^{j-1}\left(1-p_{i,k}^{r,p_{tx}}\right)}{1-\prod_{j\in F_i}\left(1-p_{i,j}^{r,p_{tx}}\right)}, \tag{6}$$

where the forwarder set F_i is prioritized based on their cost to the destination. Node j will forward the packet transmitted by node i at transmission rate r and transmission power level p_{tx} if and only if none of the lower cost (higher priority) nodes receive it.

Now that the cost $D_{i,F_i,d}^{r,p_{tx}}$ is defined, the problem of finding the shortest multi-rate and multi-power hyperpath can be solved. In this paper, an optimal algorithm with polynomial time complexity is proposed to solve this problem, considering multiple transmission rates and power levels for each node. Therefore, in addition to selecting the forward set for each destination, each node should select the transmission rate and power level to reach this set.

C. PACKET DELIVERY PROBABILITY OF THE LINK (i,j) AT THE TRANSMISSION RATE r AND THE TRANSMISSION POWER LEVEL p_{tx} ESTIMATION

To measure the power loss at distance d in dB, $PL(d)$, we use the log-distance path loss propagation model, which is defined as

$$PL(d) = p_{tx} - p_{rx}(d) = \overline{PL}(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X, \quad for\ d_f \le d_0 \le d \tag{7}$$

where p_{tx} is transmission power level in dBm, $p_{rx}(d)$ is received power at distance d in dBm, $\overline{PL}(d_0)$ is the average path loss at reference distance d_0 in dB, γ is path loss exponent, X is a random Gaussian variable with zero mean and variance σ_X^2 in dB, d_f is the far field distance, and d_0 is the reference distance. $\overline{PL}(d_0)$ is defined using the free-space path loss model according to Equation (8).

$$\overline{PL}(d_0) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right), \tag{8}$$

where λ is the wavelength of the signal.

We use MRS^r to denote the minimum receiver sensitivity at transmission rate $r \in R$. The packet delivery probability of the link (i,j) at transmission rate r and transmission power level p_{tx}, $p_{i,j}^{r,p_{tx}}$, is defined as the probability that the received power at the distance d in dBm, $p_{rx}(d)$, is greater than the minimum sensitivity of the receiver at transmission rate r in dBm, MRS^r. $p_{i,j}^{r,p_{tx}}$ is defined as

$$p_{i,j}^{r,p_{tx}} = \Pr\left\{p_{rx}(d) > MRS^r\right\} = Q\left(\frac{MRS^r - p_{tx} + \overline{PL}(d_0) + 10\gamma\log_{10}\left(\frac{d}{d_0}\right)}{\sigma_X}\right), \tag{9}$$

where p_{tx} is the transmission power level in dBm, σ_X is the standard deviation of the path loss in the distance d in dB, and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{u^2}{2}}du.$

IV. ENERGY-EFFICIENT MULTI-RATE OR (EMOR)

In this section, the general structure of EMOR is described.

A. NEIGHBOR DISCOVERY

Each node initiates the process of neighbor discovery upon deployment. Each node $j \in V$ periodically broadcasts a probe packet containing its geographic location at the minimum transmission rate and maximum transmission power level. Upon receiving a probe packet from node j, node i calculate its distance to node j by obtaining the geographical location of node j and knowing its geographical location. Then node i uses Equation (9) to calculate the packet delivery probability of the link (i,j) for each transmission rate $r \in R$ and transmission power level $p_{tx} \in P_{tx}$ and updates its neighbor's table with packet delivery probability.

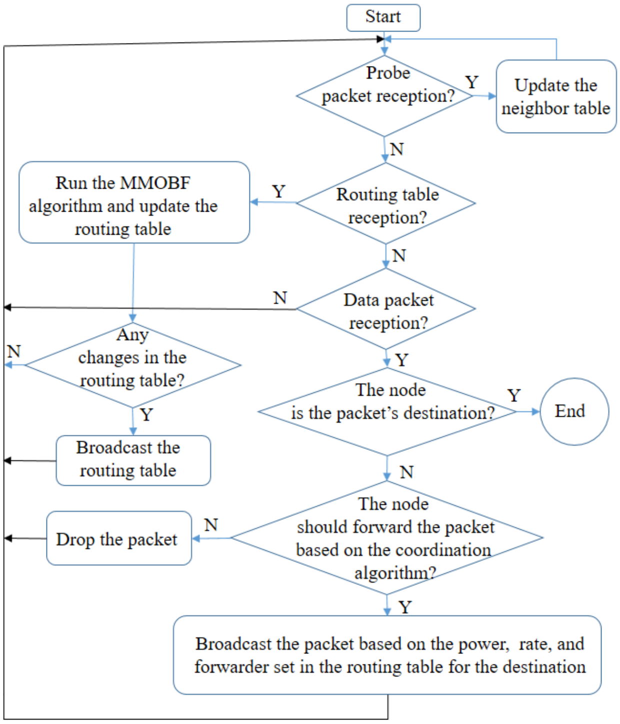

FIGURE 1. Performance flowchart of the proposed protocol in each node.

B. SELECTING A FORWARDER SET, TRANSMISSION RATE, AND POWER LEVEL

The performance of each node in the proposed protocol is depicted in Fig. 1 as a flowchart. Following the neighbor discovery phase, each node $j \in V$ sets the cost from node j to itself to 0 and periodically broadcasts a packet containing its routing table at the minimum transmission rate and maximum transmission power level. Upon receiving a routing table packet from node j, node i executes the multi-rate and multi-power opportunistic Bellman-Ford (MMOBF) algorithm to find the forwarder set, transmission rate, and power level and updates its routing table accordingly. The MMOBF algorithm is a distributed algorithm used to find the shortest multi-rate and multi-power hyperpath, a generalization of the Bellman-Ford algorithm. The MMOBF algorithm takes the hypergraph $(\mathcal{V}, \mathcal{E})$ and the destination d as input and selects the node's forwarder set, transmission rate, and power level to minimize the cost to the destination d.

For each node $i \in V$, the cost of the shortest multi-rate and multi-power hyperpath from node i to destination d is denoted by $D_{i,d}$, and the forwarder set of node i to reach destination d corresponding to $D_{i,d}$ is denoted by $F_{i,d}$. For each node $i \in V$ and transmission rate $r \in R$ and transmission power level $p_{tx} \in P_{tx}$, the cost of multi-rate and multi-power hyperpath from node i to destination d at transmission rate r and transmission power level p_{tx} is denoted by $D_{i,d}^{r,p_{tx}}$ and the forwarder set of node i to reach destination d corresponding to $D_{i,d}^{r,p_{tx}}$ is denoted by $F_{i,d}^{r,p_{tx}}$. For each node $i \in V$, the transmission rate and power level related to $D_{i,d}$ are also represented by $r_{i,d}$ and $p_{i,d}$, respectively. MMOBF algorithm pseudocode is shown in Table 1.

The MMOBF algorithm initializes the variables and sets the cost of node d to zero. Like the Bellman-Ford algorithm, the MMOBF algorithm has a maximum of $|V| - 1$ iterations. In each iteration, each node $i \in V$ stores its neighbors in the priority queue Q (the lower the cost of the neighbor to the destination, the higher the priority). If Q is not empty, the neighbor with the lowest cost to the destination (the highest priority) is extracted from Q and stored in j. Then, for each transmission rate $r \in R$ and transmission power level $p_{tx} \in P_{tx}$, the algorithm stores set j and the forwarder set $F_{i,d}^{r,p_{tx}}$ in J. Then, it checks whether the cost $D_{i,d}^{r,p_{tx}}$ is greater than the cost $D_{j,d}$ and if it is greater than that, the variables $D_{i,d}^{r,p_{tx}}$ and $F_{i,d}^{r,p_{tx}}$ are updated accordingly. Finally, the algorithm checks whether the cost $D_{i,\mathrm{d}}$ is greater than the cost $D_{i,d}^{r,p_{tx}}$ and if it is greater than that, the variables $D_{i,d}$, $F_{i,d}$, $r_{i,d}$, and $p_{i,d}$ are updated.

The execution time of the MMOBF algorithm is $O(VE \log V + VERP)$, where $O(VE \log V)$ is the accumulated time for the extract-min operation, and $O(VERP)$ is the accumulated time for lines 16 and 17. The main feature of this algorithm, which has reduced its execution time from exponential to polynomial, is that for n neighbors, there is no need to test all $2^n - 1$ possible forwarders, and a maximum of n sets are checked.

C. COORDINATION AND FORWARDING

In OR, due to the broadcast nature of wireless media and the spatial diversity of wireless mesh networks, the transmission of a packet may be received at more than one node of the forwarder set. To avoid sending duplicate packets, only one node within the set should relay the packet. To achieve this, each node in the set is assigned a priority for relaying the received packet. The forwarding decision is based on the priority order, where nodes with lower costs to the destination are assigned higher priorities. Consequently, if the node with the lowest cost in the forwarding set successfully receives the packet, it becomes the designated forwarder and sends the packet to the destination. Meanwhile, other nodes in the set withhold their transmission. If the designated forwarder fails to receive the packet, the node with the second lowest cost becomes the newly designated forwarder, and so on, following the priority sequence.

TABLE 1. Pseudo code of MMOBF algorithm.

```
Multi-rate − Multi-power − Opportunistic − Bellman-Ford ((𝒱,ℰ),d)
1   for each node i in V
2       $D_{i,d} \leftarrow \infty$
3       $F_{i,d} \leftarrow \emptyset$
4       $R_{i,d} \leftarrow NIL$
5       $P_{i,d} \leftarrow NIL$
6       for each rate r in R do
7           for each power $p_{tx}$ in $P_{tx}$ do
8               $D_{i,d}^{r,p_{tx}} \leftarrow \infty$
9               $F_{i,d}^{r,p_{tx}} \leftarrow \emptyset$
10  $D_{d,d} \leftarrow 0$
11  repeat $|V| - 1$ times:
12      for each node i in V do
13          $Q \leftarrow$ get-neighbors $(i)$
14          while $Q \neq \emptyset$ do
15              $j \leftarrow$ extract-min$(Q)$
16              for each rate r in R do
17                  for each power $p_{tx}$ in $P_{tx}$ do
18                      $J \leftarrow F_{i,d}^{r,p_{tx}} \cup \{j\}$
19                      if $D_{i,d}^{r,p_{tx}} > D_{j,d}$ then
20                          $D_{i,d}^{r,p_{tx}} \leftarrow d_{i,J}^{r,p_{tx}} + D_{J,d}^{r,p_{tx}}$
21                          $F_{i,d}^{r,p_{tx}} \leftarrow J$
22                          if $D_{i,d} > D_{i,d}^{r,p_{tx}}$ then
23                              $D_{i,d} \leftarrow D_{i,d}^{r,p_{tx}}$
24                              $F_{i,d} \leftarrow F_{i,d}^{r,p_{tx}}$
25                              $r_{i,d} \leftarrow r$
26                              $p_{i,d} \leftarrow p_{tx}$
```

To enforce this relay priority, called coordination, a reliable anycast scheme [26], achieved by using suitable MAC strategies, is utilized in this paper.

Until at least one of the nodes in the forwarder set receives the packet, the sender retransmits the packet up to the maximum retransmission threshold. Once a neighbor within the set successfully receives the packet, the same process is repeated by that neighbor until the packet reaches its final destination.

TABLE 2. **Transmission rates of each node and their corresponding minimum sensitivity in the simulation.**

MCS index	Data rate (Mb/s)	Minimum receiver sensitivity (dBm)
0	6.5	–89.3
1	13.0	–86.5
2	19.5	–84.5
3	26.0	–81.5
4	39.0	–78.0
5	52.0	–73.5
6	58.5	–71.5
7	65.0	–70.0

TABLE 3. **The power consumption of each node in the simulation.**

Parameter	Value
W_{tx}	0.2553 W
W_{rx}	0.8806 W

V. SIMULATION AND PERFORMANCE EVALUATION

This section provides the simulation and performance evaluation of the EMOR protocol and conducts a comparative analysis with the Multi-rate Anypath Routing (MAR) and Transmission power Control based OR (TCOR) protocols. All routing protocols are implemented using NS-3. Performance metrics have been evaluated, including packet delivery ratio, average delay per packet, and average energy consumption per packet. In Subsection A, the configuration of the parameters used in the simulations is explained. In Subsection B, the results of the simulation and analysis are presented.

A. SIMULATION SETTING

It is worth noting that the same packet delivery probability estimation model and coordination protocol are used to make a fair and transparent comparison between different OR protocols. After deploying nodes, each node starts discovering its neighbors and uses the MMOBF algorithm to find the forwarder set, rate, and transmission power level to reach other nodes. Then each node starts generating data packets.

The simulated network consists of 25 wireless nodes that are randomly and uniformly distributed in a square area with dimensions d m × d m. d is set with different values of 25, 50, 100, and 200 m to investigate the effect of node density on the performance metric of protocols. Between each possible pair of nodes in the network, a UDP stream (600 streams) is defined with a constant rate of 64 bytes per second and a packet size of 512 bytes. The *OnOffApplication* in ns-3 generates node traffic, received by the *PacketSink* application, enabling all nodes to function as transmitters or receivers. Traffic alternates between "on" and "off" states, generating Continuous Bit Rate (CBR) traffic when "on" and none when "off." The application is set on and active throughout our simulation. Each data point in the simulation results averages the result from all streams over ten runs with different random seeds.

TABLE 4. **Transmission power levels of each node in the simulation.**

Transmission power level (dBm)	Transmission power level (W)
0	0.001
3	0.002
6	0.004
9	0.008
12	0.016
15	0.032

TABLE 5. **Simulation parameters.**

Simulation parameter	Value
Number of nodes	25
Propagation loss model	Log-distance $\gamma = 2.7$ $\sigma_X = 6\ dB$ $d_0 = 1\ m$ $f = 2412\ MHz$
Propagation speed	Speed of light
Probe packet interval	1 s
Data packet interval	8 s
Data packet size	512 B
Data traffic type	Constant bit rate
PHY layer	802.11n
MAC layer	802.11n
Maximum retransmission threshold	7

In this paper, the parameter values are set according to the WL1837MOD wireless node [27]. Table 2 shows the minimum sensitivity of each node at different transmission rates, extracted from the node's data sheet. Table 3 shows the maximum power consumption of each node in transmission and reception mode, extracted from the node's datasheet. Table 4 shows the different transmission power levels considered for each node, and Table 5 shows the related simulation parameters. We consider Log-distance as the channel loss model, where γ is the path loss exponent, σ_X is the standard deviation of the signal strength, d_0 is the reference distance, and f is the frequency of the signal. The speed of light is also considered as the channel's propagation speed.

B. SIMULATION RESULTS AND ANALYSIS

MAR is a multi-rate but single-power protocol that dynamically selects the transmission rate. Fig. 2 compares the packet delivery ratio between EMOR and MAR at different transmission power levels. The packet delivery ratio of MAR at high transmission power levels and high density is similar to EMOR. However, any reduction in the transmission power level or density in MAR leads to a decrease in the quality of links which causes network segmentation that ultimately results in a decrease in the packet delivery ratio. Unlike MAR, the TCOR protocol is a multi-power but single-rate protocol that dynamically selects the transmission power level. In Fig. 3, the packet delivery ratio of EMOR and TCOR at different transmission rates is evaluated versus node density. The packet delivery ratio of TCOR at low transmission rates and high density is like EMOR. However, increasing the

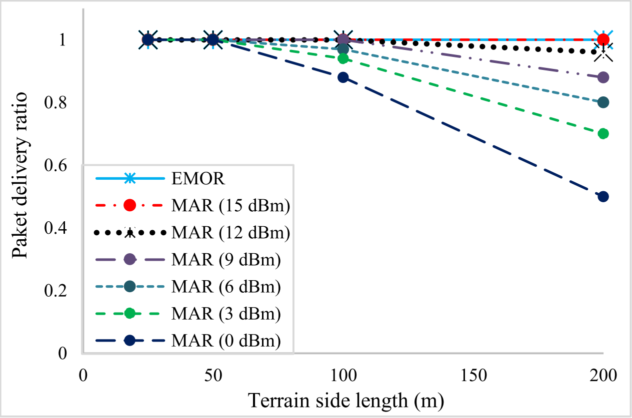

FIGURE 2. Comparison of packet delivery ratio between EMOR and MAR with varied transmission power levels at different densities.

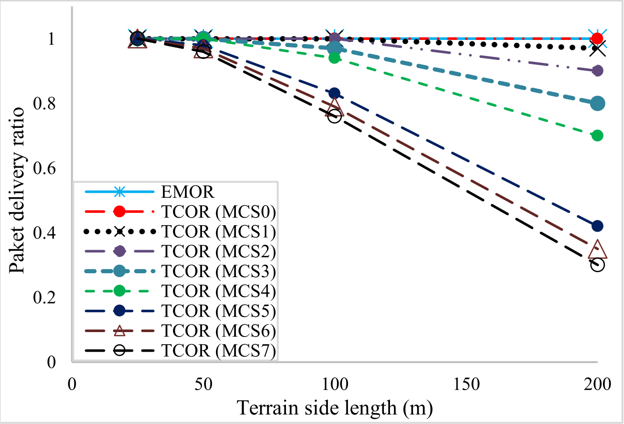

FIGURE 3. Comparison of packet delivery ratio between EMOR and TCOR with varied transmission rates at different densities.

transmission rate or decreasing density in TCOR leads to a decrease in the quality of links and, as a result, network segmentation, ultimately leading to a decrease in the packet delivery ratio.

As a result, MAR and TCOR protocols are limited to using high transmission power levels and low transmission rates to preserve network reliability, respectively, leading to a waste of bandwidth and increased energy consumption in the network. EMOR has solved this problem by dynamically selecting the transmission rate and power level while preserving network reliability.

Fig. 4 shows the average end-to-end delay per packet compared to MAR at different transmission power levels. EMOR and MAR perform almost the same in terms of end-to-end delay at the highest transmission power level. In the scenarios where nodes are uniformly distributed in the network, EMOR rarely has to reduce the rate to reduce energy consumption. On the other hand, the reduction of transmission power level or density in MAR leads to the selection of lower transmission rates to preserve the network's reliability and thus increases the delay significantly.

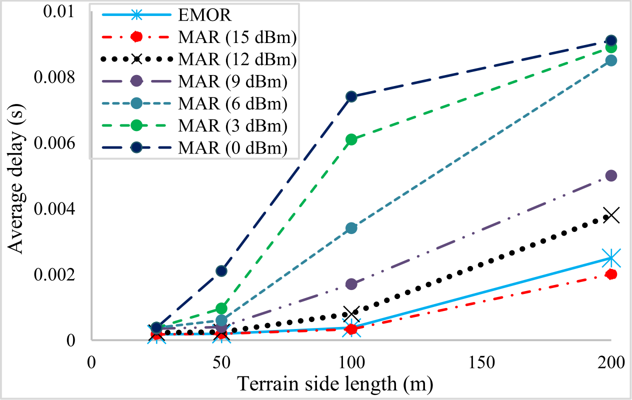

FIGURE 4. Comparison of the average end-to-end delay per packet between EMOR and MAR with varied transmission power levels at different densities.

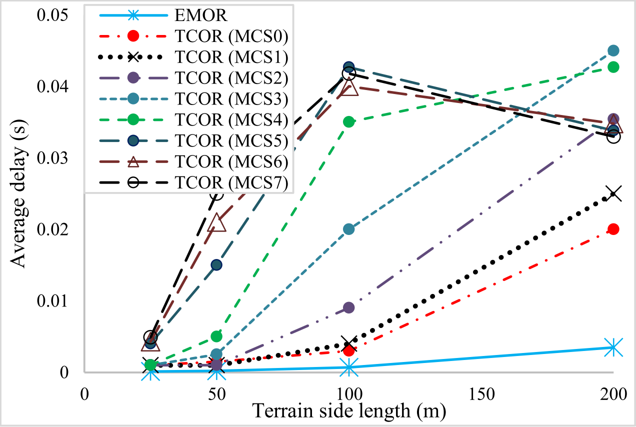

FIGURE 5. Comparison of average end-to-end delay per packet between EMOR and TCOR with varied transmission rates at different densities.

Fig. 5 shows the average end-to-end delay per packet compared to TCOR at different transmission rates. EMOR performs better than TCOR in terms of end-to-end delay at all transmission rates due to the static selection of transmission rate in TCOR that can significantly affect the average end-to-end delay per packet. On the other hand, increasing the transmission rate in TCOR results in a decrease in the quality of links and an increase in the probability of packet retransmission in the network, which ultimately leads to an increase in the delay instead of reducing it.

Fig. 6 shows the average energy consumption per packet compared to MAR in different transmission power levels. EMOR has a better performance in terms of energy consumption than MAR in all transmission power levels, especially in high density. This is because MAR statically selects transmission power level. On the other hand, transmission power level or density reduction in MAR leads to a decrease in the quality of links and an increase in the probability of packet retransmission in the network, which ultimately

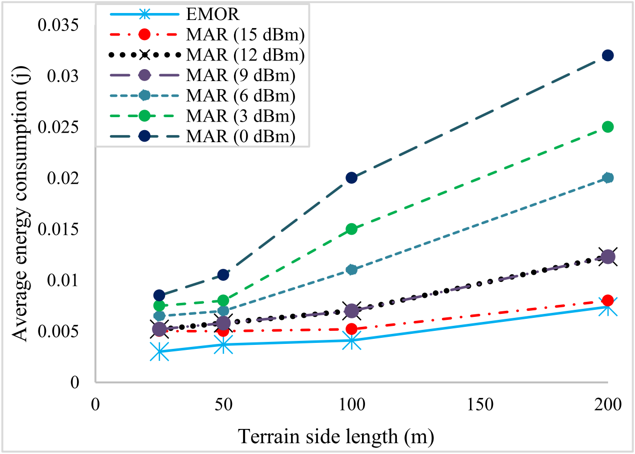

FIGURE 6. Comparison of the average energy consumption per packet between EMOR and MAR with varied transmission power levels at different densities.

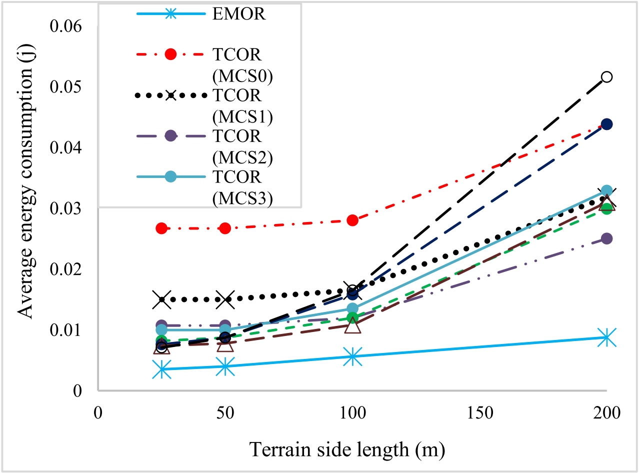

FIGURE 7. Comparison of average energy consumption per packet between EMOR and TCOR with varied transmission rates at different densities.

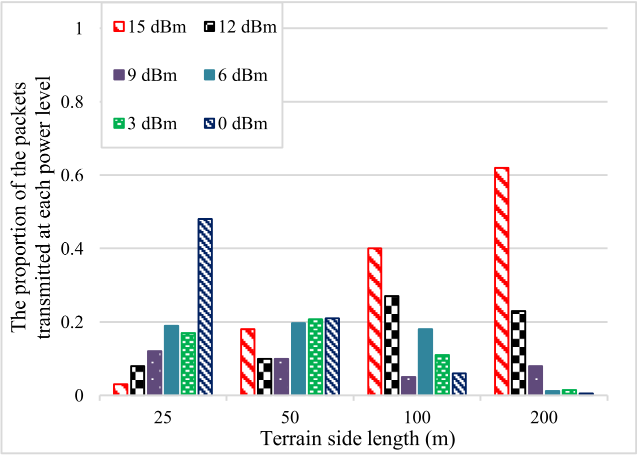

FIGURE 8. The share of each power from the total packets transferred in EMOR.

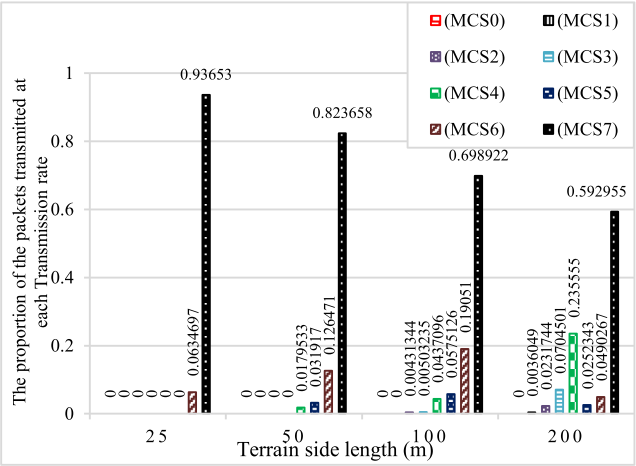

FIGURE 9. The share of each rate from the total packets transferred in EMOR.

causes an increase in energy consumption instead of reducing it.

Fig. 7 shows the average energy consumption per packet compared to TCOR in different transmission rates. EMOR performs better than TCOR in terms of energy consumption in all transmission rates, and this is because TCOR statically selects the transmission rate. On the other hand, increasing the transmission rate and reducing density in TCOR leads to a decrease in the quality of links and an increase in the probability of packet retransmission in the network, which ultimately leads to an increase in energy consumption instead of reducing it.

Figs. 8 and 9 show the share of each power level and transmission rate from the total packets transmitted in the network in EMOR, respectively. As density decreases, the higher transmission rates and lower transmission power levels are less frequently used in EMOR. Conversely, as the density increases, EMOR increases the contribution of higher transmission rates and lower transmission power levels.

Analysis of the simulation results has shown that the higher the density of nodes and the smaller the average distance between nodes, the proposed protocol uses higher transmission rates and lower transmission power levels while preserving the network reliability.

VI. CONCLUSION

Wireless devices mainly support different transmission rates and power levels in their physical layer. Most OR protocols have been designed to use a single transmission rate and power level at each node. It is necessary to consider multiple transmission rates and power levels in designing OR protocols for wireless mesh networks to take advantage of each node's different transmission rates and power levels. This paper proposed a multi-rate and multi-power OR protocol called EMOR. While preserving the advantages of OR, EMOR also benefits from the advantages of dynamic rate and transmission power level selection. This protocol uses a routing metric called EOTE to prioritize the forwarder set of each node based on transmission energy and select the forwarder set, rate, and power level of transmission for each node using a distributed polynomial algorithm called MMOBF. MMOBF aims to minimize the energy consumption of reaching the destination from each node. The simulation results showed that EMOR ensures network reliability while achieving a substantial reduction in average energy consumption per packet compared to MAR and TCOR protocols. Specifically, EMOR achieves energy savings of up to 220% and 360% compared to MAR and TCOR, respectively.

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