electronics

Review

Survey on Power-Aware Optimization Solutions for MANETs

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Received: 1 June 2020; Accepted: 9 July 2020; Published: 11 July 2020

Abstract: Mobile ad hoc networks (MANETs) possess numerous and unique characteristics, such as high channel error-rate, severe link-layer contentions, frequent link breakage (due to node mobility), and dissimilar path properties (e.g., bandwidth, delay, and loss rate) that make these networks different from the traditional ones. These characteristics seriously interfere with communication and hence, ultimately degrade the overall performance in terms of end-to-end delay, packet delivery ratio, network throughput, and network overhead. The traditional referenced layered strict architecture is not capable of dealing with MANET characteristics. Along with this, the most important apprehension in the intent of MANETs is the battery-power consumption, which relies on non-renewable sources of energy. Even though improvements in battery design have not yet reached that great a level, the majority of the routing protocols have not emphasized energy consumption at all. Such a challenging aspect has gained remarkable attention from the researchers, which inspired us to accomplish an extensive literature survey on power-aware optimization approaches in MANETs. This survey comprehensively covers power-aware state-of-the-art schemes for each suggested group, major findings, crucial structures, advantages, and design challenges. In this survey, we assess the suggested power-aware policies in the past in every aspect so that, in the future, other researchers can find new potential research directions.

Keywords: MANET; energy-efficient routing; transmission power control; power-aware routing metrics; power-aware optimization; cross-layer optimization; hybrid optimization

1. Introduction

Mobile ad hoc networks (MANETs) have gained increasing popularity for a range of applications [1], such as emergency/rescue operations, military sector applications (e.g., battlefield), health monitoring of civil structures, homeland monitoring, and ubiquitous computing. A MANET consists of mobile nodes that communicate with each other without any infrastructure. These mobile radio autonomous nodes are arranged in a mesh topology and form a dynamic, multi-hop radio network in a decentralized way [1]. The impression of forming a MANET came from the Defense Advanced Research Projects Agency (DARPA) packet radio network [2,3]. In the past few decades, several researchers [4,5] have purely focused on the issue of selecting and managing the optimum set of ad hoc routers, whereas some researchers [6–8] have suggested other effective techniques to deal with routing issues, leveraging existing features of accessible Internet routing algorithms.

Recently, MANETs have been developed promptly in the wireless communication arena due to their active features of rapid mobility, fast deployment capability, higher spatial multiplexing rate, and self-organizing nature [9–14]. Despite these fascinating and striking features of MANETs, these networks last with many constraints and challenges that certainly necessitate profound investigation before their widespread implementation and deployment. MANET devices operate with limited CPU processing capabilities, constrained battery life, inadequate bandwidth support, limited storage, etc. In MANETs, the nodes are also free to roam in any random direction and can only interact with their direct neighbor nodes (i.e., the nodes which are in its transmission range). Nevertheless, this random motion can undeniably cause frequent breakage in communication links. This leads to the issue of dynamic network topology changes and hence, ultimately makes forwarding more difficult. Along with this, all the nodes have to communicate via highly error-prone, limited capacity, and exceedingly bandwidth-constrained wireless channels. In MANETs, the wireless channel is highly utilized as the transmissions by each node are broadcast in nature, and the Medium Access Control (MAC) layer algorithm tries to control access to the shared broadcast channel. Additionally, the wireless links have the interference of signals, a higher error-rate, fading, etc. Undoubtedly, such a highly constrained environment has a profound impact on network performance. Furthermore, in MANETs, all the nodes are attached to low-powered battery devices. The energy of the battery needs to be efficiently utilized to the dodge prompt cessation of wireless nodes. The network designers should keep such battery constrained operation issues in mind while designing any forwarding scheme. This consideration is vital, since node shutdown (due to energy exhaustion) ultimately confines the capability of the dead node to forward packets, and thus it reduces the lifetime of the network as well [15–25]. Consequently, in the dynamic environment of MANETs, we cannot implement the communication system via protocols of a conventional network with infrastructure (i.e., cellular network). Rather, we have to separately implement protocol policies that can work on the fly.

In summary, MANETs have unique characteristics that impose a variety of challenges in the design of the routing protocol and complicate Quality of Service (QoS) provision. In the early stages, many routing policies were instructed to continuously update the routing information amongst nodes, since, in such an environment, the network topology changes a lot. Although the suggested schemes were doing their job well to some extent, still, if we talk about the case of dense network environment then all these schemes failed significantly in offering performance. Meanwhile, in such policies, the process of updating the routing table for each and every node increases the network overhead to a great extent and that makes such schemes highly infeasible for large dense network environments [26]. Additional traffic intensity is also generated if intense heterogeneous multimedia data (i.e., video, audio, images, etc.) are transmitted over MANET, while such multimedia data traffic can significantly increase the energy exhaustion of mobile devices. In particular, when an application sends multimedia data, such as video over a MANET, the network traffic intensity level is greater than before. Therefore, a large increase in energy consumption takes place [27], while new challenges are imposed for video streaming over MANETs [28]. This quick growth in heterogeneous traffic causes higher packet losses and excessive network delays, hence, it ultimately increases energy consumption and reduces QoS performance [27]. Indeed, congestion ensues when the total amount of transmitted load over the network exceeds the entire obtainable capacity. Such a condition causes escalated buffer usage over the available network path, leading to higher packet losses during the case of unavailability of network resources.

In MANETs, higher network congestion occurs than that of a wired network due to its unique characteristics [29]: (1) problems related to exposed and hidden terminals; (2) constraints on resources; (3) error-prone shared broadcast channel; (4) node mobility. Congestion control for MANETs requires extra demands (except efficiency of bandwidth usage and fairness in network traffic) because network congestion is not only due to the traffic of the network, but it can also be due to other factors, such as wireless signal noise, interference node, mobility, and contention [30]. Meanwhile, each node in a MANET is a relay for routing packets to other nodes [1]. When the node mobility increases, the Packet Loss Ratio (PLR) also increases, resulting in increased energy consumption during dynamic routing. The intermediate node that becomes the network relay often experiences network traffic overloading. Dynamic routing in the MANET must be energy efficient as this feature resolves the extension of how the network is practically valuable [31]. In MANETs, the routing algorithm and the congestion control scheme must be energy efficient and must reduce packet loss retransmission as much as possible to reduce energy consumption on each node. Energy conservation improves the lifespan of a MANET and ensures that the communication process is effective [32]. In MANETs, the most significant energy consumer is employed for wireless communication rather than the computing tasks from the mobile device microprocessor. Indeed, energy consumption for computation is at least 50% lower than energy consumption for communication [33,34]. As a result, energy consumption can be reduced by saving the transmission (energy) power of nodes. Over the years, researchers have focused on investigating how to reduce energy consumption in MANETs. Most of their studies have considered the energy efficiency of routing and tried to prolong the lifetime of nodes and the network. The majority of these studies [15,35–45] have introduced single-path energy-efficient routing protocols. However, in single-path routing, the nodes in the selected path quickly deplete their batteries. In light of this evidence, we understand that single-path routing schemes are incomplete. Moreover, in single-path routing, some nodes are highly congested, as they transmit most of the network traffic. As a result, single-path routing does not distribute the load among the nodes in a fair and balanced way. This, in turn, can lead to the significant degradation of network performance. The disadvantages of single-path routing protocols have led to intelligent multipath routing algorithms that address the problem of energy consumption at the network layer.

Multipath routing algorithms aim to find novel techniques for power-efficient route setup and reliably, relaying data packets between source–destination pairs in the direction of maximizing the network lifetime. To address the various constraints of MANETs, many power-efficient routing schemes [20] have been developed. Many other studies [46–51] have proposed energy-efficient cross-layer optimization solutions for MANETs. Some of these studies have reconsidered the impact of energy efficiency, but also other performance metrics, such as scalability, fairness, and delay in the presence of energy flow into the network. Moreover, in some cross-layer studies, the Physical (PHY), MAC, and routing protocols are re-designed using a cross-layer design (CLD) to optimize the rate at which the energy is consumed, rather than just minimizing the total energy expenditure.

Motivation and Scope of this Survey

The goal of this survey article is to synthesize the existing power-aware optimization solutions for MANETs from diverse viewpoints and to present a classification of them. This article extends the work done by previous surveys, presenting recent power-aware optimization solutions for MANETs. We present new techniques that do not just consider power-aware routing metrics and energy-efficient routing protocols, but we also consider other power-aware optimization solutions for MANETs. This survey analyzes state-of-the-art power-aware optimization solutions for MANETs. To the best of our knowledge, a comprehensive survey of such solutions for MANETs does not exist and is the goal of this article. This survey article comprises as follows:

- It analyzes key-issues on power-aware optimization solutions for MANETs;
- It surveys the existing power-aware optimization solutions for MANETs;
- It discusses open research areas in MANETs, such as: (1) cross-layer designs; (2) hybrid optimization algorithms for topology management in cluster-based MANETs; (3) design of cooperative MAC protocols; (4) multipath routing based on hybrid modeling; (5) fuzzy-logic support in multicast routing schemes.

The remainder of this article is structured as follows: Section 2 presents previous surveys that summarize research into energy-efficient routing in MANETs and its related power-aware routing metrics;

Section 3 delineates the leading energy-efficiency related issues unsettling numerous routing-based proposals. It analyses all the categories of power-aware optimization solutions for MANETs, such as cross-layer optimization approaches for energy conservation in MANETs; Section 4 reflects upon some lessons that we have learnt to date from this research; The survey article presents design challenges and future research opportunities in Section 5.

2. Related Work

Several studies, as shown in Table 1, have analyzed the existing energy-efficient routing schemes for MANETs. Some surveys have focused only on PHY layer methods for energy-efficient wireless communication. For instance, Feng et al. [52] reviewed only PHY layer techniques for energy-efficient wireless communication, such as orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO), cognitive radio (CR), network coding, cooperative communication, etc. Pantazis et al. [53] surveyed and analyzed energy-efficient routing protocols for Wireless Sensor Networks (WSNs). Ehsan and Hamdaoui [54] discussed the design challenges of routing protocols for Wireless Multimedia Sensor Networks (WMSNs) and classified current techniques with their limitations. Zuo et al. [55] considered diverse routing schemes, investigating the benefits of multi-antenna assisted relay nodes, the number of MAC retransmissions, and the number of hops on the performance energy consumption. Kanellopoulos [26] summarized state-of-the-art solutions on QoS routing and resource reservation mechanisms to provide multimedia communication over MANETs. The author considered the limitations of existing QoS models concerning satisfying QoS in serving multimedia over MANET. Jabbar et al. [20] discussed the challenging factors in MANETs by highlighting issues in power-based routing metrics. They classified existing power-efficient routing algorithms in MANETs into six categories and compared the routing techniques of each category using their merits and limitations. Muchtar et al. [23] exposed the critical view on why the Host-Centric Networking (HCN)-based MANET is not energy-efficient by indicating the incompatibility of the HCN paradigm with the MANET itself. They recommended a new solution for improving energy efficiency in MANETs by shifting from the HCN paradigm to the Information-Centric Networking (ICN) paradigm. Kanellopoulos [56] presented various types of scheduling techniques for MANETs. The author also analyzed load-based queue scheduling techniques and presented various cross-layer schedulers for power control. Most of the presented techniques are related to power-efficient routing. Rahman et al. [57] presented and evaluated energy-based clustering algorithms for cluster-based MANETs. Such as, clustering algorithms electing a node as a Cluster-head (CH), based on its node energy level. A CH performs cluster management and this activity causes too much energy consumption, which affects network performance. Consequently, the energy constraint of a node is a vital parameter for electing a CH because it directly impacts the overall lifetime of the network. Finally, Mendes and Rodrigues [58] presented cross-layer solutions for WSNs.

2.1. Energy-Aware Routing Protocols in MANETs

Even though improvements in battery design have not yet reached that great a level, where a device can be able to operate for a longer period, the majority of the proposed routing protocols have not emphasized energy consumption at all. In MANETs, energy-efficient routing is one of the important problems that must be considered. Keeping this issue in mind, many researchers have suggested very efficient policies. Specifically, in MANETs, energy-aware routing is undeniably the utmost design benchmark, since all the nodes are attached and operated with low-powered battery devices. The shutdown of an intermediate node, due to power failure, not only affects the node's system itself but also its capability of relaying packets on the behalf of others, and hence it ultimately reduces the lifetime of the network [15,59,60]. With the untimely shutdown of a node, the entire network system suffers a burn, since, as soon as a node stops due to power failure, forwarding packets on the route will get completely disconnected. However, the preceding node keeps on unnecessarily re-transmitting the same packets up to a certain threshold, and thus the power of that preceding node is also needlessly wasted. Then, that preceding node knows that the path is disconnected, and it ultimately notifies the source about it. Finally, the source node again performs route discovery, and this process also consumes a significant amount of energy in the network.

Table 1. Previous surveys that summarize research into power-efficient routing in mobile ad hoc networks (MANETs).

Year	Ref.	Focus
2020	[57]	It presents energy-based clustering algorithms. It proposes a cross-layer clustering framework and a hybrid self-organization clustering model that improves QoS in cluster-based MANETs.
2019	[56]	It presents various types of scheduling techniques for MANETs. It analyses load-based queue scheduling and presents cross-layer schedulers for power control. Most of these techniques are related to power-efficient routing.
2018	[23]	It exposes the critical view on why a HCN-based MANET is not energy-efficient by explaining the incompatibility of the HCN paradigm with the MANET itself.
2017	[26]	It presents existing solutions on QoS routing and resource reservation methods to support multimedia communication over MANETs. It considers the limitations of existing QoS models.
2017	[20]	It discusses the challenging factors in MANETs by focusing on power-based routing metrics. It classifies existing power-efficient routing algorithms in MANETs into six categories. It compares the routing schemes in each category, based on their merits and limitations. It also highlights their main features.
2015	[55]	It considers diverse routing schemes investigating the benefits of multi-antenna aided relay nodes, the Frame Error Ratio (FER), the number of MAC retransmissions, and the number of hops on the performance energy consumption.
2013	[53]	It classifies energy-efficient routing protocols in WSNs into four main categories. It surveys and analyses energy-efficient routing protocols for WSNs.
2012	[54]	It presents energy-efficient routing techniques for WMSNs. It discusses the design challenges of routing protocols for WMSNs and classifies current methods with their limitations.
2012	[52]	It reviews only the PHY layer techniques for energy-efficient wireless communication, such as MIMO and OFDM, cognitive radio, network coding, cooperative communication, etc.
2011	[58]	It presents cross-layer solutions for WSNs, including cross-layer energy-efficient routing protocols.

Many authors [61–67] have proposed energy-aware routing schemes for the dynamic environment of MANETs. All these schemes have conveyed a new aspect for the unnecessary consumption of the battery energy of a node. What they have suggested is that the node's battery energy can not only be consumed during its active participation in forwarding and receiving packets (active state) but also when it stays in energy preserving and idle medium (wireless) listening mode (in-active state). As a result, some of the energy-aware routing schemes consider active and in-active energy consumption states. Bearing in mind the active energy consumption state, energy-aware routing schemes reduce energy consumption, while nodes are forwarding and receiving packets. In this direction, researchers have suggested a method that regulates each node's radio (i.e., transmission) power just enough to reach the neighboring node and not more than that. On the other hand, in energy-aware routing schemes that consider the inactive energy consumption state, the researchers have recommended the optional feature of actively adapting the operation mode of radio state (i.e., either to switch the operational mode into active/idle/sleep or simply shut the radio state off). Nevertheless, we cannot simply switch the operational modes blindly; instead, it involves efficient coordination and complex synchronization to guarantee efficient delivery. In conclusion, routing schemes based on the active and in-active energy consumption states focus on minimizing the individual node's energy consumption.

In the next subsection, we analyze power-aware routing that can be used for determining optimum routes in energy-efficient MANETs.

2.2. Power-Aware Routing Metrics

The conventional forwarding (routing) protocols for wireless networks instinctively consider minimum-hop and shortest-delay forwarding as a metric to assess optimal paths. Such protocols are Destination-Sequenced Distance Vector (DSDV) [68], Wireless Routing Protocol [69], Temporally-Ordered Routing Algorithm (TORA) [8], Ad hoc On-Demand Distance Vector Routing (AODV) [70,71], and Dynamic Source Routing (DSR) [72]. While, Dube et al. [73] have suggested the Signal-Stability based Adaptive (SSA) forwarding scheme, which utilizes the steadiness of the distinguishable host, location permanence, and signal strength as forwarding metrics. The SSA scheme suggests that picking the most suitable stable links will lead to strongly connected network paths. Understandably, some of these well-known orthodox metrics have a harsh consequence on network lifetime, since such metrics unintentionally over-utilize the power resources of the nodes (i.e., no consideration of power at all had been done). Singh et al. [61] have effectively shown that none of the abovementioned forwarding metrics (currently deployed in many routing protocols) can achieve the goal of carefully utilizing power resources.

In general, energy-aware forwarding policies can be categorized based on their adjusted route selection procedures (or routing metrics used) [20,36]:

1. Induced power-cost from the transmission.
2. Residual power capacity of the node.
3. Probable node lifetime.
4. Hybrid energy-aware metrics.

Energy-aware forwarding policies often utilize more than one set of energy-allied metrics to estimate and determine the optimum routes, depending on the conditions, briefly defined as:

- *Reducing the Energy Exhaustion per Packet Transmission and Reception*: This metric shows how the overall average power consumption per packet transmission and reception can be reduced. According to [61], under lighter traffic conditions, if we utilize this metric to assess the paths then there is the possibility (in most cases) that the chosen path will be equivalent to paths that get selected by the minimum-hop forwarding metric. So, in such a case, we cannot expect much change in power consumption performance. Nevertheless, under heavy traffic conditions, the path selected via such a metric may be different from the path chosen via the minimum-hop forwarding metric. Subsequently, if a node (or more than one node) on the selected path (i.e., it may or may not be the shortest route) suffers from severe congestion, then per-packet power consumption at each congested node will also differ because there may be a case of higher variations in contention level at each congested node, hence, per-packet power consumption will also get vary. Consequently, this metric may tend to forward packets in highly congested network areas. Nevertheless, taking this metric blindly without examining the individual residual energy of nodes may lead to the problem of unfair energy residual distribution in the network. We conclude that this metric does not assist in increasing network lifetime in any case.

- *Maximizing Period to Network Segregation*: According to [61], the set of critical nodes in the network must be identified. If critical nodes detach from the network for any reason, the entire network will divide into many parts. The paths between such partitions must pass through one such crucial mobile node. The forwarding process has to be modified in such a way that the load is evenly distributed over all such critical nodes via a "load-balancing" scheme. Nevertheless, trouble will arise if multiple network parts are connecting with a single node, as shown in Figure 1—for instance, in the network topology node "0", depicted in Figure 1, is a critical node. If node "0" stops working for any reason, then this entire network will be separated into many small parts. Here, the main idea is to ensure that the rate of power consumption should be similar in all critical nodes if we want to maximize the network lifetime. Nonetheless, the idea of ensuring a similar power drain rate metric amongst critical nodes is a tough task, because such a metric is directly dependent on the packet size. Therefore, we cannot blindly choose an optimal path without having all the information about the size of future arriving data packets. However, if we assume that all the future arriving data packets have the same size, we can ensure an equivalent rate of power consumption amongst such crucial mobile nodes. However, maximizing network segregation time is challenging, especially when we expect high throughput and high performance by reducing end-to-end delay.
- *Minimize High Variance in Mobile Node Battery Energy Level*: The basis of this metric is that all mobile nodes are highly essential in the network and the untimely shut-down of any node is not good for the network's throughput and delay performance. Along with that, while designing any forwarding scheme, we have to take full care that no one mobile node is overloaded more than any of the others [61]. This metric tries to ensure that all the available mobile nodes can live and work for a longer period. Nevertheless, again, the idea of ensuring a similar power drain rate metric amongst nodes is a challenging task, since such a metric is directly dependent on the packet size. Nonetheless, if we assume that all the future inward data packets are of the same size, we can unquestionably guarantee an equivalent rate of power consumption amongst mobile nodes. Although, we cannot make such an infeasible assumption while designing any forwarding strategy.
- *Minimizing Price-Per-Packet (PPP)*: According to [61], if we need to prolong the lifetime of all the nodes, then we need to utilize the PPP metric, other than the power disbursed per packet metrics. The PPP metric is the total price of transmitting a packet along some selected routes. The main advantages of the PPP metric are: (1) it can commendably assist in integrating the battery-related features unswervingly in designing part of the routing scheme; (2) it directly reflects the congestion level along a selected path.

Singh and Raghavendra [74] effectively instigated the Energy Exhaustion per Packet Transmission and Reception and the PPP metric in their proposed scheme, called Power-Aware Multi-Access Protocol with Signalling (PAMAS). Specifically, the authors believe that incorporating the suggested PPP metric in PAMAS directly reflects the optimization in other metrics (i.e., Period to Network Segregation and Battery Energy-level Variance metric, respectively, as well). Furthermore, it is noteworthy that such metrics for forwarding do not need to be utilized constantly. Rather, initially, when the nodes are configuring and have an ample amount of battery power in the network, we can stick with a conventional forwarding scheme (i.e., minimum hop-count). Nevertheless, after a certain time, when battery power starts going down by a certain amount, nodes can switch to these mentioned power-aware metrics.

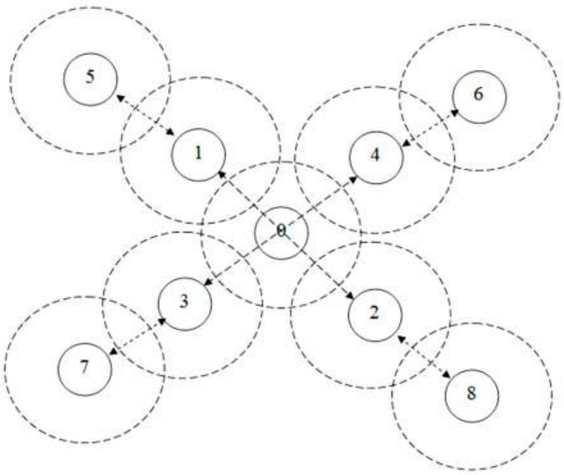

Figure 1. A mobile ad hoc network (MANET) topology illustrating the problem of network segregation.

3. Analysis of Power-Aware Optimization Solutions in MANETs

In this section, we delineate the leading energy-efficiency-related issues unsettling numerous routing-based solutions. Along with this, we introduce the problems related to such energy-efficiency related issues. Furthermore, we also apprehend the way through which research works have been made to resolve all such issues.

Power-efficient approaches for MANETs can be classified into eight categories, according to their basic operation:

1. Approaches based on adaptations of the radio state operational mode.
2. Routing protocols based on adaptive load balancing.
3. Location-based routing protocols.
4. Multicast-based routing protocols.
5. Energy-efficient proactive (link state-based) routing protocols.
6. Energy-efficient reactive (source-initiated-based) routing protocols.
7. Transmission power control-based routing protocols.
8. Cross-layer based routing protocols.

In the following subsections, we describe these categories of power-aware optimization solutions for MANETs.

3.1. Approaches Based on Adaptations of the Radio State Operational Mode

The exchange of packets consumes a significant amount of the power of a node in the network. In a MANET, the transmission from one wireless node to another is potentially overheard by all of its possible neighbors. All of these neighboring nodes consume a significant amount of power, even though such transmission is not related to them. For instance, in the small MANET topology, shown in Figure 2, the transmission from node “1” to node “2” is overheard by node “3” since it is an immediate neighbor of node “1”. Now, node “3” consumes a significant amount of power, even though such transmission is not directed to it. A solution to this problem in node “3” to turn its radio state shut off (sleep-mode) during the entire duration of such transmission to conserve battery energy. This idea of such radio state adaptation was adopted in the PAMAS routing protocol [74].

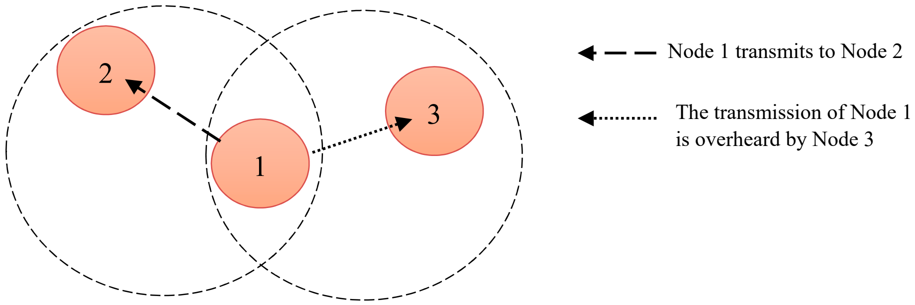

Figure 2. Simple MANET topology.

The idea of such radio state adaptation (termed "sleep mode" or "power-save mode") is highly suitable in large dense MANETs. Based on this idea, topology control routing protocols can reduce the energy consumption of mobile nodes [75]. Inactive nodes are placed in sleep (very low energy consumption) mode for a maximum duration (i.e., they do not accept packets as they automatically become slave nodes). On behalf of the slave nodes, qualified master nodes communicate with other nodes to permit slave nodes to stay in sleep mode and to save more energy. A mobile node is put in sleep mode via a wireless scheduler algorithm that takes into account the need to prolong the battery life of the mobile device. To conserve energy, the node transmits/receives in contiguous time slots and then goes into a sleep mode for an extended period rather than to rapidly switch among transmit, receive, and sleep modes. This preference is balanced against the need to maintain the QoS requirements of the current application. For instance, the sleep and awake scheduler [76] activates the channel during the data transmission only. Based on efficient scheduling, inactive nodes can be placed in sleep mode for a definite period through the use of Geographic Adaptive Fidelity (GAF) [77] and Spanning Tree (SPAN) [78] techniques. It is noteworthy that any intermediate node in an energy-inefficient routing path cannot be set in sleep mode, because the goal is to improve network capacity whilst totally reducing energy consumption [79].

The "sleep mode" control is only performed in the MAC layer. In the preceding literature, especially for the case of WSNs, the low-duty cycle, associated with contention-based MAC design, has been logically classified into two rudimentary categories: asynchronous and synchronous. Synchronous schemes synchronize the awake and sleeping slots of the neighboring nodes. On the other hand, asynchronous schemes do not need to make any synchronization between nodes and let the nodes to operate autonomously.

Ye et al. [80] and Ye et al. [81] have recognized the major reasons for energy consumption in a dynamic environment. The reasons can be transmission overhearing, routing control packets transmission overhead, collisions, and idle listening. Based on identifying such possible sources of inefficiencies, Ye et al. [80] presented a synchronous MAC design, called the Sensor-MAC (S-MAC) protocol. The main motivation of S-MAC is to reduce such unnecessary energy consumption. The scheme ideally relies on the basic problem of unnecessary power consumption due to overhearing, originally inspired by the PAMAS protocol. The S-MAC protocol, in contrast PAMAS, does not utilize any out-of-channel signaling. Along with this, S-MAC addresses the problem of idle listening power consumption as well, in contrast to PAMAS. S-MAC significantly reduces the problem of idle listening overhead by actively utilizing a periodic awakening and sleeping scheme. Nevertheless, S-MAC experiences certain degradation in both latency and fairness (per-hop) performance. Indeed, S-MAC experiences reduced throughput performance, since only the active slot of the frame is utilized for actual data communication. Meanwhile, latency, in S-MAC, escalates because data generation (from upper-layer) events may happen during the sleeping slot of the frame. Subsequently, these generated messages during the sleeping slot are unnecessarily queued and they have to wait for the next active slot of the frame. Van Dam and Langendoen [82] improved the performance of the S-MAC design and suggested another synchronous MAC protocol, called Timeout-MAC (T-MAC). T-MAC improves

S-MAC by making adaptations in the active and sleep slots of the frame. T-MAC radically abridges the active slot of the frame when the channel is idle. For a shorter instance, T-MAC senses the channel and, if no data are received during this shorter slot, the radio state turns awake to sleep mode. Otherwise, the node's radio state remains active (awake) in anticipation that either the active slot ends or no additional data are received. Additionally, T-MAC, under variable or heterogeneous load, suggested improved performance in terms of power consumption. However, as S-MAC, T-MAC experiences certain degradation in both throughput and latency performance. Similarly, RMAC [83] and DW-MAC [84] contention-based synchronous low-duty cycle-based schemes were presented in the past. These schemes significantly assist in reducing idle listening power consumptions. Still, such schemes typically require an additive synchronization, which further introduces complexity and overhead in the system. Afterwards, if we talk about contention-based asynchronous low-duty cycle schemes, such as WiseMAC [85], B-MAC [86], and X-MAC [87], these schemes incorporate the concept of low energy consumption listening. In particular, such schemes let the sender transmit a preamble, whose size is sufficiently large enough as long as the sleep instance of a receiver is activated before actual transmission. Afterwards, when the receiver turns from the sleep to awake state and subsequently senses the preamble, it stays in the awake state to accept the data. The asynchronous low-duty cycle schemes effectively assist in eradicating the problem of the complex synchronization overhead required in the synchronous low-duty cycle-based schemes and also suggested improved performance in terms of lower power consumption. Nevertheless, Sun et al. [88] have extensively discussed that asynchronous low-duty cycle schemes only achieve good performance in lighter traffic conditions. There is a serious decline in packet delivery, energy efficiency, and latency performance of such a policy as soon as traffic intensity increases. Here, Sun et al. [88] investigated the issue of high channel capturing period, due to longer preamble transmission, which may defer other nodes to transmit, since they have to wait for a longer time until the channel is freed, and ultimately, some of those nodes experienced higher delay than normal. Hence, considering such issues, the authors [88] introduced Receiver-initiated MAC (RI-MAC), that aims to reduce the channel capturing period in variable load conditions. Recently, a reinforcement learning-based MAC design has been suggested by Savaglio et al. [89], called Quality-learning MAC (QL-MAC). The main objective of QL-MAC is to provide a self-adjustable feature to a conventional MAC design. Consequently, the conventional MAC design is able to self-adapt against various dynamic changes in the network (e.g., topological changes).

In conventional networks, such as IEEE 802.11, better channel or bandwidth utilization is a prime concern. However, switching and making certain adaptations in the radio state (i.e., energy saver mode) is certainly an optional feature in IEEE 802.11 and generally happens in the WSN scenario, where nodes have been idle for most of the time. In the WSN environment, achieving maximum possible bandwidth utilization is not as important as in other networks. The design of a MAC protocol that is suitable for MANETs requires smart amendments because various performance parameters in the MANET are acute. These performance parameters are the chances of dynamic changes in link characteristics (i.e., bandwidth, delay, channel error, loss rate, and level of interference), mobility induced topology changes, bursty and highly-loaded traffic, channel error and contention induced losses. We will not only have to think at MAC level design, but we will have to contemplate through every level of the traditional layered structure and bring appropriate changes.

A cross-layer-based routing protocol (described extensively in Section 3.8) may trigger sleep mode by sending a command to the MAC layer. The sleep mode mechanism is easy to deploy and can be adapted into well-established routing protocols, such as AODV. For example, the Efficient Power Aware Ad hoc On-Demand Distance Vector (EPAAODV) protocol [90] is a modification of AODV, that uses the "power-save" idea to improve the energy efficiency of AODV to extend network lifespan. Other power-save approaches [91,92] are based on the minimum energy threshold (limit) to decide whether a node should remain in active mode or to be in sleep mode to save energy. Remya et al. [93] designed the Energy-efficient

Multipath Routing protocol using Adjustable Sleeping window (EMRAS) by employing two algorithms: (1) Power and Delay Aware Multipath Routing Protocol (PDMRP) and (2) Slow start Exponential and Liner Algorithm (STELA), using a cross-layer design. The STELA algorithm improves the energy efficiency of the network by adjusting the sleeping window if there are no network activities. If there is any network activity, PDMRP selects the path that is energy efficient and that is the shortest. The EMRAS protocol increases the overall residual energy and reduces the total energy consumption without degrading the QoS parameters.

In summary, a drawback of the "power-save" method is that it increases the end-to-end delay. As nodes in sleep mode cannot transmit and receive any packets, packet retransmission is required. Such retransmission of packets from the source node leads to increased energy consumption. The increased waiting period for the route request or reply for the new routing path provokes the whole situation if the intermediate node in the routing path is in sleep mode. Another drawback is that, in any energy-inefficient routing path, the intermediate nodes cannot be set in sleep mode, as the goal is to improve network capacity and totally reduce energy consumption [79]. Additionally, some low-duty cycle energy-aware MAC designs (S-MAC, T-MAC, X-MAC, R-MAC, DW-MAC, B-MAC, RI-MAC) are highly limited to some applications, where the data generation rate is not very bursty, and mostly these schemes have been evaluated over WSN environment where the nodes are mostly in a sleeping state. Another category of power-aware optimization solutions is routing protocols, based on adaptive load balancing, which consider power consumption.

3.2. Routing Protocols Based on Adaptive Load Balancing

For selecting the optimum path, an energy-efficient load distribution-based routing protocol well utilizes energy-rich nodes that are under-utilized in the network and distributes the load amongst them accordingly. Such protocols mainly concentrate on efficiently balancing the load amongst under-utilized higher-energy-rich nodes by competently selecting the path. Nevertheless, in such schemes, the path chosen may not necessarily be the shortest one. Nonetheless, the main aim of such schemes is not to estimate the minimum power consumption path, but such schemes effectively assist in preventing certain low energy nodes from being over-utilized and, hence help in improving the lifetime of the network.

Some of the energy-aware techniques [61,62,94–96] that we have discussed so far have a major disadvantage that they have presumed a stationary network structure where nodes are not moving at all. Although this hypothesis simplifies their analyses, the legitimacy of their suggested conclusions is practically limited. It is difficult to say which policies or which class policies will be effective in all kinds of scenarios of MANETs.

Many researchers implemented adaptive load balancing approaches to reduce the problems of minimum power control communication methods. For example, Woo et al. [97] introduced an energy-aware load balancing technique called Local Energy-Aware Routing (LEAR). The LEAR scheme extends the route-discovery basic structure of DSR. In LEAR, every node decides whether to take part in routing or not. Whenever a node receives a Route Request (RREQ) packet, instead of directly processing it, the node firstly checks whether it has a certain amount of power or not. If it has, then the node takes part in the route-discovery process, otherwise, it will not take part in route-discovery. Consequently, the chosen path will automatically contain energy-rich intermediate nodes. This will significantly reduce the chances of route disconnections in the network and will also result in a significant drop in power loss and, hence, it results in improved network lifetime. However, Kim et al. [98] extensively discussed that considering only the residual power metric of a node does not give assurance that a high energy-rich node along a path will successfully sustain its battery power during the lifetime of intense traffic conditions. That means that, if a node is highly proficient enough in terms of residual power metric, it could accept all the incoming RREQ packets and, hence, much traffic load will have passed through it. It means that the energy consumption drain rate of the nodes, which are essentially participating in forwarding, will likely be very high, which results in a severe drop in their battery power lifetime. Consequently, there is the danger of the premature death of such high energy-rich nodes. Typically, considering such an issue, Kim et al. [98] suggested a drain rate metric-based Minimum Drain Rate (MDR) scheme. In the MDR scheme, every node estimates the average energy dissipation drain rate per unit second. The MDR scheme regularly monitors such drain rate caused by the reception, overhearing, and transmission events. The MDR scheme explicitly calculates a cost function (i.e., the ratio of residual battery power and drain rate), which suggests the lifetime of a path. Similarly, in succeeding years, many energy-aware schemes [99–103] have been suggested, considering an extension of the DSR basic route-discovery structure. Since most of these energy-aware metrics have been applied with DSR, some of the researchers have decided to evaluate these metrics via a proactive routing scheme, called the Optimized Link State Routing (OLSR) [104] protocol. Consequently, many energy-aware schemes [105–108] have been suggested in the past, considering an extension of OLSR basic structure as well. De Rango et al. [59] extensively evaluated the performance of OLSR and DSR protocols in terms of power consumption. The authors extensively assessed these routing protocols in terms of parameters, such as mobility, protocols' schemes (i.e., link-failure announcement and reply via route-cache), overhearing effects, and idle power consumption. The authors determined that, in a dense network environment, the issue of overhearing severely affects the lifetime of the network, no matter the underlying network routing protocol. The authors also suggested that the performance of OLSR in terms of power consumption worsens as the network density and size increase. Tarique et al. [109] brought another energy-aware policy—Energy Saving DSR (ESDSR)—which also extends DSR's basic route-discovery structure. ESDSR incorporates the advantages of the minimum power control communication and adaptive load-balancing scheme together. Chang et al. [110] introduced the Color-theory-based Energy-Efficient Routing (CEER) scheme, which shows more scalability than ESDSR on increasing network size. Additionally, the CEER scheme is capable of preserving more power than ESDSR in a dense network environment because it effectively utilizes the concept of optimal CH selections and effective data aggregation. Numerous energy-efficient resource allocation policies [111–114] have been suggested to maximize efficiency in terms of energy usability for multiple fading wireless channels. Classically, due to the severe insufficiency of the spectrum, the network designers should consider spectrum efficiency as an important design feature in a highly dynamic MANET environment, typically for high rate multimedia communication systems. Unfortunately, spectrum efficiency and energy efficiency are two oppositely natured features, and they both mostly conflict with each other; hence, how to balance them is a hot research topic. Zhou et al. [115] comprehensively investigated the characteristics of the spectrum and energy efficiency required for video-streaming in MANETs, respectively. Subsequently, the authors came up with a novel technique, called Energy-Spectrum-Aware Scheduling (ESAS), which enhances video quality and decreases power consumption as well.

According to [20,23,116–119], there are two subcategories of load-balancing approaches:

- Concurrent path forwarding/routing/transmissions-based schemes: These schemes utilize multiple available paths at once, regarding the least energy consuming path. Examples of such schemes are LEAR, MDR, ELGR, Adaptive-sleep + Adaptive MAC-Retx [22], Disjointed Multi-Path routing_Extended OLSR (DMP_EOLSR) [120].
- Alternate path forwarding/routing/transmissions-based schemes: Such schemes utilize alternate path for transmissions. Examples of schemes that utilize either single path or alternate paths for transmissions are the prediction and smart-prediction energy-aware protocol [42], Power-aware Heterogeneous AODV (PHAODV) [45,121], Energy-level based routing protocol (ELBRP) [122], and Multi-path OLSR (MP-OLSR) [123]).

According to [13,124], there can be three subcategories of multipath routing policies:

- The node disjointed path policy, which does not share the identical links or intermediate nodes between each available network paths.
- The link non-disjointed path policy, in which the multiple available network paths can share identical links or intermediate nodes.
- The link disjointed path policy, which can have an identical relaying node, but it does not allow for a shared link between each path. Mueller et al. [124] suggested that disjointed based routing schemes can have significant advantages over non-disjointed-based routing policies. Nevertheless, it is not always possible to fully estimate disjoint paths in MANETs, especially in high mobility scenarios [13].

Chettibi and Benmohamed [125] developed a power-aware and multipath on-demand source routing scheme, called Multipath and Energy-Aware DSR (MEA-DSR), which effectively utilizes the residual battery power of nodes and path diversity. The main goal of MEA-DSR is to decrease the number of dead node-induced path disconnections in the network. Through performance evaluation, the authors demonstrated that the overall power consumption in the MEA-DSR scheme is significantly lesser than that of DSR, especially in higher mobility scenarios. Nevertheless, the routing overhead and PDR performance of MEA-DSR is not up to the mark in scenarios with lower mobility. This occurs since MEA-DSR dismisses the idea of DSR packet salvaging, hence, it certainly upsurges the packet loss probability compared to the original DSR. Meanwhile, MEA-DSR allows for the propagation of duplicate RREQs (by relaying nodes), which undoubtedly assist in increasing routing overhead. Afterwards, Guodong et al. [126] introduced Energy-efficiency and Load-balanced Geographic Routing (ELGR), which associates both load balancing and energy efficiency metrics to make forwarding conclusions. The ELGR scheme effectively assesses the link's quality for the packet reception level to increase the power efficiency of the network. Moreover, the ELGR protocol also suggests the method of identifying the network load (local) by adaptive learning policy to improve the load balancing in the network. Through experimental results, the authors exhibited that the ELGR scheme effectively improves the PDR performance than other geographical forwarding algorithms (i.e., DREAM [127], GPSR [128], GEAR [129]). However, high complexity in estimating the forwarding and reception rate parameters is the main drawback of this scheme. Moreover, the ELGR scheme blindly assumes that each node knows its location information, which is not fair to assume in such a constantly changing MANET environment. Balachandra et al. [130] introduced the Multi-constrained and Multi-path QoS-Aware Routing Protocol (MMQARP) which estimates multiple paths by considering path link delay, reliability, and energy constraint as QoS parameters. Indeed, MMQARP, with the help of these QoS-based parameters, estimates multiple node disjointed paths. Subsequently, the scheme heavily relies on the overhead of maintaining proper management to calculate the geographical information and average delay to estimate path reliability. Consequently, MMQARP suffers from the problem of high routing overhead in the network. Additionally, MMQARP is not able to offer good QoS demands to the user in the case of lower mobility scenarios.

In summary, the adaptive load-balancing schemes do not care whether the chosen path is smaller or larger. It depends on the availability of intermediate nodes that have a sufficient power level. Hence, such schemes will undoubtedly influence the overall end-to-end delay performance of the network. Moreover, the idea of dynamically utilizing multiple available paths for load-balancing does not always guarantee that the selected paths are optimized (paths) in terms of minimum energy consumption. That is why, instead of being completely dependent on such load-balancing policies, we also have to include other policies in the study so that we can design a better routing policy which is good in every way.

3.3. Location-Based Routing Protocols

A location-based routing protocol uses the geographic location of each node to select the best routing path, while the routing decision is based on the location of the destination node that is obtained through location services [131]. For the period of the data routing process, a Global Positioning System (GPS) acquires the location information used as the network address. Location-based routing assumes that each node is a GPS-enabled mobile device, but this is not always true. Location-based routing can achieve high scalability in large MANETs but encounters numerous challenges, such as inaccurate positioning, local optimum problems, optimum forwarder selection, and broadcasting overheads. Additionally, location-based routing is difficult when holes exist in the network topology, and nodes are roaming or are often disconnected to preserve energy. These issues can be addressed by using the terminode routing protocol [132]. Terminode routing combines location-based routing (i.e., terminode remote routing) and link state-routing (i.e., terminode local routing). Terminode remote routing is applied to a faraway destination node, while terminode local routing is applied to a local destination (i.e., destination is close).

The Greedy Perimeter Stateless Routing (GPSR) protocol [128] and the Location Aided Routing (LAR) protocol [133] are two common location-based routing protocols for MANETs. The problem of finding energy-efficient routes, based on geographical information, has been addressed in many power-aware routing protocols. These protocols are based only on the local information and the reduced routing overhead to find the best route. As each node in a MANET keeps only local information, a power-aware routing protocol of this category does not exploit global information, such as the generation rate of data.

An interesting energy-efficient location routing protocol is the Localized Energy-Aware Restricted Neighborhood (LEARN) [134]. To guarantee the high-power efficiency of a route, the node selects the neighbor node (within a restricted neighborhood) as the next-hop node, having the largest energy mileage (i.e., the distance traveled per unit of energy consumed). The LEARN algorithm performs as a greedy routing algorithm when such a neighbor node (inside the restricted neighborhood) cannot be found. The total energy consumed by the established path (from the source to the destination) constitutes a constant factor of the optimal energy consumption. LEARN has a similar performance in terms of throughput and latency, compared to a typical location-based routing protocol. LEARN performs better in random networks in terms of energy consumption because it only focuses on the energy consumption of the path and does not take into account other decisive factors for selecting the best neighbors. Such factors could increase the maximum throughput per unit of energy consumption by the network. For example, such a factor could be to select a neighbor node that maximizes the bandwidth of links. The main drawback of LEARN is that it selects a long routing path (having more hops), since it frequently uses links that are shorter than those used in greedy routing. This is probably due to the fact that, a long routing path affects the average end-to-end delay. Another scheme is the Location-aided Energy-Efficient Routing (LEER) algorithm [135]. Every node in LEER has a table that stores the node location information of the entire network during the route discovery phase. From this table, the source node can achieve its destination's location. In LEER, intermediate nodes transmit packets to a destination with fewer route discovery messages. This is obtained from the existence of a GPS and a suitable packet block that contains: (1) the message-ID; (2) a source location (X,Y); (3) a destination location (X,Y); (4) the length of the entire packet; (5) the DATA of the packet. If a node leaves the network or if a link failure occurs, the route maintenance phase is performed using a cache to set up new routes. In LEER, it was proven [135] that the sum of the energy transmitted over multiple-hops (routing) is less than the transmission energy consumed for a single hop (routing).

Finally, the Zone-based routing with a parallel Collision-Guided broadcasting protocol (ZCG) [136] employs a parallel and distributed broadcasting method to reduce redundant broadcasting and accelerate the path discovery process. This broadcasting technique guarantees low node energy expenditure and preserves a high reachability ratio. In ZCG, a one-hop clustering algorithm is used for splitting the network into zones guided by powerful Cluster-heads (zone leaders). Zone leaders have high battery power and are normally static (they have zero/low mobility). The broadcasting technique used in ZCG reduces redundant broadcasting by the use of the zone-to-live (ZTL) technique. The ZTL technique decides the number of zones a broadcast needs to propagate from end-to-end before it is discarded by member nodes. The main drawbacks of ZCG are the following:

- The cluster-heads (CHs) can probably perform selfish behavior. Therefore, there is a need to increase fairness among nodes to protect zone members from such selfish CHs.
- ZCG generates higher routing overheads compared with other protocols. The main reason is that inactive member nodes change their location/status frequently.
- The clustering procedure of ZCG and the zone selection mechanism may limit the scalability of ZCG in a highly dynamic MANET.

Vehicular Ad hoc Networks (VANETs) and Flying Ad hoc Networks (FANETs) are subclasses of MANETs. Recently, Srivastava et al. [137] presented various location routing protocols which are suitable for VANETs, while Bujari et al. [138] conducted an interesting performance analysis of position-based packet routing algorithms for FANETs.

Hereafter, we discuss multicast-based routing protocols which additionally consider the energy consumption issue. This category of power-aware optimization solutions is specifically designed for group-oriented applications.

3.4. Multicast-Based Routing Approaches

Group-oriented applications use multicast flows in which the delivery of real-time multimedia content must fulfill particular QoS requirements. Strict QoS constraints, along with energy conservation, must be satisfied by considering the QoS profile of the current application. For example, Figure 3 depicts the multi-constraint QoS profile of an application that emphasizes reliability, throughput, and energy efficiency.

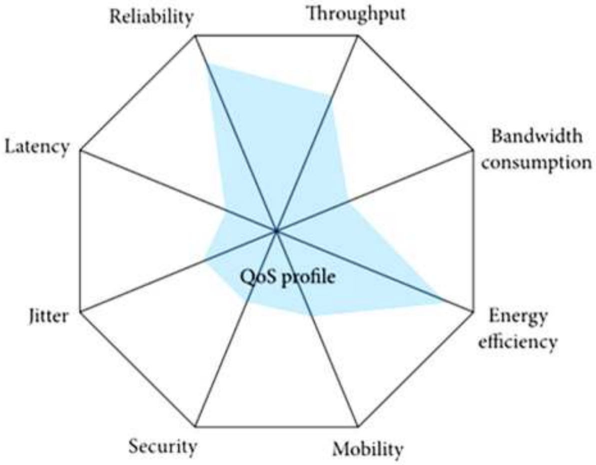

Figure 3. Quality of service (QoS) parameters in MANETs [139].

A group-oriented application, such as multicasting video over a MANET, requires mainly inter-destination multimedia synchronization, reliable delivery, and a multicast routing mechanism to route one-to-many multicast data transmissions under time-critical conditions. From another viewpoint, group communication requires the dynamic construction of resourceful and reliable multicast routes in an environment with high node mobility and dissimilar path properties.

Multicast routing mechanisms in MANETs [140] consider different performance criteria, such as power-efficient route establishment, PDR, network lifetime, quicker and faster proactive route recovery, reliability, QoS based on bandwidth, delays, jitters, and security. Such routing mechanisms can be categorized into different topological routing groups, such as mesh, tree, zone, and hybrid [140]. In multicasting, in every session there is only one sender and many receivers, while a multicast tree is used. In a multicast tree, a root node also suffers from greater energy depletion. Therefore, it can shut down earlier than other nodes as it is responsible for performing more tasks than other nodes. For the period of route discovery, multiple paths are discovered for each of the multicast destinations. Among them, an energy-efficient multicast routing protocol (combining power-awareness with the multicast capability) must select only one path, depending upon its lifetime. Priority can be given to the paths that will survive up to the completion of the present session of packet transfer from the particular source to the destination node. From another viewpoint, a power-efficient multicast routing protocol must also address the mobility of the nodes by supporting multicast membership dynamics (joining and leaving), since the multicast tree is no longer static [141].

The Lifetime-aware Multicast Tree (LMT) [142] routing algorithm discovers routes that minimize the residual energy variance of nodes. Thus, LMT maximizes the lifetime of the source-based multicast tree network. Still, the LMT algorithm assumes that the energy required for packet transmission is comparable to the source–destination distance. In this sense, LMT is theoretically unfair to the bottleneck node. The tLMT algorithm calculates the least expensive path from the set of unconnected multicast receivers to the partially constructed tree. To estimate the cost of a path between the source and each receiver, LMT examines two metrics in the multicast tree:

- The transmit power level, that helps in selecting a path having the minimum total power consumption;
- The remaining battery capacity which helps in balancing energy consumption over all nodes in the network.

Through simulation experiments, the authors [142] evaluated the performance of LMT and demonstrated its effectiveness over a variety of simulated scenarios. Regardless of the size of the multicast group, LMT did better than several other multicast routing schemes in terms of the residual battery energy, the network lifetime, PDR, and the energy consumed per delivered packet. However, LMT increases the number of flooding procedures. In particular, if the number of receivers in the multicast group increases, the number of flooding procedures increases too.

The Predictive Energy-efficient Multicast Algorithm (PEMA) [143] was designed for large-scale MANETs. PEMA uses network statistical parameters to address scalability and overhead issues. PEMA does not depend on information about the route or the network topology. The size of the multicast group determines how fast the PEMA algorithm is running, and thus PEMA is scalable for dense MANETs. The following three parameters are required to select the optimum routing path based on the predicted path energy values:

- The location of group members;
- The average node density in the network;
- The individual unicast routes from the source node to the group members.

PEMA can exactly predict the communication energy consumption by defining two bounds (upper and lower) on energy consumption. After that, the predicted energy values become weighted averages of these two bounds. Using these predicted energy values, PEMA decides how to efficiently send packets to the destination (group) members. PEMA improves energy conservation compared to other related algorithms. However, the energy model used in PEMA does not take into account the energy consumed by retransmissions, due to the MANET dynamic conditions (e.g., interference and packet collision). This information was neglected in the performance analysis of PEMA.

In MANETs, the quality of group communication depends on various QoS parameters, such as path loss, link life, mobility, channel fading, signal quality, the transmission and reception energy of nodes, and battery backup. In general, the problem of QoS multicast routing with multiple QoS constraints is NP-complete [144]. To resolve this problem, Yen et al. [145] proposed an energy-efficient genetic algorithm mechanism. Particularly, they deployed a source-tree-based routing algorithm and constructed the shortest-path multicast tree to minimize the delay time. For this reason, a small population size was used in the genetic algorithm. In the route computation, only a few nodes were involved. The genetic sequence and topology encoding, which calculate the residual battery energy of all nodes in the multicast tree, were improved significantly. As a result, the lifetime of mobile nodes was prolonged. Extensive simulation results showed that their method is a competent and robust algorithm used for multicast route selection.

An energy-efficient and delay-constrained genetic algorithm for MANETs was proposed in [146]. For the period of route selection, the genetic algorithm examines two criteria: (1) the bounded end-to-end delay; (2) the minimum energy cost of the multicast tree. The second criterion is examined to reduce the total energy consumption of the multicast tree. This source-based genetic algorithm performs crossover and mutation processes on probable trees. This facilitates the coding operation and rejects the coding/decoding process. A heuristic mutation method can reduce the entire energy consumption of a multicast tree and, as a result, extend the battery lifetime of nodes. The performance of the genetic algorithm was proven through simulation experiments. The authors [146] demonstrated its efficiency in terms of success ratio, convergence performance, and running time, compared to the least delay multicast tree algorithm. A drawback of the suggested algorithm is that it does not examine shared multicasting trees and it focuses completely on source-based routing trees. Varaprasad [147] suggested an energy-aware multicast algorithm that enhances the network lifetime using a tradeoff. This tradeoff is based on minimizing energy consumption and load. It is also achieved by discovering a multicast that is inclined to minimize the variation of residual battery energy across all nodes. Particularly, if a source node wants to send multicast packets, it selects a node with greater residual battery energy. If all middle nodes have the same residual battery energy, it selects a node with the larger relay capacity. The algorithm takes into account two metrics: (1) the capacity of the residual battery; (2) the relay capacity of the node to multicast packets from the source to the destination nodes. Further, the proposed algorithm forwards data packets through three tables: (1) the neighboring-node table; (2) the routing table; (3) the group table that includes information for all the destination nodes. The author claims that the algorithm can select more reliable paths and achieve the best results in terms of node lifetime, network lifetime, and throughput, compared to previous multicast algorithms. However, the main disadvantages of this algorithm are the following:

- The algorithm is inclined to produce extra control traffic (although the same happens in any power-aware multicast protocol).
- It ignores an important practical issue—it does not examine packet loss in the network.

The Residual-Energy-based Reliable Multicast Routing (RERMR) protocol [148] achieves a longer network lifetime, improved path reliability, and forwarding rate. In RERMR, an energy model observes the residual energy of nodes used for selecting paths with nodes with a high energy level to maximize the network lifetime. RERMR selects the most reliable path for forwarding data, and thus it improves data delivery. In RERMR, a network model is also used to estimate the reliability of a path. It can be said that RERMR achieves a balance between data forwarding and energy reserves. RERMR selects a higher-quality path with minimal packet loss and minimal energy consumption, while it reduces the number of route request packets and retransmissions. In a high-mobility environment, RERMR outperforms similar schemes in terms of network stability rate, packet reliability rate, end-to-end delay, and communication overhead. However, RERMR is based on assumptions that are inappropriate in practice. Such assumptions are prior knowledge of the nodes' directions of motion, the location of the center of a trustable loop, and the constant rate of data delivery, irrespective of the transmission power.

The demand for an optimal path amongst MANET nodes has attracted the use of Swarm Intelligence (SI)-based techniques, such as Particle Swarm Optimization (PSO) and Ant-Colony Optimization (ACO). SI-based techniques can solve many routing problems because routing in MANETs must be implemented by considering node mobility. Robinson et al. [149] introduced an interesting SI-based scheme for multipath routing. It is called particle swarm optimization-based bandwidth and link availability prediction algorithm for multipath routing. Their scheme is based on local rerouting and ensures forwarding continuity with compound link failures. The authors used particle swarm optimization based on available bandwidth and link quality. To provide the multipath routing in MANET, their scheme is based on the mobility prediction algorithm. In the prediction phase, the available bandwidth, link quality, and mobility parameters are used to select the node based on their fuzzy logic. The selected node broadcasts information among all the nodes and the details are verified before transmission. In the case of a link failure, the nodes are stored into a blacklisted link. Furthermore, the routes are diverted and sent back again to find a good link as a forwarder or intermediate node. The proposed scheme can achieve a significant improvement in PDR, path optimality, and end-to-end delay.

The Predictive Energy-Efficient and Reliable Multicast Routing (PEERMR) protocol [150] uses a PSO algorithm to construct a reliable, energy-efficient multicast tree. The fitness function of the PSO algorithm takes into account various parameters to extend the node lifetime and ensure the stability of the path among the source and the destination. These parameters are path delay, expected path energy, and path stability. In PSO, each node moves to random destinations in the search space and has a randomized speed. The best global and individual positions are set by the fitness value. The PSO algorithm entails three basic steps: (1) calculation of the fitness value of each node; (2) renewing of positions and individual and global fitness values; (3) renewing of the velocity and position of every particle. The authors [150] declare that PEERMR is more energy-efficient and reliable than the algorithm proposed in [151], but it is noteworthy that the root nodes in PEERMR are overloaded.

Sinwar et al. [152] introduced the Ant-Colony Optimization Protocol (ACOP), that provides optimized PDR, throughput with low power consumption, and reduced packet delay. Moreover, they performed a comparative study of ACOP with various existing routing protocols (DSDV, AODV, and AOMDV) using the Random Waypoint Mobility Model. The purpose of using this mobility model was to generate different scenarios for the same purpose. The analysis of these protocols was done by implementing irregularities in the scenario using Network Simulator (NS2). Various performance metrics, including packet delivery fraction, throughput, and end-to-end delay, were used for validating the comparative study. Experimental simulation results indicated that the performance of the ACOP protocol was better than the other routing protocols.

The Energy-Efficient Lifetime Aware Multicast (EELAM) route selection strategy [153] is a multicast route discovery scheme for MANETs that was developed using an adaptive genetic algorithm. EELAM functions based on tree topology and adapts an evolutionary computation strategy (a genetic algorithm). This genetic algorithm plays a vital role in terms of selecting optimal middle nodes with maximal residual energy and minimal energy usage. The proposed adaptive genetic algorithm formulated the fitness function that aims to improve the energy consumption ratio, the residual battery life, and the multicasting range. Simulation results showed that EELAM is the best route discovery approach in its category because the process and the methods adopted are contemporary. Furthermore, the adaptive algorithm used in EELAM is different from conventional genetic algorithms. Finally, the Weight-based Energy-efficient Multicasting (WEEM) scheme [154] selects the path with the highest lifetime (weight) as optimal. If more than one path is expected to remain alive till the multicast session is over or none of the available path options have a chance to live till the end of the multicast session, weight is assigned to the paths by the destination. Three parts contribute to the calculation of Weight: (1) the residual energy; (2) the multicast packet transmission capability of nodes in a path; (3) the number of multicast destinations residing in that path. If more than one path has the same weight, then priority is given to the one path suffering less delay. Extensive simulation results demonstrated that WEEM produces more packet delivery ratio and alive node ratio at much less control message cost than other competing multicast protocols.

In summary, existing power-aware multicast algorithms often produce additional control traffic. Moreover, they do not consider any packet loss, or the energy consumed by retransmissions because of the dynamic conditions (e.g., packet collision and interference) [20].

3.5. Proactive (Link-State-Based) Routing Protocols

In proactive routing, each node is exchanging information about the current network topology with other nodes to update its own routing table. Thus, proactive routing can immediately find the shortest path as the route discovery process has no delays. Based on the algorithm used, proactive routing can be categorized into groups: (1) link-state-based routing protocols, such as OLSR; (2) routing schemes, which are based on the distance–vector algorithm, such as DSDV.

In this subsection, we focus on the first group and analyze OLSR-based energy-efficient routing approaches, since the OLSR is the leading proactive (hop-by-hop) routing protocol for MANETs. In OLSR, each node distributes topology control (TC) messages all over the network. This information is used by individual nodes to compute routes to all destinations. To reduce TC message overheads (traffic), the OLSR routing algorithm selects a small set of nodes (called Multi-Point Relays (MPRs)) among one-hop and two-hop neighbor sets of host, while the MPR selection algorithm is based on topological information. MPRs are responsible for forwarding link-state information and improving flooding in the network. To further reduce the number of TC messages, Boushaba et al. [155] suggested two policies to improve the MPR selection algorithm. Both policies are employed to select MPR by using a simple modification in the OLSR protocol without extra signaling overheads. The improved OLSR variants outperform simple OLSR and cooperative OLSR in terms of routing cost and the number of TC messages.

Many OLSR-based algorithms have tried to optimize the selection of MPR sets for efficiently reducing the consumption of network topology control, the delivery rate of data packets, and the end-to-end delay of packet transmission between nodes. In their attempt to make OLSR more energy-aware, Kunz and Alhalimi [42] introduced an energy-efficient routing scheme that is based on accurate state information about the available energy levels of nodes. This routing scheme exploits the nodes' energy levels as QoS metrics for route selection. To increase the accuracy of the energy levels at all traffic rates, the authors proposed two new techniques: (1) Prediction; (2) Smart Prediction. In the first technique, the energy level of a node is regulated based on its previous consumption rate. The second technique is an improved version of the first technique, where a node's energy level is adjusted based on the average of all known consumption rates for other nodes if no consumption rate can be determined for the node. However, both techniques have similar overheads as those in the simple OLSR since they use the same MPR selection mechanism. Moreover, both techniques do not take into account load balancing or other QoS metrics which should be involved in the routing process. Consequently, these techniques are incomplete as they address only the energy level issue.

Guo et al. [43] proposed the OLSR-energy-aware (OLSR_EA) routing scheme, in which the route calculation algorithm selects paths based on a composite energy cost. This cost is considered the energy routing metric and computed by combining the residual energy and consumed transmission power of each node. OLSR_EA uses the auto-regressive integrated moving average time-series method to measure and predict the per-interval energy consumption. Similarly, Jabbar et al. [156] introduced a proactive forwarding for MANETs that is based on a multi-metric criterion. Another proactive routing scheme for MANETs that incorporates an energy conservation mechanism was proposed in [157]. This scheme exploits the new Energy Conserving Advanced Optimized Link State Routing (ECAO) model used for the prediction of the energy consumption level of the node. Such a prediction is used for the calculation of the energy cost. The performance of the ECAO model was compared with the existing OLSR and other advanced OLSR models. The ECAO model attains better performance in terms of the number of transmission control messages, PDR, average time, end-to-end delay, and link delay and energy consumption. Jain and Kashyap [158] introduced a new mechanism for selecting MPR among the nodes' neighbor sets to make OLSR more energy-efficient by taking into account the willingness of the node. The proposed energy-aware MPR selection mechanism was incorporated in Modified Dynamic OLSR (MD-OLSR) and compared with the conventional OLSR. Simulation results showed improved performance, such as higher throughput, larger Packet Delivery Ratio (PDR), and lesser end-to-end delay.

In [159], a novel location-based routing protocol has been proposed. It improves routing in MANETs in terms of both link stability and energy efficiency. The protocol is called GBR-DTR-CNR and uses the stable routing protocol Greedy-based Backup Routing (GBR) with a Dynamic Transmission Range (DTR) with Conservative Neighborhood Range (CNR) for neighbor selection. The GBR-DTR-CNR algorithm selects the links of the route based on two criteria: (1) an estimation of link expiration time; (2) a conservative neighborhood range. The GBR-DTR-CNR protocol enables high connection throughput but it enhances energy efficiency by exploiting an adjustable dynamic transmission range that considers node mobility. Consequently, GBR-DTR-CNR chooses the next node from those stable neighboring nodes that will not move out of the transmission range. It was proven that the connections formed in GBR-DTR-CNR are substantially more stable than other routing algorithms. Compared to similar routing schemes, GBR-DTR-CNR achieves higher throughput and PDR. It also improved the energy efficiency in terms of maximum energy consumed per node and average energy consumed per packet delivered, while requiring fewer routing control message exchanges. Nevertheless, over various node densities, GBR-DTR-CNR did not outperform the other protocols in terms of the average energy consumed per node. This is because in GBR-DTR-CNR, the nodes in the idle state do not forward packets, and they consume slightly more energy than idle nodes in other routing algorithms. Thiyagarajan and SenthilKumar [25] proposed the Memetic Optimized Adjacent Exponentially Distributed Routing (MO-AEDR) which considers route distance and power during route selection. In MO-AEDR, the route discovery selects a route that optimizes a weighted function of route distance and energy. In particular, MO-AEDR includes route energy consumption in its calculations and employs the Adjacent Exponentially Distributed Route Maintenance mechanism to include an energy awareness feature with mean data packet arrival rate and link breakage rate to the identified route discovery mechanism. The simulation results showed that MO-AEDR increases the PDR while reducing the end-to-end delay and routing overhead.

Some link-state-based routing protocols for MANETs are based on a Q-Routing algorithm that embeds a learning policy at every node to adapt itself to the changing network conditions, which leads to a synchronized routing. For example, the Mobile Q-Routing (MQ-Routing) protocol [160] has a modified Q-Routing algorithm that is quickly adaptable to the changes in the network topology. During the routing process, MQ-Routing considers resource usage and link stability by examining three metrics:

- The residual energy of the nodes. This metric is used for increasing the (minimum) lifetime of nodes and for balancing the traffic among them.
- The prediction of GPS-based link availability. This metric is used in order of Q-Routing to avoid the loss of a constant traffic part if it is required to manage a link failure due to node mobility.

- Node mobility. The MQ-Routing algorithm chooses more stable nodes with a high mobility feature. These nodes are not expected to rapidly change their neighbor sets.

By using these metrics, changes in the network topology and the levels of node energy are taken into account. These metrics enable MQ-Routing to be fully adaptable in such changes. Proper energy-efficient policies in MQ-Routing can also increase the minimum lifetime of a node and may lead to a fairer balance of energy. The main disadvantage of MQ-Routing is that it exploits only a single path at a time for data transmission and rapidly switches to the best path along with the Q-values in the routing table. Finally, Zhang et al. [161] proposed QG-OLSR, a kind of new quantum–genetic-based OLSR protocol for MANETs. QG-OLSR adopts the MPR technology in OLSR. QG-OLSR can effectively reduce the consumption of network topology control, improve the delivery rate of data packets, and reduce the end-to-end delay of packet transmission between nodes. This is because it embeds a new augmented Q-Learning algorithm (i.e., a model-free reinforcement learning algorithm that learns a routing policy) and combines the OLSR algorithm to optimize the selection of MPR sets. Simulation results showed that the QG-OLSR protocol is reliable and highly efficient.

In high mobility MANETs, proactive routing protocols exhibit the highest packet delivery ratio and the shortest end-to-end delay, while costing the most in protocol overhead. In such MANETs, we can measure the variation in links set by using the topology instability metric (TIM). TIM is defined by the number of links established and failed in a certain statistical period. In high mobility MANETs, a glitch in the TIM causes unnecessary protocol overhead. To address this problem, Jiayu et al. [162] proposed a scheme using the exponential weight-moving average (EWMA) of the topology instability metric (TIM) to dynamically adapt the topology update intervals in proactive routing protocols. Simulation results showed that EWMA of TIM exhibits better glitch suppression than the instantaneous value of TIM and decreases the unnecessary protocol overhead effectively in relatively stable scenarios.

3.6. Reactive (Source-Initiated-Based) Routing Protocols

Reactive routing does not depend on the periodic exchange of routing information or route calculation. When a route is required, the node must start a route discovery process. A reactive routing protocol finds a route from a source to a destination if the source node must send data packets. In particular, the source node checks its routing table to decide if it has a route to the destination. If there is no available route, the source node tries to find a path through a route discovery process performed more frequently as the node's mobility increases. As a result, reactive routing requires lower control overhead traffic compared to proactive routing. Typical reactive routing protocols for MANETs are AODV, DSR, and TORA.

Apart from energy conservation, the stability of the end-to-end path is a key issue for transmitting multimedia traffic over MANETs. The Weight-Based DSR (WBDSR) [163] is an improved DSR-based scheme that selects the optimum path by considering the weight of an intermediate node as a metric. The Node weight is used to select the most energy-rich and stable intermediate nodes to forward packets to the destination node. In MANETs, the stability of a node can be defined as the possibility of this node to be as long as possible within the same neighborhood [163]. As shown in Equation (1), the node weight is calculated as:

$$Node\ weight_i = Baterry\ level_i + Stability_i \tag{1}$$

The weight of a route is the minimum weight of all nodes forming the route. WBDSR selects the most efficient route (i.e., the route with the maximum route weight). However, if two or more routes have an equal route weight, WBDSR selects that route with the minimum number of hops. The performance of the WBDSR routing algorithm depends on the network size, as this parameter affects the node's stability. Thus, we conclude that WBDRS performs well only in small MANETs. Afterwards, Tiwari et al. [164] proposed an enhanced protocol of WBDSR called Bandwidth Aware Weight-Based DSR (BAWB-DSR). This new energy-efficient routing protocol not only considers the battery power and stability of the node, but also the bandwidth to determine the optimum path. Such a consideration of bandwidth is vital for satisfying the QoS requirements imposed by video applications.

Dhurandher et al. [165] proposed an energy-efficient ad hoc on-demand routing protocol (EEAODR) for MANETs, that balances energy load among nodes so that a minimum battery energy level is preserved among nodes, and thus the network lifetime increases. To prevent nodes from becoming exhausted, EEAODR locates a superior energy-saving path, while the routing path is calculated by examining the time, the energy level of each node, and the number of hops. Precisely, EEAODR has an optimization function that examines all those factors leading to the depletion of node energy. Such factors are packet type, packet size, and the distance between nodes. The optimization function decides the best route by considering energy conservation, while paths with nodes that exhibit low energy levels are excluded. Through simulation results, the authors showed that EEAODR is superior to AODV regarding performance. However, if the energy levels of all nodes are equal, the EEAODR algorithm does not perform well because the cost of links is based on the minimum battery power among nodes in the route. It is noteworthy that, if all routes have an equal energy-based cost, the shortest path will be selected as the best path. However, from the viewpoint of energy, the shortest path is not always the optimal path. EDSR [166] is an energy-efficient routing algorithm for MANETs that preserves the main concepts of DSR. It maximizes the network lifetime by minimizing the power consumption during route selection. Besides, EDSR can locate and address selfish intermediate nodes that might drop packets for other nodes to save their own batteries. In EDSR, most packets are allowed to be routed without an explicit source route header. This results in a reduction in the protocol overhead. Experiment results showed that EDSR increased the PDR and the average node lifetime, while it decreased the total energy consumed. Nevertheless, the modified route discovery process causes an increase in the time delay since the enhanced route discovery process requires extra time to process the path cost. Shivashankar et al. [167] proposed the Efficient Power-Aware Routing (EPAR) scheme, that identifies the capacity of a node not just by its residual battery power, but also by the expected energy consumed in consistently forwarding data packets over a detailed link. EPAR chooses the path that has the biggest packet capacity at the minimum residual packet transmission capacity. This goal is obtained by using a mini-max formulation. EPAR was compared with two other ad hoc routing protocols (MTPR, and DSR) in different network scales, taking into consideration the power consumption. It was found that EPAR reduces for more than 20% of the total energy consumption and decreases the mean delay, especially for high load networks, while achieving a high PDR.

The Energy-Level-Based Routing Protocol (ELBRP) [122] decreases the delay of data packet delivery, reduces energy consumption, and extends network lifetime. ELBRP is based on the energy level of nodes and uses different forwarding mechanisms. The energy level of a node is classified into four phases which map the four states: very dangerous; dangerous; sub-safe; safe. Additionally, nodes are classified into five states (transmitting, receiving, listening, sleep, and dead), where a node with a zero-energy level is dead. The ELBRP protocol has a modified request delay mechanism that is based on the delay mechanism of AODV. The protocol forces nodes to sleep in the “very dangerous” state and preserves “danger” and “safety” states without a delay function, as in the original forward strategies of AODV. ELBRP only adopts the delay function in the “sub-safe” state. In ELBRP, nodes with lower energy levels send request packets that are forwarded after a longer delay (sub-safe state) to the neighborhoods. As these request packets arrive after the request packets from nodes with higher energy, they are discarded. This happens because each node accepts only an earlier request packet and discards later duplicate requests. As a result, the nodes with high energy levels are only involved in routing packets to the destination. Through simulation results, the authors proved that ELBRP is a practical and energy-efficient routing scheme. Particularly, they proved that ELBRP balances the energy consumption, prolongs the network lifetime, and decreases the delay of data packet delivery. However, in the performance analysis of ELBRP, the authors focused only on energy-based metrics and ignored the impact of other parameters, such as network size and traffic load. Furthermore, QoS metrics, such as throughput, the delivery of packets, and overhead, were not examined. Er-rouidi et al. [168] introduced an energy-efficient AODV-based routing protocol (EE-AODV) that considers, in each period, the rate of energy consumption instead of being limited to the current residual energy of a node. The rate of energy consumption permits EE-AODV to obtain accurate information about the energy that is consumed when transmitting and receiving the packets. This is achieved without the complex calculation of these values. Based on the residual energy and the estimated consumption rate, EE-AODV calculates a more accurate remaining lifetime of nodes. The EE-AODV was compared with the basic AODV and EQ-AODV (Energy and QoS-supported AODV), and it was proven that it significantly reduces the energy consumption of the nodes.

Anand and Sasikala [169] proposed a routing protocol that improves the energy-efficiency in MANETs. Their protocol is an enhanced AODV, called Intelligent Routing AODV (IRAODV) that improves the routing strategy in packet transmission. IRAODV is based on the calculation of the distance of the packet transmission by the individual nodes with other nodes. For this calculation, it uses the RSSI (Received Signal Strength Indication) parameter. The authors simulated IRAODV and compared its performance with AODV. They found that IRAODV outperforms AODV in terms of PDR, throughput, end-to-end delay, and residual energy. Bamhdi [170] proposed another protocol, called Dynamic Power-AODV (DP-AODV). DP-AODV adapts the AODV protocol to dynamically adjust transmission power usage. To achieve this improvement, the DP-AODV protocol uses the dependence of a transmission range on density. Simulation results demonstrated that, as density increases, DP-AODV shows a decrease in delay, compared to AODV, and offers better performance for highly-populated networks exceeding 200 nodes. The simulation results showed that DP-AODV increases network throughput whilst reducing node interference in a dense region, as well as enhancing the overall network performance concerning the increased packet delivery fraction, reducing the control overheads and jitter, enhancing overall throughput, reducing interferences and finally, shortening the end-to-end delay in medium–high-density conditions.

In summary, energy-efficient reactive routing protocols have better scalability than the link-state-based (proactive) routing protocols. Nevertheless, in reactive routing schemes, the overall time delay is high since the node needs extra time to wait for the route discovery process after the node tries to deliver a packet. Another interesting category of power-aware optimization solutions follows. It includes routing protocols that are based on transmission power regulation methods. Such methods can improve the overall MANET performance by increasing throughput and simultaneously reducing power consumption.

3.7. Transmission Power Control-Based Routing Protocols

In general, each node can decide the transmission power level, rate adaptation method, and routing strategy that it will use. However, if the transmission power level is very high, the node would sense and interfere with several neighbors. This might cause channel saturation, contentions, and collisions. On the other hand, if the transmission power level is low, a node could detect very few neighbors (or none) which would lead to a failed transmission. A transmission power control routing protocol saves energy by selecting the best routing path from the source to the destination in order nodes to consume the minimum amount of energy [20]. To determine the cost of the routing path, a few energy-related metrics can be used. For example, the amount of energy stored in each node (battery) and/or the amount of energy required to perform wireless signal transmission for next-hop forwarding can be used for determining the cost of each potential routing path. Four criteria are often used for estimating the cost of routing paths: (1) transmission power; (2) remaining energy capacity; (3) estimated node lifetime; (4) combined energy metrics. In practice, a power-aware routing protocol uses more than one energy-related metric to get the best routing path. Such energy-related metrics are: (1) the path crossed using minimal wireless signal transmission power;

(2) the intermediate node having sufficient residual battery power; (3) avoiding network partitioning caused by overused nodes; (4) selecting the routing path with the least power consumption per packet [23].

In the late 1990s, many authors [94–96] proposed topology control policies considering active energy consumption states. Those studies aimed to find the optimum path that has a minimized consumption of transmission power between a pair of senders and receivers. Later, based on this idea, various researchers introduced smart energy-efficient routing policies. Chang and Tassiulas [62] framed the routing issue to optimize the network's lifetime and subsequently suggested the Flow Augmentation and Redirection (FAR) scheme. The FAR scheme actively stabilizes the rate of power consumption amongst the node in fractions of their power reserves. Nevertheless, the FAR scheme needs to have prior information about the rate of data generation at the source. Along with this, the performance of the FAR scheme was measured only on the static networks. Afterwards, Li et al. [63] introduced an energy-aware smart routing called the On-line Max–Min (OMM) scheme. The OMM scheme, in contrast to FAR, effectively improves the network lifetime without having prior information about the rate of data generation at the source. However, OMM preferably requires information about the current residual energy of all other nodes in the network. Therefore, the OMM scheme may not be scalable enough in a dense network environment. Along with this, the FAR and OMM schemes assumed that there is a fixed or constant pattern in rates of message arrival between the different sender and receiver pairs, and that assumption makes these schemes highly infeasible. Then, Kar et al. [171] and Liang and Guo [172] suggested another energy-aware smart routing scheme, which explicitly improves the OMM scheme. The scheme's main objective is to maximally route the total amount of data without getting any advanced information on the upcoming rate of message arrivals and data generation, respectively. Nevertheless, these schemes do not perform well in the case of the larger networks. Doshi et al. [65] have shown the specialties of their work by addressing some of the following issues: (1) how can we gather exact power information? (2) how much routing overhead is allied with the energy-aware scheme? (3) how are we able to sustain minimum power paths in the presence of high mobility? Considering these issues, Doshi et al. [66] introduced the Minimum Power Routing (MPR) scheme. For this, they extended the original implementation of the DSR protocol and made proper amendments in the IEEE 802.11 (MAC) standard as well. Badal and Kushwah [173] proposed the Modified DSR that applies an energetic-aware mechanism to DSR protocol and by using energy consumption for transmission as part of routing cost calculation. Additionally, the Modified DSR uses energy consumption metrics for energy consumption balancing purposes as it also incorporates the energy-aware routing protocol with a load distribution solution.

To find the optimal paths between the communicating nodes in MANET, Prasath and Sreemathy [174] modified the traditional DSR algorithm by using the Firefly algorithm. In particular, the Firefly algorithm, as used in their framework, improves the DSR routing performance with well-organized packet transfer from the source to the destination node. The optimal route is found based on link quality, node mobility, and end-to-end delay. The authors conducted simulation experiments (with 25 nodes) and compared the performance of the traditional DSR, link quality-based DSR for selecting a route, and the proposed Firefly algorithm for optimal route finding. For this comparison, they used QoS parameters, such as throughput, end-to-end delay, number of retransmitted packets, and the number of hops to the destination. Moreover, they found that their method, with the Firefly algorithm, outperforms the other DSR schemes. From another perspective, Zhang et al. [175] proposed a genetic algorithm (GA)-bacterial foraging optimization algorithm to perform the selection of the optimal routing in DSR. After searching out multiple routes to the destination node, the paths are initialized. Then, the GA algorithm is started. This algorithm quickly finds the positions of the maximum probability optimal paths, which are the initial positions of bacteria for the bacteria foraging optimization (BFO) algorithm. Through using the BFO algorithm, it is easy to search out the extreme value and the optimal path to compensate for the poor accuracy of the GA algorithm. The proposed optimized strategy improves the routing selection algorithm without changing the complexity of DSR and proves the convergence of the algorithm to the global optimal solution.

The Ad hoc On-demand Multipath Distance Vector (AOMDV) [176] is an enhanced routing protocol based on AODV that provides multipath extensions. In AOMDV, the end-to-end delay is reduced by the utilization of parallel paths. AOMDV guarantees loop freedom and the disjointedness of alternate paths. The performance comparison of AOMDV with AODV showed that AOMDV, compared to AODV, can effectively cope with mobility-induced route failures. It can reduce the packet loss by up to 40% and can achieve an extraordinary improvement in the end-to-end delay. By reducing the frequency of route discovery processes, the AOMDV protocol also decreases the routing overhead by about 30%. Javan et al. [177] modified the AODV protocol, that results in a selection of zone-disjoint paths, to the extent feasible, and thus their protocol (ZD-AOMDV) achieves less end-to-end delay. The efficiency of the Zone-Disjoint (ZD) paths-AOMDV protocol was evaluated on various scenarios and there was a remarkable improvement in the PDR, and also in the reduction in end-to-end delay, compared to AOMDV.

Nayak et al. [178] suggested the Energy-Aware Routing (EAR) protocol, that is designed based on the transmission range that needs to be used when delivering network packets to their destinations. EAR was used in the AODV routing protocol as a case study for the required routing discovery when it is performed. Lalitha and Rajesh [179] proposed the AODV range routing (AODV-RR) protocol; an improved version of AODV that includes the "range routing" mechanism. According to this mechanism, AODV-RR selects particular nodes to be responsible for receiving and processing any routing request based on the Received Signal Strength (RSS). Then, it increases the one-hop distance of each hop and it reduces the path lengths in terms of the number of hops. In summary, AODV-RR is a routing protocol that maximizes the transmission range and minimizes the transmission power and the overall energy consumption of the network by minimizing the communication overhead. The authors evaluated AODV-RR for different network sizes and they found that it performs better than AODV in terms of PDR, routing load, throughput, end-to-end delay, and energy consumption. However, the "range routing" mechanism is not currently implemented for multipath routing.

The Ad hoc On-demand Multipath Routing with Lifetime Maximization (AOMR-LM) [79] is an energy-efficient multipath routing protocol that preserves the residual energy of nodes and balances the consumed energy to increase the network lifetime. The residual energy of nodes is used for calculating the node energy level. This energy level is used by the multipath selection mechanism to categorize the paths. AOMR-LM has been compared with two other protocols: AOMDV and ZD-AOMDV. The performance of AOMR-LM was evaluated in terms of energy consumption, network lifetime, and end-to-end delay. Finally, in [180], the Fitness Function technique was applied to optimize the energy consumption in a new routing protocol, called "Ad Hoc On Demand Multipath Distance Vector with the Fitness Function" (FF-AOMDV). In FF-AOMDV, the fitness function is used to find the optimal path from the source to the destination to decrease the energy consumption in multipath routing.

De Rango et al. [181] suggested the Link- stAbility and Energy-aware Routing protocol (LAER), that combines energy metrics with other metrics (i.e., link stability) for use in the routing decision. LAER not only focuses on routing protocol, but also on forwarding policy to make a reliable and energy-efficient MANET solution. The ECAO protocol [157] calculates the energy cost as extra metric performance in OLSR, as well delay, throughput, and the number of hops to calculate the cost of each identified routing path.

Katiravan et al. [182] suggested the energy-efficient and link quality-aware routing protocol (ELRPP). This protocol selects a route using three metrics—residual energy, SNR, and link quality—and has a variable transmission power control. Particularly, in the route discovery mechanism, there is a transmission power control deployed to set the optimal transmit power of nodes by classifying the nodes into Clusters using their transmission radius. As a result, ELRPP conserves residual energy, minimizes the power consumption, and improves network lifetime. Additionally, ELRPP exploits a steady link monitoring mechanism with error notification, which initiates a route discovery process for a poor link. Therefore, it minimizes the overhead incurred due to the usage of periodic control packets and improves the network throughput while it maintains network connectivity. For each link, the authors proposed a Cost Function (CF) based on Link Quality (LQ), and Available Energy (AE) as follows in Equation (2):

$$\mathrm{CF} = \alpha \cdot \mathrm{LQ} + \beta \cdot \mathrm{AE} \tag{2}$$

where α and β are the weights given to each metric with $\alpha + \beta = 1$.

Depending on the application requirements, different weights can be assigned to the metrics. LQ examines the actual channel conditions by taking into account the mobility and fading effects. The value of LQ is defined with the value of the SNR. In particular, each node continuously estimates the SNR of its neighbors. If the SNR is equal to or above a vital threshold required for successful packet transmission, the LQ is set to "1". Otherwise, the LQ is set to "0" as the SNR falls below the vital threshold. Bhople and Waghmare [183] proposed the Efficient Power-Aware Routing (EPAR) that measures the amount of remaining battery energy and estimates the cost of energy required when a route is selected. Route selection is based on the number of minimum hops along with the highest throughput value. Nevertheless, in EPAR the amount of energy used for the route process and the amount of remaining energy at each relay node are taken into consideration. Havinal et al. [184] proposed the Minimal Energy Consumption with Optimized Routing (MECOR) protocol that focuses on the use of energy consumption as the main performance metric for routing decisions.

From another perspective, Ourouss et al. [185] proposed an energy-aware routing protocol (called Double Metric), that obtains increased effectiveness by combining QoS and energy-efficiency in determining the best routing path to be selected. This approach ensures a balance between the robustness of routing and the energy efficiency of routing. The advantage of this energy-aware routing protocol method is that it is very efficient in obtaining the routing path with a minimal cost value. However, the main drawback of this protocol is that, if not combined with another energy-efficient approach, it will result in the overuse of limited energy resources from the battery of the intermediate nodes, thus resulting in network failure. Yang et al. [186] examined the packet delivery ratio and energy consumption under a multicast scenario by taking into account the transmission power control for each node. In their multicast scenario, a packet from the source node can be delivered to up to f different relay nodes. Each of the d destination nodes may receive the packet from these relay nodes (or the source node) before the packet lifetime τ expires. It can be said that, in this scenario, we have a redundancy factor f, multicast scale d, packet lifetime τ, and a power control parameter w for packet routing. The power control parameter w is fixed and equal for all nodes. Initially, the authors assumed a general two-hop relay RT (f, d, τ, w) algorithm with redundancy factor f, multicast scale d, packet lifetime τ and power control parameter w for packet routing. Next, they developed a Markov chain framework to depict the packet propagation process under this two-hop relay algorithm. Using this framework, they derived two analytical expressions for PDR and energy consumption. Finally, they validated their theoretical analysis and investigated how the abovementioned network parameters affect the PDR and energy consumption performance. Finally, Das and Tripathi [187] proposed the Multi Criteria Decision Making (MCDM) method combined with Intuitionistic Fuzzy Soft Set (IFSS) method. The authors placed special emphasis on the efficiency of utilizing energy capacity as part of route cost calculation by considering the rapid changes that occur in the identified routes. The use of the MCDM method, combined with the IFSS method, can calculate the cost of changing network routes efficiently and accurately. Table 2 summarizes the previous schemes and methods described.

Table 2. Important works on transmission power control routing protocols for MANETs.

Year	Ref.	Contribution
2019	[186]	A Markov chain framework that depicts the packet propagation process under a general two-hop relay algorithm. Two analytical expressions were derived for estimating PDR and energy consumption.
2018	[187]	Multi-Criteria Decision-Making method combined with Intuitionistic Fuzzy Soft Set (IFSS) method.
2017	[180]	The Fitness Function technique was applied to optimize the energy consumption in a new routing protocol (FF-AOMDV). In FF-AOMDV, the fitness function is employed to discover the optimal path from the source to the destination to reduce the energy consumption in multipath routing.
2016	[185]	The "Double Metric" energy-aware routing protocol obtains increased effectiveness by combining QoS and power-efficiency in determining the best routing path to be elected.
2016	[184]	The MECOR routing protocol addresses the use of energy consumption as the most important performance metric for routing decision.
2016	[183]	The EPAR routing algorithm measures the amount of remaining battery energy and estimates the cost of energy required when a route is selected.
2016	[157]	The ECAO protocol calculates the energy cost as extra metric performance in OLSR as well as throughput, delay, and the number of hops to measure the cost of each known routing path.
2015	[182]	The ELRPP routing scheme selects a route based on residual energy, SNR, and link quality. ELRPP incorporates a variable transmission power control mechanism.
2014	[79]	The AOMR-LM multipath routing protocol preserves the residual energy of nodes and balances the consumed energy to increase the network lifetime. The residual energy of nodes is used for calculating the node energy level.
2014	[179]	The AODV_RR protocol (an improved version of AODV) includes the "range routing" mechanism. AODV_RR selects certain nodes to be responsible for receiving and processing any routing request based on the RSS. It maximizes the transmission range and minimizes the transmission power and the overall energy consumption of the network by minimizing the communication overhead.
2015	[173]	The Modified DSR applies an energetic-aware mechanism to DSR protocol and uses energy consumption metrics for energy consumption balancing purposes.
2014	[188]	An energy-efficient routing algorithm finds routes, minimizing the total energy required for end-to-end packet delivery.
2013	[146]	An energy-efficient genetic algorithm-aided mechanism depends on bounded end-to-end delay and minimum energy cost of the multicast tree to solve QoS-based multicast routing problems.
2012	[189]	A cooperative routing algorithm considers electronic power consumption when constructing the minimum-power route leading from source to destination.
2012	[181]	The Link-stability and Energy-aware Routing protocol (LAER) combines energy metrics with other metrics (link status) for use in the routing decision.

Subsequently, we discuss cross-layer optimization-based routing approaches, which are based on effective cross-layer designs (CLDs) and provide better network management in terms of QoS, and energy consumption.

3.8. Cross-Layer Optimization for Energy Conservation in MANETs

3.8.1. Cross-Layer Optimization Defined

The Open Systems Interconnection-Reference Model (OSI-RM) provides a networking framework to implement the protocols within seven layers [190]. However, in the context of wireless networks, the OSI model has two main limitations: the principles of abstraction and encapsulation at each layer. The principle of abstraction dictates that the implementation details and interior parameters of the protocols within a layer are hidden to other layers. The inter-layer communication (that is restricted to procedure calls and responses) is performed only between adjacent layers. The principle of encapsulation maintains modularity in the network development and improves testing and error checking, but it prevents sharing critical information among the layers in the protocol stack. Because of the shared nature of the wireless channel, the different layers of MANET depend on each other. The conventional OSI layered design is, therefore, ineffective, resulting in redundancy within layered wireless protocols. If we design communication protocols intended for QoS provisioning on resource-controlled mobile devices, it is recommended [49] to consider the cross-layer coupling of functionalities. All cross-layer (CL) optimization processes have a common format that involves taking a set of parameter values from one (or a subset) of protocol layers and returning optimized parameter values to the same or other protocol layers. Khan et al. [191] defined a three-stage process of cross-layer optimization, as shown in Figure 4.

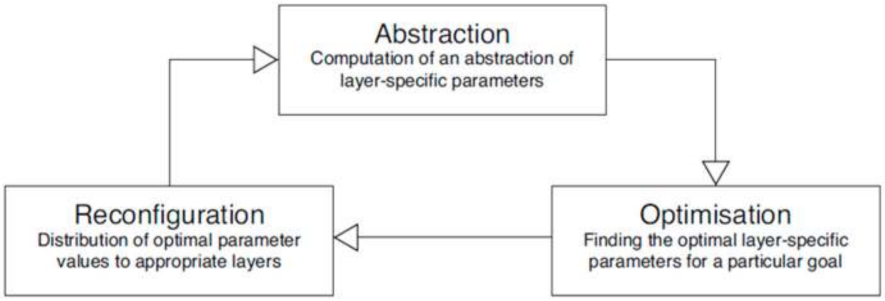

Figure 4. The stages of cross-layer interaction [191].

The first stage (Abstraction) is vital for reducing the processing and communication overheads. It decides if a small number of parameters are to be distributed, and underlying technologies covering. Then, Optimisation and Reconfiguration enable protocol adaptation to the existing network conditions and QoS requirements to maximize network performance. This is obtained by the tuning of the abstracted (or other related) parameters that are then returned to the network stack. These three steps can be repeated along with changing QoS requirements and resource capabilities.

3.8.2. Cross-Layer Designs for MANETs

Researchers have proposed numerous cross-layer routing protocols for ad hoc networks [192]. A Cross-Layer Design (CLD) [193] permits the communication architecture to operate as a system rather than a stack with different co-existing protocols. Particularly, CLD allows for interactions between different non-adjacent layers to defeat the OSI model's limitations (discussed previously) and provide better network management in terms of QoS, energy consumption, and other performance parameters. Thus, in a CLD approach for MANETs, the protocols and algorithms of the MAC, NET, Transport, and APP layers can function cooperatively to achieve: (1) high energy efficiency; (2) lower end-to-end delay; (3) minimization of energy consumption. A cross-layer approach can extract the cross-layer information from multiple layers, which can be additionally utilized to improve the overall performance and QoS in MANET. The sharing of cross-layer information can also satisfy the demand for high-quality multimedia communication and QoS provision in MANETs. In cross-layer approaches, video codecs can prioritize packets, split the source media into multiple streams, and generate redundant information that can be utilized by protocols and algorithms of different OSI-RM layers. In MANETs, each layer of the protocol stack is fully involved in providing QoS guarantees. New schemes are required at each layer of the protocol stack. For instance, MAC protocols are required for providing service differentiation and reducing end-to-end delay. Advanced coding techniques are also required, that will decrease encoder complexity and achieve maximum compression. In MANETs, where all layers depend on each other, QoS guarantees are achievable via the Cross-Layer Interaction (CLI) of different layers. For example, the MAC layer can be informed of the QoS requirements of the APP layer to obtain better scheduling for the execution of a multimedia application, and the Channel State Information (CSI) can be provided to the NET layer so that the routing protocol can keep away from paths containing channels in a bad state, as shown in Figure 5.

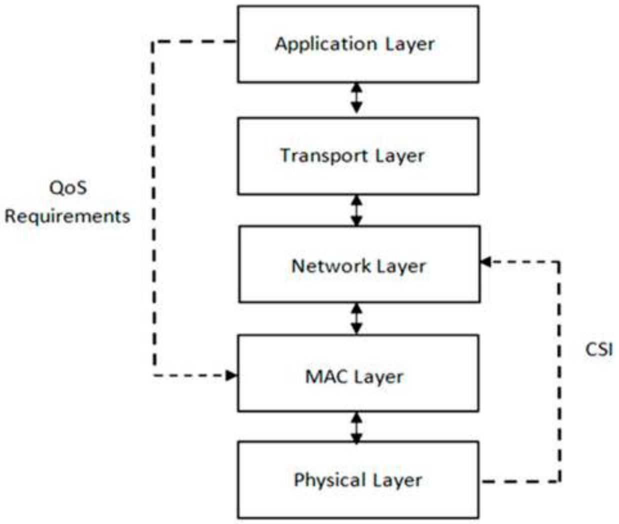

Figure 5. Two examples of cross-layer (CL) interactions in the protocol stack for MANETs (Adapted from [58]).

The applications in MANETs have different QoS requirements that determine the aim of the cross-layer design needed. Such cross-layer designs might be intended for reducing energy consumption and the end-to-end delay to improve the network's throughput, for striking an elastic tradeoff between any two of them, and for multiple-constraint optimization. Cross-layer design solutions use other layers to provide joint routing and scheduling, as well as power efficiency [194]. In MANETs, the routing process in the NET layer can interact with the access control module in the MAC layer. Additionally, there is the coupling between schedules in the MAC layer and power control in the PHY layer. Protocol designers can use cross-layer designs to adjust the system to the highly variable conditions of MANETs and confront system performance problems in an ideal way. For instance, a CLD can perform both local and global adaptations to network congestion. The MAC layer reacts locally to congestion by exponential back-off. If congestion is high, this response is deficient and it necessitates dual option compensation: (1) either the forwarding scheme can reroute traffic to avoid the bottleneck; (2) if alternate routes do not exist, the optimization can use transport protocol mechanisms to freeze traffic transmissions [30].

Hereafter, we describe some important works based on CLD that address transmission power in MANETs.

Ramachandran and Shanmugavel [195] proposed a CLD approach for power conservation based on transmission power control. Their approach includes three CLD proposals, which share the Received Signal

Strength (RSS) information among PHY, MAC, and routing layers: (1) in the first proposal, the minimum sufficient transmit power is computed to obtain energy conservation, interference reduction, and spatial reuse; (2) in the second proposal, the path loss incurred is computed to identify and reject the unidirectional links which greatly affect the performance of the routing protocol (AODV) in heterogeneously powered networks; (3) the third design proposal uses the RSS information to select reliable links to form stable routes by monitoring the signal quality to evaluate whether the neighbors are approaching or leaving.

It is well-known that a heterogeneous MANET has normal nodes (i.e., B-nodes) and powerful nodes (i.e., P-nodes). B-nodes are equipped with batteries, while P-nodes, have relatively unlimited power supplies (e.g., power scavenging units, such as solar cells or dynamos), when they are installed in mobile vehicles, etc. By utilizing the inherent device heterogeneity, Liu et al. [196] proposed a cross-layer designed Device-Energy-Load Aware Relaying framework (DELAR) that achieves energy conservation from multiple facets, including transmission scheduling, power-aware routing, and power control. The researchers implemented a power-aware routing protocol that integrates nodal residual energy information, device heterogeneity, and nodal load status to conserve energy. They developed a hybrid transmission scheduling scheme, that is a combination of reservation-based and contention-based MAC schemes, to coordinate the transmissions. Furthermore, they introduced the novel notion of "mini-routing" into the Data Link layer and proposed an Asymmetric MAC (A-MAC) scheme to support the MAC-layer acknowledgments over unidirectional links originated by asymmetric transmission power levels among normal nodes and powerful nodes. Additionally, they presented a multi-packet transmission scheme to enhance the end-to-end delay performance.

Tavli and Heinzelman [197] proposed an energy-efficient real-time data multicasting architecture for MANETs. This architecture is based on a CLD and is called Multicasting through Time Reservation using Adaptive Control for Energy efficiency (MC-TRACE). MC-TRACE is designed particularly for group communications (i.e., multicast and broadcast), and provides superior energy efficiency while producing competitive QoS performance and bandwidth efficiency.

Zoulikha and Amal [198] proposed another CLD among PHY, MAC, and Network layers. Their CLD uses the RSS information as a CLI parameter to provide reliable route discovery, stable links with strong connectivity, and energy conservation in transmitting data in a shadowing environment. Through simulation results, the authors have demonstrated that their cross-layer approach may reduce the packet latency and the routing overheads and may enhance the end-to-end performance of UDP flows when compared with customary solutions (single-path AODV routing protocol, and IEEE 802.11 DCF at the MAC layer). Ahmed et al. [193] suggested a cross-layer optimization framework that combines the PHY layer for controlling the transmission power, and the MAC layer for retrieving information about the RSS of a node. The modification of transmission power facilitates the node to adjust the transmission range dynamically at the PHY layer. With a dynamic transmission power control mechanism, each node calculates minimum RSS, average RSS, and maximum RSS. Using this information, each node knows its neighbor positions and guides itself to dynamically manage its power levels. As a result, the optimal transmission power and reliable communication range are obtained. Equations (3)–(5) calculate the average, minimum, and maximum receiver signal strength (RSS), correspondingly:

$$A_{RSS} = \frac{\sum_{i=1}^{m} RSS_i}{n} \tag{3}$$

$$A_{Min_{RSS}} = \frac{\sum_{i=1}^{Min_{node}} RSS_i}{Min_{node}}, \text{ for } RSS_i < A_{RSS} \tag{4}$$

$$A_{Max_{RSS}} = \frac{\sum_{i=1}^{Max_{node}} RSS_i}{Max_{node}}, \text{ for } RSS_i > A_{RSS} \tag{5}$$

where m is the sum of single-hop neighbor nodes of node X_i with RSS_i representing the sum of the RSS value of neighbor nodes. Each node determines the communication region by using these values. The RSS value is inversely proportional to the transmission distance. This means that a low value of RSS can cover a larger communication region and vice versa.

Iqbal et al. [49] presented a cross-layer multipath routing protocol for MANETs that is efficient and fault-tolerant in a diversity of application environments. The protocol is adaptive as it exploits those routes that are capable of providing more data rates with a lower packet loss ratio (PLR). The authors assume that MANETs are established for three types of applications: (1) simple; (2) multimedia; (3) applications with security requirements. A multimedia application needs such routes that have more bandwidth and minimum end-to-end delay. Taking into account the type of the application, the routing protocol chooses proper multipaths. For example, for a multimedia application, the proposed protocol selects two (or more than two) routes which are bandwidth-rich and have minimum delay from source to destination. Some important features of their protocol are as follows: (1) the APP layer defines the type of application; (2) the security module is working at the network layer; (3) bandwidth and end-to-end delay parameters are taken from the MAC layer. Their protocols were compared with other routing protocols (DSR, AODV, OLSR, CEDAR, PLQBR, QAODV, SAODV, and CSROR) using PDR, average delay, and routing overheads metrics with and without malicious nodes, and it was found to be efficient and fault-tolerant in most scenarios. Carvalho et al. [199] implemented a cross-layer routing protocol for a hybrid MANET that uses a fuzzy-based mechanism for all layers by employing two input parameters: energy and mobility. This mechanism offers a better quality of network resources and enhanced network lifetime. It consists of a decision metric in each layer, based on QoS and Quality of Experience (QoE) to enhance network lifetime and energy efficiency. Wang et al. [200] proposed and evaluated a cross-layer routing protocol, considering power control and rate adaptation by using a delay-based non-selfish cost function with a multi-agent Q-learning coordination mechanism. Simulation results showed that this protocol improves the average end-to-end latency and throughput with acceptable power consumption level. In the simulation experiments, various parameters were examined, such as node density, node mobility, traffic load, and the number of flows.

Mehta and Lobiyal [201] considered the problem of adjusting the transmission power of the nodes to an optimal power level. They incorporated low power consumption strategies into the routing protocol through an upward information flow cross-layer model between the MAC layer, and the Network layer. They proposed a new energy-efficient CLD to AODV, called Cross-Layer Energy Efficient AODV (CLEE-AODV). Using this CLD approach, they implemented the required changes in the route discovery process in the AODV. Through simulation results, they showed that the CLEE-AODV routing protocol has better performance enhancements than AODV, in terms of total transmission power, energy consumption per node, energy efficiency, and throughput. Singh and Verma [202] proposed an energy-efficient cross-layer routing protocol for heterogeneous cluster-based WSNs. The protocol is named ATEER to justify that it is Adaptive Energy-Efficient and based on the Threshold concept. The ATTER protocol assigns a node as CH, using the concept of weighted probability that is calculated based on the average energy of the whole network divided by the residual energy of every single node. The simulation results showed that ATEER has improved stability and prolonged the network lifespan when it was compared to other algorithms. Maitra and Roy [203] have suggested a cross-layer based protocol design explicitly for mix WSNs, called XMSN. This scheme effectively utilizes the concept of low power listening with a back-off congestion window scheme in order to accumulate neighbor information. Meanwhile, XMSN tries to accumulate the information of a suitable node, which will act as a parent for it. For this, XMSN utilizes the factors such as node and link quality, respectively. In fact, the authors have implemented and evaluated XMSN over Castalia simulator, and have concluded that the performance of XMSN is better than the previous approaches in terms of goodput, power consumption, and delay.

Chander and Kumar [204] suggested the Cross-layer Multicast Routing (CLMR) approach, that enhances the QoS based on a tree-based multicast routing protocol. To obtain QoS, the optimization of the tree management cost and tree operations was done. CLMR takes advantage of the functionality of the application layer, PHY layer, and network layer for QoS communication. The performance of CLMR is analyzed using the Multicast Ad Hoc On-Demand Distance Vector (MAODV) routing protocol under various parameters (i.e. throughput, delay, PDR, link cost, and energy consumption).

As was mentioned previously, it is vital to provide a mechanism that will effectively control the transmission power of a node. In this direction, Maygua-Marcillo and Urquiza-Aguiar [205] proposed a CLD mechanism that controls the transmission power of a node based on the detection of its neighbors. Such detection is performed by using AODV. The proposed mechanism is based on a cross-layering criterion to allow for the coordination, interaction, and exchange of information among the PHY layer and the network layer. Finally, Sekar and Latha [206] suggested a cross-layer-based, lightweight, reliable, and secure multicast routing protocol for MANETs. The protocol has three stages:

- In the first stage, a reliable multicast route discovery is completed. A multicast tree is set up and is hierarchically divided into clusters using the depth of the tree. Then, the CHs are chosen, based on link stability, residual energy, and residual bandwidth. Gateway nodes are selected depending on their residual energy and PDR.
- In the second stage, the trust value of each node is estimated and updated depending on each activity. Throughout multicast transmission, the trust values of CH and its gateway are monitored. CH and gateway are considered as misbehaving when their trust value is less than a minimum threshold. For protecting the data transmitted from the sender, a one-way hash function-based Message Authentication Code is used.
- In the third stage, bulk data loss recovery is performed at the receiver by applying the Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) methods.

Table 3 presents previous works on CLD in MANETs.

Table 3. Important contributions of cross-layer designs in MANETs.

Year	Ref.	Contribution
2008	[195]	A CLD approach for power conservation based on transmission power control. This approach includes three CLD proposals aiming to solve special problems.
2011	[196]	The DELAR framework achieves energy conservation from multiple facets, including power-aware routing, transmission scheduling, and power control. DELAR focuses on heterogeneous MANETs.
2011	[197]	A cross-layer energy-efficient real-time data multicasting architecture (MC-TRACE) for MANETs. MC-TRACE addresses group communications and provides superior energy efficiency while producing competitive QoS performance and bandwidth efficiency.
2012	[207]	A cross-layer scheme jointly considers flow control, multipath routing, and random access control. The scheme is based on network utility maximization.
2013	[208]	A CLD for random-access-based fixed wireless multi-hop networks. This CLD is based on a physical interference model.
2014	[209]	A cross-layer distributed approach for maximizing the network throughput by jointly selecting stable routes and assigning channels based on mobility prediction.

Table 3. *Cont.*

Year	Ref.	Contribution
2014	[198]	A CLD among PHY, MAC, and network layers. The CLD uses the RSS information as a CLI parameter to provide reliable route discovery, stable links with strong connectivity, and energy conservation in transmitting data in a shadowing environment.
2015	[193]	A CL optimization framework combines the PHY layer for controlling the transmission power, and the MAC layer for retrieving information about the RSS of a node. The change in transmission power enables the node to adjust the transmission range dynamically at the PHY layer. Optimal transmission power and reliable communication range are obtained.
2016	[49]	A cross-layer multipath routing protocol is efficient and fault-tolerant in a variety of application environments. The protocol is adaptive as it exploits those routes which are capable of providing more data rates with less PLR.
2016	[199]	A cross-layer routing protocol for a hybrid MANET uses a fuzzy-based mechanism for all layers by employing two input parameters: energy and mobility. The fuzzy mechanism offers a better quality of network resources and enhanced network lifetime.
2016	[200]	A cross-layer routing protocol considers power control and rate adaptation by using a delay-based non-selfish cost function with a multi-agent Q-learning coordination mechanism.
2017	[201]	An energy-efficient cross-layer design to AODV (CLEE-AODV) adjusts the transmission power of the nodes to an optimal power level.
2017	[202]	An energy-efficient cross-layer routing protocol (ATEER) for heterogeneous cluster-based WSNs. ATTER assigns a node as CH using the concept of weighted probability that is calculated based on the average energy of the whole network divided by the residual energy of every single node.
2018	[204]	The CLMR approach enhances the QoS using a tree-based multicast routing protocol. This approach optimizes the tree operations and tree management cost to obtain QoS. CLMR exploits the functionality of the PHY, application, and routing layers for QoS-oriented communication.
2019	[205]	A mechanism controls the transmission power of a node based on the detection of its neighbors. The mechanism is based on a cross-layering criterion to allow for the coordination, interaction, and exchange of information between the PHY layer and the Network layer.
2020	[206]	A cross-layer based lightweight reliable and secure multicast routing protocol for cluster-based MANETs.

3.8.3. Cross-Layer Schedulers for Power Control

In the previous sections, we discussed how an important aspect is the energy efficiency of power-aware routing in MANETs [27,210–212]. Scheduling policies can contribute to this aspect. In particular, suitable periodic scheduling can reduce energy consumption and, as a result, conserve the battery power of MANET nodes to a great extent [213].

The cross-layer design framework in [214] considers the next neighbor node transmissions and eliminates multiuser interference. A node can only relay (send) data packets if the Signal-to-Interference-and-Noise Ratio (SINR) is an acceptable SINR level (i.e., single-hop transmission requirements). So, this framework increases single-hop throughput and reduces power consumption. Thus, it preserves battery power as much as possible. The framework includes two main algorithms: (1) the scheduling algorithm that synchronizes the transmissions of independent users (nodes) to eradicate strong levels of interference, such as self-interference; (2) the distributed power control algorithm that decides the admissible power vector (if one exists), that can be used by the scheduled users (nodes) to assure their single-hop transmission requirements. Moreover, the power control algorithm can cooperate with two types of wireless ad hoc schedulers: TDMA and TDMA/code-division-multiple access schedulers. For example, to minimize power consumption and decrease packet delivery delay in nodes, the TDMA MAC protocol can allocate time slots to nodes efficiently. The joint distributed interference-based TDMA link scheduling and power control algorithm in [215] is suitable for MANETs and is based on the SINR parameter. The algorithm supports multicast traffic and eradicates those links that generate a large amount of interference. In this way, it permits the remaining links to achieve an acceptable SINR level. In wireless networks, SINR provides theoretical upper bounds on channel capacity. The joint link scheduling and power control TDMA in [216] maximizes network throughput. The joint link scheduling algorithm is based on a Mixed Integer Linear Programming (MILP) formulation that describes the problem in wireless ad hoc networks. Then, the authors [216] suggest two options:

(1) By solving the MILP formulation, the joint link scheduling algorithm finds optimal solutions and allocates the bandwidth reasonably among all links;
(2) A polynomial-time heuristic algorithm is applied to unravel the matter. Using this heuristic algorithm at the value of a minor reduction in network throughput, the joint link scheduling algorithm allocates the bandwidth among all links. In this case, the polynomial-time heuristic algorithm is called Serial Linear Programming Rounding (SLPR) heuristic. It must be noted that it is very difficult to evaluate the performance of SLPR when optimal solutions are not known.

In a TDMA scheduling scheme, we know that time is divided into frames and each frame includes time slots. The number of time slots in each frame defines the frame length. To minimize the total frame length in TDMA scheduling, Behzad and Rubin [217] designed a mathematical programming formulation for MANETs that is based on an optimal joint TDMA scheduling and power control algorithm under the physical interference model. This physical interference model is based on a power-based interference graph that depicts the interference relationship of every two links along with the SINR of the receiver. Based on this graph, the authors tried to find a maximal link-independent set using a heuristic algorithm called the Minimum Degree Greedy Algorithm (MDGA). For a TDMA-based MANET, Li and Ephremides [218] proposed an algorithm of joint power control, scheduling, and routing. The use of this centralized and joint algorithm enhances network performance in terms of delay, throughput, and power consumption. However, in this algorithm, there is a trade-off among energy consumption and delay performance or network throughput. In the area of wireless sensor networks, Mao et al. [219] developed a joint link scheduling and power control algorithm for many-to-one communications. This algorithm minimizes TDMA frame length and energy consumption by applying a hybrid genetic and particle swarm optimization algorithm that improves the searching ability. The algorithm does better than the traditional node Max Degree First coloring algorithm. However, it is not appropriate for a MANET environment with high node mobility. An adaptive and distributed TDMA scheduling scheme (AD-TDMA) for MANETs was proposed in [220]. The AD-TDMA scheme causes energy saving by presenting a high-quality awake-sleep scheduling state for MANET nodes. AD-TDMA has a good performance against changes in MANET topology. The AD-TDMA performance implies a large improvement in energy saving and a decrease in packet delivery delay. Last but not least, Padmavathy and Jayashree [221] implemented an enhanced delay-sensitive data packet scheduling algorithm that can increase throughput, energy efficiency, and network lifetime. This scheduling algorithm can reduce delay, latency, and drop rate. Moreover, it schedules the data packets adopting high-weighted priority scheduling. After that, data packets are forwarded based on the channel medium, whether it is in a busy or idle state to avoid drop-rate and delay.

To summarize the main concepts discussed in Section 3, we present Table 4, which shows a comparison of the categories of power-aware optimization solutions for MANETs.

Table 4. A comparison of the categories of power-aware optimization solutions for MANETs.

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
Approaches based on adaptations of the radio state operational mode	PAMAS [74], Sleep and Awake Scheduler [76], GAF [77], SPAN [78], S-MAC [80,81], T-MAC [82], R-MAC [83], DW-MAC [84], WiseMAC [85], B-MAC [86], X-MAC [87], RI-MAC [88], QL-MAC [89]	**Problem to address:** These approaches deal with the issue of unnecessary energy consumption during overhearing and idle listening during communication. **Objectives:** To minimize needless energy consumption during in-active periods.	The idea of radio state adaptation is suitable in large dense MANETs. In such MANET environments, the issue of overhearing and idle listening gradually increases. Therefore, the energy consumption of nodes increases too. These approaches prolong network lifetime by reducing unnecessary energy consumption during inactive periods.	These approaches increase the overall end-to-end delay in the network. Nodes in sleep mode cannot transmit and receive any packets. Thus, packet retransmissions are required, which lead to increased energy consumption. These approaches require complex coordination and synchronization amongst nodes which are difficult issues to be implemented in MANETs.	The approaches/schemes [74–77] are specifically designed for static and dynamic ad hoc networks. The MAC designs [80–89] are highly limited to some applications where the data generation rate is not very bursty and these MAC designs have mostly been evaluated over the WSN environment where the nodes are mostly in a sleeping state.
The adaptive load balancing/distribution-based approach	Sharma and Kumar [19], Adaptive-sleep + Adaptive MAC-Retx [22], Toh [64], LEAR [97], MDR [98], DSR extension-based load-balancing schemes [99–103], OLSR extension based load-balancing schemes [105–108], DMP_EOLSR [120] PHAODV [45,121], ELBRP [122], MP-OLSR [123], MEA-DSR [125], ELGR [126]	**Problem to address:** Routing based on adaptive load balancing aims to solve the problem of minimum energy consumption by adopting various load balancing methods. **Objectives:** The main aim of these routing protocols is not to estimate the minimum energy consumption path, but these routing protocols effectively assist in preventing certain low energy nodes from being over-utilized and, hence, they help in prolonging the network lifetime.	The idea of dynamic load-balancing and distribution is highly suitable in dense MANETs and network environments with heavy traffic load. These routing protocols can effectively assist in maintaining the proper balance of the power consumption amongst all the competent nodes either by choosing the route with the relaying nodes, which have sufficient energy-level, or by dynamically distributing the traffic over multiple available network paths.	These routing protocols do not care whether the chosen path is smaller or larger; it depends on the availability of intermediate nodes that have sufficient power level. Hence, such routing protocols influence the overall end-to-end delay performance of the network. The idea of dynamically utilizing multiple available paths for load-balancing does not always guarantee that the selected paths are optimized (paths) in terms of minimum energy consumption.	These routing protocols can be applied in the form of two scenarios: (I) Concurrent path forwarding/routing/transmissions-based schemes (e.g., LEAR, MDR, DMP_EOLSR, and ELGR); (II) Alternate path forwarding/routing/ transmissions-based schemes (e.g., PHAODV, ELBRP, MP-OLSR, MEA-DSR).
The location-based routing method	GPSR [128], Terminode Routing Protocol [132], LAR [133], LEARN [134], LEER [135], ZCG [136]	**Problem to address:** Many existing routing protocols heavily rely on the current state regarding links on a path between a pair of source and destination or all links in the network. Subsequently, this may lead to poor network scalability when these existing protocols are directly applied over a dense network environment and when nodes are moving rapidly (high mobility) to save battery. **Objectives:** These routing protocols aim to rely on the geographic location (and perhaps mobility) of each node for finding the best routing path. These protocols aim to improve network scalability by decreasing the routing overhead and providing improved performance in terms of energy consumption.	These routing protocols efficiently assist in improving the network scalability by decreasing the network overhead significantly, (especially in high mobility scenarios). By utilizing the location information, these protocols ensure that the least amount of control packets have to be transmitted over the network.	These routing protocols encounter numerous challenges, such as inaccurate positioning, local optimum problem, optimum forwarder selection, and broadcasting overheads. Location-based routing is difficult if holes exist in the MANET topology, and when nodes are roaming or often disconnected to preserve energy.	These routing protocols are specifically designed for high mobility scenarios and dense network environment. When the nodes' mobilities are too high, these routing protocols can outperform other conventional policies/schemes.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The multicast-based routing method	LMT [142], PEMA [143], Varaprasad [147], RERMR [148], EELAM [153], WEEM [154]	**Problem to address:** Conventional routing cannot efficiently utilize the available bandwidth while a source node is relaying multiple copies of its packets to a group of multiple destinations. **Objectives:** Multicast routing aims to route data from one source to multiple destinations of a specific group while utilizing the available network bandwidth in the presence of high mobility-induced topology changes.	Multicast-based routing protocols can consider different performance criteria, such as power-efficient route establishment, PDR, network lifetime, quicker and faster proactive route recovery, reliability, QoS based on bandwidth, delays, jitters, and security.	In a multicast tree, a root node suffers from greater energy depletion. Thus, it can shut down before other nodes as a root node is responsible for performing more tasks than other nodes. As the multicast tree is no longer static, multicast routing must support multicast membership dynamics. Existing power-aware multicast algorithms often produce extra control traffic in the network.	Multicast-based routing protocols are specifically designed for multicasting scenarios (i.e., group-oriented applications). In multicast scenarios, there is only one sender and multiple receivers per session, where a sender transmits multiple copies of packets to a specific group of multiple destinations. Multicast routing assumes the use of a multicast tree.
The proactive (link-state-based) routing method	Kunz and Alhalimi [42], OLSR_EA [43], Boushaba et al. [155], Jabbar et al. [156], MQ-Routing [160], QG-OLSR [161]	**Problem to address:** Traditional routing protocols operate on less accurate computations of network conditions. Hence, these protocols react slower to sudden significant network changes. These protocols also highly suffered from the issue of route oscillations and long-term loops. **Objectives:** The main idea of proactive routing is that each competent node shares its local topological view to its immediate neighbors. Then, this information is propagated, utilizing a flooding scheme throughout the network. Consequently, each node gets updated with a full topological view of the network. Additionally, proactive routing aims to maximize performance in terms of throughput while minimizing packet loss, energy usage, and network overhead.	In proactive link-state-based routing, each node tends to exchange information about the current network topology with other nodes to update its own routing table. Thus, proactive routing can immediately find the shortest path as the route discovery process has no delays. By utilizing the concepts of triggered apprises and flooding, link-state-based schemes are able to converge more speedily since, in case of flooding, the changing network information is flooded almost instantaneously and estimated concurrently.	The amount of memory storage required for accumulating neighbored information, topological databases, and the routing table is very high. Additionally, frequent topological changes in the network (during high mobility scenario) lead to the issue of the uncontrolled dissemination of triggered update messages. Hence, routing overhead is very high in such scenarios. Additionally, such routing protocols are not suitable for dense networks at all.	These protocols can be applicable in two ways: (1) link-state-based routing protocols, such as OLSR; (2) schemes which are based on the distance–vector algorithm, such as DSDV. These protocols can be effective in low density and static network (i.e., where mobility is almost negligible) environments since, in such a network environment, the frequent topological changes are almost negligible. Hence, the overall bandwidth prerequisite is not that high for control packet transmission. Consequently, the data transmission phase are not hampered too much in terms of bandwidth availability. These protocols can be efficient in long or continual data connections (sessions) in the network since, in such a scenario, there is a definite sense of the overhead for sustaining the information of paths being comprehended as the maintained paths are mostly utilized.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The reactive (source-initiated-based) routing method	WBDSR [163], BAWB-DSR [164], EEAODR [165], EDSR [166], EPAR [167], EE-AODV [168]	**Problem to Address:** Reactive routing confronts the problem of high control overhead associated with the previous proactive routing method. **Objectives:** Reactive routing protocols perform path discovery on an on-demand basis. Reactive routing aims to handle the regular node mobility issue more cleverly than proactive routing. Additionally, reactive routing tries to maximize performance in terms of throughput, while minimizing packet loss, energy usage, and network overhead.	Reactive routing does not depend on the periodic exchange of routing information or route calculation. A reactive routing protocol finds a route from a source to a destination when the source node must send data packets. The path discovery takes place if the node does not have the information of the most current route. Reactive routing eradicates the overhead of periodic and triggered update flooding for sustaining route information. It reduces the issue of higher network overhead and improves network scalability compared to proactive routing.	In reactive routing protocols, the overall time delay is large, since the node needs extra time to wait for the route discovery process after the node tries to deliver a packet.	The proactive routing method is perceived as the pure extension of existing routing protocols from the common wired domain. While the reactive (source-initiated-based) routing method is purely designed for MANETs. The reactive routing method is best adapted to a network environment where mobility is too high and any constructed routing path between a pair of senders and receivers will certainly be momentary.
The transmission power control-based routing method	FAR [62], OMM [63], Doshi et al. [65,66], AOMR-LM [79], Kar et al. [171], Liang and Guo [172], Badal and Kushwah [173], EAR [178], AODV_RR [179], FF-AOMDV [180], LAER [181], ELRPP [182], EPAR [183], MECOR [184], Double Metric [185], MCDM [187]	**Problem to Address:** This type of routing confronts the following problem: If the transmission power level is very high, the node would sense and interfere with several neighbors. This causes channel saturation, contentions, and collisions. On the other hand, if the transmission power level is low, a node could detect very few neighbors (or none) which would lead to a failed transmission. **Objectives:** To reduce unnecessary energy consumption by selecting the best routing path between a pair of sources and destinations in order for the nodes to consume the minimum amount of energy.	A transmission power regulation method can improve the overall network performance by increasing throughput performance and simultaneously reducing energy consumption. This method has also suggested a pronounced viewpoint to reduce unnecessary energy consumption.	This type of routing must satisfy the challenging feature of complex transmission power adaptations. Since, in such routing protocols, a high possibility of network segregation could be there, which ultimately leads to the issue of high latency and packet losses when the transmission power is adapted to some lower value.	This type of routing can address the dynamic environment of MANETs. However, it can only improve network performance under discrete conditions (i.e., fixed packet sizes and mobility speed). In the past, some transmission power regulation schemes were also able to reduce the possibility of avoidable power consumption, but they failed in improving throughput performance. Later, many authors insisted on the combined usage of the MAC and network layers for such protocols. Subsequent power-aware methods have been given by accumulating power information along with node positioning and topological state information.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The cross-layer optimization-based routing method	Iqbal et al. [49], Ramachandran and Shanmugavel [195], DELAR [196], MC-TRACE [197], Zoulikha and Amal [198], Ahmed et al. [193], Carvalho et al. [199], Wang et al. [200], CLEE-AODV [201], ATEER [202], CLMR [204], Maygua-Marcillo and Urquiza-Aguiar [205], Sekar and Latha [206]	**Problem to address:** The conventional OSI layered design is ineffective as it results in redundancy within layered wireless protocols. Due to the OSI–RM model policy of restricting interactions between non-adjacent layers, it is quite challenging to provide better network management in MANETs in terms of QoS, energy consumption, and other performance constraints. **Objectives:** These routing protocols (based on cross-layer designs-CLD) provide dynamic interactions among non-adjacent and adjacent layers. These routing protocols are intended for reducing the energy consumption and the end-to-end delay, for improving the network's throughput, for striking an elastic tradeoff between any two of them, and for multiple-constraint optimization.	This type of routing allows interactions between different non-adjacent layers and provides better network management in terms of QoS, energy consumption, and other performance parameters. In this type of routing, the protocols and algorithms of the MAC, NET, Transport, and APP layers can function cooperatively to achieve: (1) high energy efficiency; (2) lower end-to-end delay; (3) minimization of energy consumption. A CLD approach can extract the cross-layer information from multiple layers. This information can be additionally utilized to improve the total performance and QoS in MANETs. The sharing of cross-layer information satisfies the demand for high-quality multimedia communication and QoS provision in MANETs.	The implementation of these routing protocols requires an extensive change in terms of conventional layered architecture. Thus, regarding the involvement of every layer to perform certain estimations, calculating channel conditions at once becomes quite challenging when the designers implement them. To implement such routing protocols, especially for real-time applications, many amendments are required both at the hardware and software levels. Therefore, the practicability of such protocols and their performance evaluation conclusions are highly limited.	This type of routing can effectively handle the dynamic properties of MANETs. The traditional layered model is not able to do so because of its stern and rigid architecture. Hence, for the sake of handling these unusual properties of MANETs well, reactive/proactive forwarding methods can be jointly applied with the proposed cross-layer design (CLD).

4. Some Lessons Learnt

Recently, the wireless services over MANETs added dynamic competencies, such as QoS and multimedia. The design of energy-aware forwarding schemes is one of the imperative research topics in wireless communication. Until the late 1990s, various power-aware schemes considered energy management at the PHY layer only. Later on, numerous power-aware designs considered other issues of the higher-level protocol stack (wireless). Initially, many power-aware forwarding approaches took into account the power information for two tasks: (1) selection of routes with minimum power consumption; (2) balanced usage of multiple available nodes (i.e., load-sharing and balancing, respectively). Despite the presence of routes with high-power, the resulting performance of the network lifetime by these policies (i.e., mostly based on the single-path communication paradigm) was not very high. This is because some of the suggested policies suffer from the problem of inefficient load sharing, distribution, and balancing amongst available nodes. Moreover, many of the energy-aware forwarding methods in MANETs were considered effective against unnecessary power consumption. Nevertheless, such a reduction in power consumption comes at the cost of increasing the end-to-end delay and reducing the throughput performance.

Next, many approaches focused on topology control methods using transmission power regulations in MANETs as a transmission power regulation method to improve the overall network performance. Along with this, such a method has also suggested a pronounced viewpoint to reduce unnecessary power consumption. Some of these policies proved sufficient in improving throughput performance and simultaneously reduced energy consumption. However, these policies were able to do so only under some discrete conditions (i.e., fixed packet sizes and mobility speed). Some transmission power regulation schemes were also able to reduce the possibility of avoidable power consumption, but they considerably failed in improving throughput performance. Later, many authors insisted on the combined usage of the MAC and network layers for such schemes. Subsequent power-aware methods have been given by accumulating power information along with node positioning and topological state information. In the dynamic environment of MANETs the probabilities of mobility induced network topology changes and dissimilar wireless channel characteristics are reasonably high. In this environment, it is very difficult to assess the precise information of efficient energy-aware paths in the network. Even after assessing such a path, there is no guarantee of how long that estimated path will survive. Therefore, further research is needed to assess such highly varying wireless channel characteristics simultaneously with power-correlated parameters in finding the most suitable paths.

Meanwhile, other researchers proposed schemes based on the low-duty cycle associated with contention-based MAC design, especially for WSNs. Such a design has a great perspective to improve the overall network throughput performance and simultaneously reduces unnecessary power consumption as well. Nevertheless, most of these proposed schemes were completely tested, keeping a particular environment in mind, where the maximum possible bandwidth utilization was not important at all. Additionally, it is quite evident that such policies should be tested on a regular heterogeneous environment where throughput and delay performance are equally important, along with energy performance. Afterwards, not only at the MAC level, several works contemplated every level of the traditional layered structure and brought appropriate changes to the optimal energy-aware path selection scenario. Recently, many authors proposed many cross-layering-based energy-aware routing schemes which simultaneously take into account various parameters of the network and MAC layers. The incorporation of many optimization schemes simultaneously with the cross-layering concept for assessing energy-aware optimal paths, is an exposed concern for the forthcoming research. Nonetheless, the practical implementation of the cross-layer designed policies is highly infeasible, since most of them require extensive changes to existing network devices and already implemented conventional layered architectures, which are quite impractical. This is why most energy-aware schemes fail in practical scenarios. The cross-layering concept is an open research topic in itself as it is not only being used to solve the power-related issue but also other issues (i.e., congestion) as well. Moreover, whatever energy-aware forwarding policies were suggested until now focused on the concept of the single-path communication paradigm. Unfortunately, even though the prevalent route diversity has been accessible on the Internet, past schemes have entirely concentrated on the single-path communication paradigm just for the sake of its less composite feature and lower overhead (network). Nonetheless, this less complex natured paradigm is neither able to handle the rapidly growing traffic nor deliver appropriate stability and reliability in terms of energy consumption as well.

Subsequently, researchers brought about the concept of the multi-path communication paradigm that introduces new power-aware policies by utilizing the concept of load-balancing. Such multi-path power-aware approaches significantly assist in managing the network's lifetime by actively exploiting the available paths' resources (i.e., buffer availability and channel capacity). Awkwardly, if we consider the multi-path communication paradigm only, then this paradigm has further serious issues as well. Indeed, the biggest question is whether we should use multiple paths concurrently for transmissions or whether have to use other paths only after fully using one path. If we use all the paths together and schedule our load concurrently (equally) to all the available network paths, then we make full competency of multiple available paths. Now, a new issue comes from here, whether all those routes are completely disjointed or not. If yes, this policy will offer benefits in terms of throughput and reduced power consumption performance. Otherwise, there can also be a situation in which there can be some common nodes in all those paths, and transmitting huge loads on all those available network paths simultaneously could lead to the premature death (i.e., battery exhaustion) of all those common nodes. Hence, it ultimately leads to the problem of network segregation. Meanwhile, other issues ultimately degrade overall network performance, such as inter-path interferences and the un-ordered delivery of data chunks to the receiver (i.e., buffer-blocking problem). In a broader sense, we can say that the ability of a multi-path scheme is entirely dependent on the physical distribution of paths. Indeed, if the physical distribution of all the estimated paths is in such a way that all of them are not within interfering range of each other, the multi-path forwarding scheme will perform better. Otherwise, their performance can be degraded further, since more inter-path interference leads to higher link-layer contention-induced losses, which further results in a high number of retransmissions, which ultimately leads to the problem of high energy consumption in the network. If we use one path at a time, it means that we are not using the full competency of multiple available paths, which is more or less the same as that of a single path communication scenario.

Hereafter, we present Table 5, which summarizes and compares important power-efficient proposals and some conventional routing protocols.

Table 5. A qualitative comparison of the important power-efficient proposals and some conventional routing protocols.

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
DSDV [68] (1994)	Network Layer	Not Specified	Newest, Next available, or Shortest Path	-	-	-	-	-	-	Looping problem of the Bellman–Ford Algorithm in the Routing Table.	DSDV maintains up-to-date topological information (status) of the network.	Routing overhead is high, especially when the node mobility is very high. Not suitable for dense networks at all. DSDV severely floods the destination generated sequence number, which ultimately causes high network and communication overhead.	High
WRP [69] (1996)	Network Layer	Not Specified	Shortest Path	-	-	-	-	-	-	Transient Looping problem of the Bellman–Ford Algorithm in the Routing Table and slow convergence problem.	WRP assists in eradicating transitory looping circumstances. Thus, it offers quicker path convergence than other schemes when a link failure occurs.	Memory requirement is very high, especially when the network density is large.	Low
CGSR [222] (1997)	Network Layer	Not Specified	Newest, Next available, or Shortest Path	-	-	-	-	-	-	Dynamic changes in wireless channel characteristics.	Numerous heuristic approaches, such as gateway code scheduling, resource reservation of path, and priority-based token scheduling, can be employed to improve the performance of the CGSR scheme.	The LCHC algorithm of CGSR may lead to the problem of the rippling effect in the network.	High
PAMAS [61,74] (1998)	MAC and Network Layer	Not Specified	PPP and supreme node cost or Shortest Cost Forwarding	Y	Y	Y	-	Y	Y	Shorter life of node and network problems associated with conventional routing approaches.	The radio state adaptation idea of PAMAS significantly assists in reducing unnecessary power consumption in the case of a large dense network environment.	Nodes involved in excessive transmission will lose their power faster than other lighter (or non-loaded) nodes in the network. Subsequently, it leads to the problem of the unbalanced power-level of nodes in the network. PAMAS assumes that there is no mobility scenario in the network.	Low

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
[223] (1999)	Not Specified	Not Specified	It is based on the fixed groups of sender and receiver pairs and the rate of traffic producing flows (i.e., one to one)	Y	Y	-	-	-	-	Nodes involved in extreme transmission will lose their power quicker than other lighter or less loaded nodes in the network. Afterwards, it leads to the problem of low network lifetime.	The scheme forwards the transmission in such a way that the power consumption is well-poised amongst all nodes in the network.	The scheme has been evaluated over a static network scenario (i.e., almost no mobility in nodes). Hence, the applicability of the evaluated results is highly limited. Additionally, the energy required for data reception had not been considered at all.	Low
FAR [62] (2000)	Transmission EnergyControl	Not Specified	FAR is based on the fixed groups of sender and receiver pairs and the rate of traffic producing flows (i.e., one to many)	Y	Y	-	-	-	-	Nodes that are involved in extreme transmission will lose their power quicker than other lighter or less loaded nodes in the network. Afterwards, it leads to the problem of low network lifetime.	The scheme forwards the transmission in such a way that the power consumption is well-poised amongst all nodes in the network.	The scheme has been evaluated over a static network scenario (i.e., almost no mobility in nodes). Hence, the applicability of the evaluated results is highly limited. Moreover, the energy required for data reception had not been considered at all. FAR needs to have prior information about the rate of data generation at the source.	Low
OMM [63] (2001)	Transmission EnergyControl	Not Specified	Min–Max Remaining Energy Level	Y	Y	-	-	-	-	OMM focuses on the problems based on minimizing energy depletion that arise during communication. OMM also emphasizes the problem of acquiring prior information about the rate of data generation at the source.	The OMM scheme effectively improves the network lifetime without having prior information about the rate of data generation at the source.	OMM preferably requires information about the current residual energy of all other nodes in the network. Therefore, the OMM scheme may not be scalable enough in a dense network environment.	High
[65,66] (2002)	Network Layer (Transmission Energy Control)	Constant Bit Rate (CBR) Sources	Newest, Next available, or Minimum Hop-count Path	-	Y	Y	-	-	-	The scheme addresses some issues, which are: (1) how to gather exact power information; (2) how much routing overhead is allied with the energy-aware scheme; (3) how we can sustain minimum power paths in the presence of high mobility.	The scheme effectively assists in minimizing overall power consumption during transmission by avoiding the low power nodes.	In high mobility scenarios, the scheme's performance was significantly affected as compared to minimum hop-count forwarding performance.	High

Table 5. *Cont.*

Protocol (Year)	**Solution Type**	**Traffic Pattern**	**Path Metric**	**Factors Considered**						**Problem to Address**	**Advantages**	**Disadvantages**	**CO/NO**
				NE				**NC**	**ND**				
				RE	**TE**	**NO**	**IL**						
S-MAC [80,81] (2002, 2004)	MAC Layer (Synchronous MAC design)	Not Specified	Not Specified	-	-	Y	Y	-	-	S-MAC deals with a basic problem of unnecessary power consumption, due to overhearing and idle listening (IL).	S-MAC significantly reduces the problem of idle listening overhead by actively utilizing a periodic awakening and sleeping scheme.	S-MAC experiences certain degradation in both latency and fairness (per-hop) performance.	Low
T-MAC [82] (2003) RMAC [83] (2007) DW-MAC [84] (2008)	MAC Layer (Contention-based Synchronous low-duty cycle based scheme)	Not Specified	Not Specified	-	-	Y	Y	-	-	The schemes address the problem of a fixed duty cycle of S-MAC's scheme in order to reduce idle listening consumption.	These schemes have suggested an improvement in S-MAC by making adaptations in the active and sleep slot of the frame. They radically abridge the active slot of the frame when the channel is idle. These schemes significantly assist in reducing idle listening power consumption.	T-MAC experiences certain degradation in both latency and fairness (per-hop) performance. RMAC and DW-MAC schemes typically require an additive synchronization which further introduces complexity and overhead in the system.	High
LMT [142] (2004)	Network Layer (Multicast-based approach)	CBR Sources	Transmit energy level and Residual battery power.	Y	Y	-	-	-	-	LMT addresses the problem of low network lifetime.	LMT discovers routes that minimize the residual energy variance of nodes. Thus, LMT maximizes the lifetime of the source-based multicast tree network.	LMT scheme assumes that the energy needed for packet transmission is analogous to the source–destination distance. In this sense, LMT is theoretically unfair to the bottleneck node.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
Blazevic et al. [132] (2005)	Location-based Routing	CBR Sources	Geo-graphical map and Friend-assisted-based path metrics.	-	-	-	-	Y	-	The scheme addresses the issues of location-based routing, such as local optimum problem, inaccurate positioning, optimum forwarder selection, and broadcasting overheads.	The scheme assists in maintaining the scalability advantages of location-aware forwarding.	The Geo-graphical map-based path discovery may require an additive network overhead of dispensing exact topographical information. Nevertheless, building and maintaining a full geographical map, especially in a high mobility environment, incurs high CO.	High
Liang and Guo [172] (2006)	Multicasting-based approach	Not Specified	Minimum Energy (multi-cast tree)-based optimal path.	Y	-	-	-	-	-	The scheme deals with throughput (multicast) maximization problem.	The scheme maximally routes the total amount of data without getting any advanced information on the upcoming rate of message arrivals and data generation.	The scheme is not able to perform well in case of the larger networks.	Low
EA-OLSR [35] (2006)	Network layer/MAC layer	CBR Sources	Minimum Energy-based optimal path.	-	Y	Y	-	-	-	The scheme deals with the issue of the selection of the optimal power-aware MPR set in OLSR.	EA-OLSR suggests improved performance in terms of network lifetime and lesser energy consumption, since the scheme considers energy consumption at both network and MAC layer level.	The scheme has been evaluated over low mobility scenarios. Hence, the applicability of the evaluated results is highly limited. EA-OLSR should be evaluated considering RE metric as well.	It depends on the identified MPR set size. If the chosen MPR set size is big, NO will be high. Otherwise, NO will be low.

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
WiseMAC [85] (2004) B-MAC [86] (2004) X-MAC [87] (2006)	MAC Layer (Contention-based Asynchronous low-duty cycle-based scheme)	Not Specified	Not Specified	-	-	Y	Y	-	-	These schemes deal with a basic problem of unnecessary power consumption due to overhearing and idle listening.	These schemes effectively assist in eradicating the problem of the complex synchronization overhead required in the synchronous low-duty cycle-based systems and also suggest improved performance in terms of lower power consumption.	Sun et al. [88] have extensively discussed that asynchronous low-duty cycle schemes only achieve good performance in lighter traffic conditions. There is a serious decline in packet delivery, energy efficiency, and latency performance in such a policy as soon as traffic intensity increases.	Low
[224] (2007)	PHY, MAC, and network Layer (Adaptive Transmission Power Control)	CBR Sources	Not Specified	-	Y	-	-	-	-	The scheme effectively considers the restrictions and trade-offs of utilizing a fixed-range transmission method.	The suggested variable-range transmission-range scheme utilizes lower transmission energy and increases network capacity.	The scheme adopts that the intermediate or relaying nodes are available at the edge of the overlapping section [224]. Still, it does not imitate the chances of finding such relaying nodes within this section already. Consequently, the suggested path-duration estimation model does not advocate actual real-time values.	Low
EE-OLSR [107] (2008)	Link-state-based solution	CBR Sources	MDR-based optimal path	Y	-	Y	Y	-	-	EE-OLSR addresses the problem of low network lifetime.	The scheme assists in increasing network lifetime without compromising throughput, delay, and overhead performance.	EE-OLSR should be evaluated considering the RE metric as well.	Low

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
EEAODR [165] (2009)	Source-initiated-based solution	Not Specified	Hop count and link cost	Y	-	-	-	-	-	This scheme deals with issues such as high power consumption and lesser network consistency.	The scheme assists in increasing network lifetime by effectively balancing load amongst other high-rich energy nodes.	This scheme does not perform well when the energy levels of all nodes are equal. EEAODR takes much time in estimating an optimal path, since the receiver node has to wait for some time after getting its first RREQ packet.	High
ELGR [126] (2010)	Energy-aware load distribution (balancing) solution	CBR Sources	Newest, Next-hop (minimum cost)	Y	Y	-	-	-	-	ELGR deals with the decrease packet reception rate issue of greedy forwarding in unpredictable MANET environments.	ELGR scheme effectively improves the PDR performance compared to other geographical forwarding algorithms (i.e., DREAM, GPSR, GEAR).	The high complexity in estimating the forwarding and reception rate parameters is the main drawback of this scheme. Moreover, ELGR blindly assumes that each node knows its location information, which is not fair to assume in such a constantly changing MANET environment.	High
OLSR_EA [43] (2011)	Link-state-based solution	CBR Sources	Newest, Next-hop (composite power cost)	Y	Y	-	-	-	Y	OLSR_EA addresses the problem of low network lifetime.	OLSR_EA effectively uses the auto-regressive integrated moving average time-series method to measure and predict the per interval energy consumption.	OLSR_EA scheme is not scalable enough in a high dense network environment, since collision and interferences significantly hamper its QoS performance.	High
Sharma et al. [17] (2012)	Network Layer	Not Specified	Quality-value-based path cost	Y	-	-	-	-	-	This scheme deals with the issue of high power consumption during the transmission, reception, idle, and sleep states.	The scheme significantly assists in managing unnecessary power consumption in the network.	The scheme is specially designed for a special WSN environment. The scheme has been evaluated over low mobility scenarios. Hence, the applicability of the evaluated results is highly limited.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
Lu and Zhu [146] (2013)	Energy-aware Multicasting solution	Not Specified	Quality-value-based path cost	-	Y	-	-	-	Y	The scheme assists in resolving the QoS multi-cast forwarding issue.	The scheme shows its effectiveness and efficiency in terms of convergence performance, success ratio, and running time, compared to the least delay multicast tree algorithm.	It does not consider shared multi-casting trees and it focuses completely on source-based forwarding trees.	Low
MMQARP [130] (2014)	Energy-aware load distribution (balancing) solution	CBR Sources	QoS parameters, such as path reliability, link delay, and energy constraint-based path estimation.	Y	-	-	-	-	Y	MMQARP addresses the problem that conventional forwarding strategies pose to energy-aware and reliable paths.	MMQARP estimates multiple paths by considering path reliability, link delay, and energy constraint as QoS parameters. MMQARP, with the help of these QoS-based parameters, estimate multiple node disjointed paths and accordingly balance the load effectively.	MMQARP suffers from the problem of high routing overhead in the network. Additionally, MMQARP is not able to offer good QoS demands to the user in the case of lower mobility scenarios.	High
ELBRP [122] (2015)	Network Layer	CBR Sources	RREQ delaying based path estimation	Y	-	Y	-	-	Y	ELBRP addresses the problem of conventional forwarding strategies to not offer energy-aware and reliable paths.	ELBRP's RREQ delaying mechanism significantly assists by guaranteeing that only those nodes will participate in route discovery, which will have a significant amount of power.	ELBRP's abrupt energy-level-based classification scheme leads to the problem of unbalanced energy-levels in the network. Subsequently, this greatly increases the probability of network partitioning.	Low
ECAO [157] (2016)	Link-state-based solution	Not Specified	Newest, Next-hop (power cost)	-	-	-	-	-	-	ECAO addresses the problem of conventional forwarding strategies to not offer energy-aware paths.	ECAO assists in improving the network's lifetime.	ECAO has the problem of unbalanced energy levels in the network. Subsequently, this greatly increases the probability of network partitioning.	High

Table 5. *Cont.*

Protocol (Year)	**Solution Type**	**Traffic Pattern**	**Path Metric**	**Factors Considered**						**Problem to Address**	**Advantages**	**Disadvantages**	**CO/NO**
				NE				**NC**	**ND**				
				RE	**TE**	**NO**	**IL**						
Sharma and Kumar [19] (2017) Sharma et al. [22] (2018)	Energy-aware load distribution solution (Network/MAC/Physical layer solution)	CBR Sources	RREQ delaying-based path estimation	Y	-	Y	Y	Y	Y	These schemes address the problem of conventional forwarding strategies in that they do not offer energy-aware and reliable paths. Additionally, these schemes address the problem of ELBRP's abrupt energy-level-based classification scheme.	The RREQ delaying mechanism significantly assists these schemes by guaranteeing that only those nodes with a significant amount of power will participate in route discovery. Moreover, the schemes' adaptive fuzzy-based energy level classification scheme further assists in managing proper energy-level balancing in the network.	These schemes typically require additive synchronization, during the high danger phase state of a node, which further introduces complexity and overhead in the system.	High
Jabbar et al. [21] (2017)	Energy and Mobility aware multi-path load balancing Link-state solution	CBR Sources	RE and mobility conscious stable links	Y	-	-	-	-	Y	This scheme deals with the issue of not taking mobility into consideration while designing the power-aware schemes.	The scheme works significantly fine in comparison to traditional OLSR protocols by choosing more stabilized forwarding links.	The scheme can be modified and requires extensive evaluation in a dense and heterogeneous network environment. Hence, the applicability of the evaluated results is highly limited. Extensive evaluation regarding normalized routing and MAC load is required for this scheme.	Low
EELAM [153] (2019)	Multicast route discovery-based solution	CBR Sources	Not Specified	Y	-	-	-	-	-	This scheme deals with the issue of choosing sub-optimal relaying nodes in terms of RE and energy usage.	This scheme plays a vital role in terms of selecting optimal intermediate nodes with maximal residual energy and minimal energy usage. EELAM is the best route discovery approach in its category because the process and the methods adopted are contemporary.	EELAM has been evaluated over a low mobility scenario. Hence, the applicability of the evaluated results is highly limited. The energy required for data transmission, reception, overhearing, and sleep, which also consume a significant amount of power, had not been considered at all.	Low

NE: Node Energy; RE: Remaining Energy; TE: Transmission Energy; NO: Node Overhearing; IL: Idle Listening; NC: Network Congestion; ND: Network Delay; CO/NO: Communication Overhead/Network Overhead.

5. Challenges and Future Research Directions

Although a large amount of work has been completed on energy-efficient optimization techniques in MANETs, there are still some challenges that need to be addresses.

5.1. Challenges

Hereafter, we present the main research challenges, as shown in Table 6, in energy-efficient optimization for MANETs.

Table 6. Challenges in the development of energy-efficient optimization solutions for MANETs and their solutions.

Challenge in the Development of Energy-Aware Optimization Solutions/Goal	Solution	Reasons
A wireless transmission among a couple of terminals is considered as interference in other terminals. Close terminals relay the overhearing information without gains. **Goal:** To improve the performance of MANETs in the MAC layer.	Design of Cooperative MAC protocols for MANETs	• Cooperative transmission can utilize close terminals to relay the overhearing information and obtain a variety of gains. • A CMAC protocol exploits the medium access layer interactions and signaling overhead due to cooperation.
Conventional prediction methods are based only on the past locations of the node and they are ineffective for setting up a routing path with longevity. **Goal:** To set up a routing path with much longevity. This goal requires the prediction of the location of nodes based on the temporal and spatial characteristics (about its node's neighborhood).	Multipath routing based on hybrid modeling	• New hybrid methods are based on the temporal and spatial characteristics concerning its node's neighborhood. • Such a routing protocol is based on predicted node positions. Heuristic methods can use soft computing approaches, such as ML algorithms, to predict the future location of nodes.
In a multicast on-demand routing protocol, a method to select optimal multiple routes to a set of destinations is required. **Goal:** To improve the performance of multicast routing protocols.	Fuzzy-logic support in multicast routing	• A fuzzy set of rules can be used for selecting optimal multiple routes to a set of destinations. Such rules can be based on available network bandwidth, route stability, and node-to-node delay. • Fuzzy-logic support can be adopted in a cross-layer design.

(1) Design of Cooperative MAC protocols for MANETs: Using cooperative transmission, the performance of an ad hoc network can be improved [225]. Cooperative Communication (CC) [226] is a capable method that utilizes close terminals to relay the overhearing information to obtain a variety of gains. Traditionally, a wireless transmission among a couple of terminals is considered as interference in other (third) terminals. In CC, third terminals can receive and process this wireless transmission for performance gains. The broadcast nature of the wireless channel is also exploited cooperatively. However, to cope with the complex medium access interactions made by relaying and influencing the advantages of such cooperation, we must design capable Cooperative MAC (CMAC) protocols. The CMAC protocols must consider the medium access layer interactions and signaling overhead due to cooperation. Otherwise, the performance gain through the PHY layer cooperation may not improve end-to-end performance. Wang and Li [225] suggested a cross-layer distributed energy-adaptive location-based CMAC protocol (DEL-CMAC) for MANETs. DEL-CMAC improves the performance of MANETs in terms of network

lifetime and energy efficiency. Akande and Salleh [227] proposed another CMAC protocol for MANETs called network Lifetime Extension-Aware CMAC (LEA-CMAC). The LEA-CMAC protocol enhances network performance through cooperative transmission to complete a multi-objective target orientation. To accomplish a multi-objective target-oriented CMAC protocol, the authors formulated the optimization problem to extend the network lifetime. They considered symmetric and asymmetric transmit power rules. In particular, they suggested a distributed relay selection process to choose the finest retransmitting node among the qualified relays. This selection process takes into account the transmit power of the node, the sufficient residual energy after cooperation, and a high cooperative gain. The LEA-CMAC protocol can obtain a multi-objective target orientation by exploiting an asymmetric transmit power rule to improve the network performance. Recently, Su et al. [228] have suggested a reinforcement learning-based (e.g., Q-Learning) relay selection scheme without considering any prior information and network models. The suggested scheme has been extensively evaluated over parameters, such as system capacity, power consumption, and outage probability. Their widespread evaluated results show that the performance of the suggested scheme is better than other approaches in terms of the abovementioned parameters. As was mentioned previously, unplanned energy conservation methods decrease the node's lifetime and deface the consistency of packet flows. This results in a tradeoff between network throughput and node energy, resulting in post-network failure. The post-network failure results in limited Time to Live (TTL) values of the nodes and retarded network throughput with higher control overhead. To bridge the gap between network throughput and energy conservation under limited control overhead, Yamini et al. [229] proposed a Transition State supporting cooperative MAC broadcast (TSMP) protocol for both conserving node energy and to utilize available nodes efficiently before their energy drain. The TSMP protocol reduces the total energy consumption to a maximum extent of 14–21% higher than the Dynamic Power Consumption MAC protocol (DPCMP) and 24–33% higher than the Static Power Consumption MAC protocol (SPCMP). Comparatively, the routing overhead falls almost 45–52% higher than SPCMP and 27–31% higher than DPCMP.

(2) Multipath routing based on hybrid modeling: Multipath routing schemes can be based on predicted nodes positions. New hybrid methods are required for estimating the node location. Indeed, to set up a routing path with much longevity, it is supportive to have a routing protocol that is based on predicted node positions. Most conventional prediction methods are based only on the past locations of the node. New hybrid methods are required that will be based on the temporal and spatial characteristics concerning the node's neighborhood. Heuristic methods can use soft computing approaches to predict the locations of nodes. Precisely, machine learning (ML) algorithms can be trained by using features extracted from mobility patterns. The future locations of the node can be obtained by using this ML predictor. For instance, Ghouti et al. [230] proposed a mobility prediction based on an extreme learning machine. Every node knows its position, direction of movement, and velocity. Future node positions, velocity, and movement can be predicted. Based on the predicted future distances, the routing protocol is adjusted to choose the next hop. The effectiveness of the method depends on the training volume. At each node, the mobility is predicted using past information and it involves a lot of cost in exchanging this information to neighbor nodes. Recently, Farheen and Jain [231] suggested a multipath routing protocol that uses estimated probability locations with path diversion at required places along the path for improving routing performance without bigger packet overhead.

(3) Fuzzy-logic support in multicast routing protocols: Multicast on-demand routing protocols use tables for selecting optimal multiple routes to a set of destination nodes. A fuzzy set of rules can be used for this purpose. The integration of the cross-layer design idea with fuzzy-logic support can enhance the performance of multicast routing protocols. In this direction, Sivakumar et al. [232] proposed the Cross-layer optimized Multicast Route finding Protocol (C-MRP), integrated with a light fuzzy-logic set of rules for selecting optimal multiple routes to a set of destination nodes based on available network

bandwidth, route stability, and node-to-node delay. Experimental results demonstrated that C-MRP outperforms other multicast routing protocols in all characteristics.

5.2. Future Directions

- Modeling Optimizations: In MANETs, flooding strategies such as Multi-Point Relays (MPRs) flooding can enhance the efficiency of routing protocols for MANETs in terms of energy and time consumption through the use of an energy-aware mechanism. Indeed, an energy-aware mechanism is required to control the flooding process in MANETs when route discovery is performed. Such an energy-aware mechanism (called Energy Aware Flooding) was proposed in [233]. It is noteworthy that this mechanism also improves the security of routing schemes to avoid Denial-of-Service (DOS) flooding attacks in MANETs. Creating and testing new mathematical models for flooding techniques, those mainly working under well-established power-efficient routing schemes will be very challenging and promising [234]. This direction will help researchers to propose new energy-aware flooding mechanisms in MANETs.
- Hybrid optimization algorithms for topology management in cluster-based MANETs. In cluster-based MANETs, new optimization algorithms are required for making effective clustering and adjusting power and energy parameters using topology management. The management of the network topology demands the construction of a graph that is equivalent to the real network. After that, the optimization algorithm will perform the clustering of this graph to make an optimal CH. To adjust power, the optimization algorithm can be based on an objective function that considers some factors that involve power, connectivity, mobility, link lifetime, and distance. An example of such an optimization algorithm is the Chronological-Earth Worm optimization Algorithm (C-EWA) [11] that does effective clustering and adjusts power and energy parameters using topology management. In MANETs, the regular re-clustering of nodes is required, but this process generates a network overhead (overload). To reduce this overload, Sharifi and Babamir [235] presented a clustering method that optimizes energy consumption in routing. The authors proposed a method called Imperialist Competitive Algorithm (ICA) that is based on evolutionary algorithms. ICA via numerical coding can find proper CHs. By estimating the mobility direction of nodes, it prevents the additional re-clustering of nodes. As a result, it reduces the overload generated from the re-clustering process. In ICA, a fitness function is used that accepts various parameters (e.g., battery power, network range, node degree, node velocity, and coverage rate of nodes) as inputs to increase the efficiency of routing. The authors validated the accuracy and reliability of their method using statistical tests and three sample case studies, including different numbers of nodes and ranges.
- Energy-efficient routing based on Learning Automata (LA): The LA theory can be used for improving the performance of energy-efficient routing protocols for MANETs. A learning automaton is a machine learning algorithm that selects its current action based on past experiences from the environment. Recently, based on the LA theory, Hao et al. [236] suggested a stable and energy-efficient routing algorithm for MANETs. First, they constructed a novel node stability measurement model and defined a successful energy ratio function. On that starting point, they gave the node a weighted value, used as the iteration parameter for LA. After that, the authors developed an LA theory-based feedback mechanism for the MANET environment to optimize the selection of available routes and to verify the convergence of their algorithm. The experiments showed that the suggested LA-based routing algorithm obtained the best performance in route survival time, energy balance, energy consumption, and satisfactory performance in end-to-end delay and PDR.
- Energy-Efficient Routing Mechanisms for Cloud-Assisted MANETs: In 5G networks, the Device-to-Device (D2D) communication has increased the rate of data transmission among mobile nodes.

A Cloud-Assisted MANET enhances the features of a MANET by joining it with cloud data centers and D2D communication. In a CA-MANET, cloud and MANET are formed in an overlay, while the MANET accesses the data centers of cloud servers via the super-peer nodes. Peer nodes are the mobile devices that are connected directly or indirectly within the MANET. Due to various causes (e.g., link failure, mobility, routing overhead, and even low battery power), the connection among the mobile nodes and peer nodes often renew. During this time, CA-MANET consumes a large amount of energy in seeking and connecting the mobile nodes. Therefore, in CA-MANETs, we must propose new energy-efficient routing mechanisms that will perform fast local route discovery between mobile nodes and peer nodes to minimize energy consumption. Such a scheme was proposed recently in [14].

Author Contributions: Writing—review and editing, D.K.; Writing—review and editing, V.K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AD-TDMA: Adaptive and Distributed TDMA; AMC: Adaptive Modulation and Coding; AODV: Ad Hoc On-Demand Distance Vector; AODV_RR: AODV Range Routing; AOMDV: Ad Hoc On Demand Multipath Distance Vector; AOMR-LM: Ad Hoc On Demand Multipath Routing with Life Maximization; CEER: Color-theory based Energy-Efficient Routing; CH: Cluster-Head; CL: Cross-layer; CLD: Cross-Layer Design; CLI: Cross-Layer Interaction; CLSP: Cross-Layer Scheduling Protocol; CR: Cognitive Radio; CSI: Channel State Information; DARPA: Defense Advanced Research Projects Agency; DSDV: Destination-Sequenced Distance Vector; DMP_EOLSR: Disjointed Multi-Path Routing Extended OLSR; DSR: Dynamic Source Routing; EAR: Energy Aware Routing; EELAM: Energy Efficient Lifetime Aware Multicast route selection strategy; ELBRP: Energy-Level Based Routing Protocol; ELGR: Energy-efficiency and Load-balanced Geographic Routing; EPAR: Efficient Power Aware Routing; ESAS: Energy-Spectrum-Aware Scheduling; ESDSR: Energy Saving DSR; FANET: Flying Ad hoc Network; FAR: Flow Augmentation and Redirection; FF-AOMDV: Ad Hoc On Demand Multipath Distance Vector with the Fitness Function; GPS: Global Positioning System; GPSR: Greedy Perimeter Stateless Routing; HCN: Host-Centric Networking; LAER: Link-stability and Energy-aware Routing protocol; LAR: Location Aided Routing; LEAR: Local Energy-aware Routing; LEARN: Localized Energy-Aware Restricted Neighborhood; LEER: Location-aided Energy-Efficient Routing; LMT: Lifetime-aware Multicast Tree; MAC: Medium Access Control; MANET: Mobile Ad hoc Network; MDR: Minimum Drain Rate; MTPR: Minimum Transmission Power Routing; MEA-DSR: Multipath and Energy-Aware on-Demand Source Routing; MECOR: Minimal Energy Consumption with Optimized Routing; MILP: Mixed Integer Linear Programming; MIMO: Multiple-Input Multiple-Output; MPF-MH: Modified Proportional Fairness model with Multi-Hop; MP-OLSR: Multi-Path OLSR; OFDM: Orthogonal Frequency Division Multiplexing; OLSR: Optimized Link State Routing; OMM: On-line Max–Min scheme; PAMAS: Power Aware Multi-Access protocol with Signaling; PEERMR: Predictive Energy-Efficient and Reliable Multicast Routing; PEMA: Predictive Energy-efficient Multicast Algorithm; PHAODV: Power-aware Heterogeneous AODV; PLR: Packet Loss Ratio; PSO: Particle Swarm Optimization; QoS: Quality of Service; QoE: Quality of Experience; RERMR: Residual-Energy-based Reliable Multicast Routing; RI-MAC: Receiver-Initiated MAC; RSS: Received Signal Strength; SINR: Signal-to-Interference-and-Noise Ratio; SLPR: Serial Linear Programming Rounding; S-MAC: Sensor-MAC; TORA: Temporally-Ordered Routing Algorithm; TDMA: Time Division Multiple Access; T-MAC: Timeout-MAC; VANET: Vehicular Ad hoc Network; WEEM: Weight-based Energy-Efficient Multicasting; WMSN: Wireless Multimedia Sensor Network; WSN: Wireless Sensor Network; ZCG: Zone-based routing with a parallel Collision-Guided broadcasting protocol.

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