Neighbor Coverage and Bandwidth Aware Multiple Disjoint Path Discovery in Wireless Mesh Networks

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Abstract
With the ease of appending new nodes without re-installing the whole network, the Internet of Things (IoT) builds several smart applications on Wireless Mesh Network (WMN). One of the important aspects of integrating WMN and smart IoT applications is to provide an energy-efficient and reliable routing protocol. Seeking the communication route that delivers the high-quality stream quickly over WMN is an important issue, but the maximum utilization of a single high-quality path leads to poor throughput and large communication delay, including route discovery and data forwarding delay. The broadcasting mechanism creates redundant transmissions of control packets into the network and reinitializes the blind route discovery process due to link disconnections leading to network resource constraints and high delay during the route discovery process. Moreover, the congestion in the communication route incurs data transmission latency. This paper proposes the Multiple Disjoint Path Determination (MDPD) mechanism based on-demand routing in WMN to formulate the path discovery and data transmission latency. Reducing the neighbor list into the uncommon neighbor set reduces the unnecessary latency in route discovery, and deriving high capacity multiple disjoint communication routes reduce the communication delay in the proposed work. The proposed work employs the queue dynamics in queuing delay, which mainly provides adaptability to the dynamics in network capacity and efficient diversity paths to the gateway node to infer the available bandwidth and optimize the network traffic. To fully utilize the advantage of heterogeneous routers, it disables the flooding of control packets across the stable mesh routers, excluding the initial route discovery process, because it enables the available route storage system in each mesh router. Hence, the proposed work efficiently supports wireless broadband internet access with reduced delay and control overhead. The simulation results demonstrate the fast detection of the multiple disjoint routes and data traffic optimization over the discovered disjoint routes in the proposed MDPD mechanism over WMN.

Keywords Wireless mesh networks (WMN) · Communication Delay · Multi-path routing · Interference · Uncommon neighbor Set
1 Introduction

A self-organized and self-configured Wireless Mesh Network, WMN consists of wireless mesh routers and mobile clients, where the mobile clients dynamically form the ad-hoc network and maintain the wireless mesh connectivity among them [1, 2]. The WMN is great for applying in IoT-based smart applications, where the clients always need to remain online [3, 4]. The WMN enforces a new router to maintain the connection alive if one router loses its wireless connectivity. Thus, the WMN becomes more viable for industrial and commercial IoT applications. There are several benefits of using WMN for IoT solutions since the Mesh-enabled nodes can capture live data and provide smart applications. IoT aware WMN has gained significant attention recently in supporting the routing as it generates a large volume of data that significantly impacts the routing operations in WMN. A cluster-based routing is proposed that supports load balancing and interference to overcome the networking-related issues [5]. In WMN, the wireless mesh routers with gateway/bridge function can integrate with various wireless networks such as WiFi and cellular networks. The mesh clients can connect to the internet or external network by forwarding the data packets to the gateway node. Key features of a WMN are flexibility and self-organizing capability. Building multihop routes for wireless communication in smart applications based on mesh topology requires an energy-efficient and reliable routing protocol. However, the traffic transmitted from the mobile clients to the gateways incurs overload on certain links. Thereby the routing performance is degraded in smart applications. Thus, it is necessary to introduce the modified routing strategy into the routing process over WMN.

According to the routing strategy, the existing routing protocols are divided into table-driven and source-initiated routing protocols. The table-driven routing protocols need to determine the routes constantly, and the routes are stored in the routing tables. However, in on-demand routing protocols, the source node initiates the route discovery process when necessary. Thus, the on-demand routing protocols utilize less bandwidth and incur less overhead than the table-driven routing protocols. Each time, the source node initiates the flooding of Route Request (RREQ) packets to discover the communication routes into the network. The path discovery latency is an important factor in WMN, where the data packets need to deliver quickly. It is necessary to control the unnecessary RREQ flooding to reduce the route discovery latency and utilize the complete network capacity to increase the communication speed.

The multi-path routing, which uses multiple diversity paths for data forwarding concurrently, is the best solution for improving communication efficiency and reducing the communication delay in WMN. The multi-path routing technique offer advantages such as resource maintenance, load balancing, bandwidth allocation, and fault tolerance [6, 7] over single path routing. Concurrent multi-path routing to the intended gateway through disjoint wireless routers reduces the impact of a link failure on communication. When a link is over-utilized, the alternative path diverts the traffic to ease the burden of the congested links. It effectively aggregates the bandwidth by allocating the data traffic through multiple paths to the same gateway. Moreover, it reduces the data delay in multi-path routing, as the alternative disjoint routes are identified to deliver the data packets quickly. In this work, the uncommon neighbor list knowledge and bandwidth-aware data transmission reduce route discovery latency and improve communication efficiency. To support the hybrid WMN, the proposed work makes the mesh routers silent without forwarding the RREQ packets, excluding the first route discovery process, because each stable mesh router retains the available routes to the gateway node always.
1.1 Aim and Objectives

The main aim and objectives of the paper are as follows:

- A primary aim of the proposed work is to improve the routing capabilities of WMNs for supporting several smart IoT applications.
- The main aim of the proposed work is to reduce the redundant transmission of RREQ packets across the network using the uncommon neighbor set that reduces the route discovery latency.
- To avoid the re-initialization of the route discovery process among stable mesh routers due to the link disconnections between the mesh clients enables the route storage system in each mesh router during the first route discovery.
- To provide a guarantee that the protocol never misses the best routes without incurring a large delay, include extra time in RTT after receiving the first RREP packet.
- To support the full utilization of channel capacity without incurring the congestion and unnecessary packet loss in the queue implements bandwidth aware traffic allocation among multiple disjoint routes.
- To evaluate the performance of the proposed work using Network Simulator 2 (NS2).

1.2 Problem Statement

In wireless communication, a major problem in the existing routing protocols is the communication latency, including route discovery latency due to blind broadcasting and data transmission latency due to the congestion in the communication route. In the case of a blind broadcasting mechanism, the routing overhead increases with respect to the network size. Often the link disconnection incurs data interruption, thereby reinitializing the route discovery process for establishing the new routes. The redundant re-broadcasting of control packets increases the collision in the physical layer as the data and control packets share the same medium in the network. The reinitialized route discovery process increases the discovery delay due to the frequent link disconnections and high medium access. Existing techniques implement random channel or slot selection for exchanging the control packets to avoid the broadcast collision in the MAC layer. However, it does not resolve the hidden terminal problem. It is necessary to propose the multi-path disjoint routes between the source and gateway. The congestion of one link influences other routes resulting in lower routing performance than expected. Thus, discovering independent routes in WMN needs to guarantee the routes with interference-edge disjointness and tolerable communication delay, including route discovery delay and data transmission delay.

1.3 Paper Organization

The paper is organized as follows: Sect. 2 discusses the previous works related to the multi-path routing and broadcasting mechanism in the WMN environment. The proposed MDPD routing scheme is discussed in Sect. 3. Section 4 shows the experimental results of the proposed MDPD mechanism, and Sect. 5 concludes the work.
2 Related Works

The recent advances in wireless mesh networks may impose different requirements on the design of routing protocols. Thus, it is important to know which routing protocol performance is better for mesh networks. In existing, many routing protocols are designed for the WMN, such as cross-layer based joint routing and rate adaptation protocol [8], trustworthy and energy-aware routing protocols based on software-defined wireless mesh networks [9], flow interference mitigation routing [10] are applied to various WMN environments. However, multi-path routing is preferred due to the potential benefits. The following section provides a detailed review of multi-path routing protocols.

2.1 Multi-path Routing Protocols

In order to address and support the occurrence of stable mesh routers in mesh networks, need different approaches used in the MANET. The multi-path routing is preferable since new routes under a large-scale network cannot be discovered quickly. Several multi-path routing protocols [11] have been proposed for discovering multiple communication routes between the source and gateway in MANET. In these protocols, a source node uses a single path for routing the data packets, and other routes that are already discovered between the source and gateway are used as the backup routes. The backup routes or the alternative paths are used only when the main route is failed. In case of a link failure on the main route, the source node switches the data transmission to alternative routes to the gateway instead of rediscover the communication routes. Moreover, when all the discovered routes are disconnected, reinitialize the route discovery process. However, it is not sufficient for WMN due to a stable backbone system. The reinforcement learning technique is used for energy-sensitive mesh networks [12]. The reinforcement learning technique populates and updates the routing table constantly to find a better route. It increases power efficiency, failure rate, and spectrum efficiency. However, with the increase in network scalability, the routing algorithm without learning capabilities becomes more significant.

Several works implement a multi-path routing method for improving the performance of mesh networks. However, without selecting the proper routing metrics, there is no use with multiple routing paths. Some routing works use a single aggregated value to determine a set of feasible paths [13, 14]. Although they reduce the route selection delay, this might not meet the constraints of important metrics and the requirement of high traffic networks, so a single aggregated value may not guarantee the reliable communication. In [6], the multiple discovered routes are used for the packet routing concurrently. In such a case, a node selects and forwards the packets through multiple paths for the same gateway. It increases network throughput and alleviates the problem of link disconnections among mobile clients. The number of multiple path routing is comparatively evaluated in [15] for various network parameters. The main advantage of these protocols is their distributed on-demand nature routing, but a more reliable solution is essential for multi-path routing in WMN. A local repair-based multi-constrained routing protocol is proposed in [16] for WMMNs. It provides a fast and cost-efficient route recovery, especially when the QoS is degraded on the routing path. It exploits the congestion threshold for each link based on its link quality, end-to-end path quality, and multiple constraints. Even though, to satisfy the end-to-end reliability, the multi-path routing technique needs to reduce the end-to-end route discovery
latency and link capacity measurement before selecting the communication paths for data forwarding.

### 2.2 Broadcasting Mechanisms

The important mechanism for the route discovery process is broadcasting. However, the broadcasting mechanisms of MANET incur unnecessary delay and resource utilization in the MANET environment [17, 18]. Moreover, the mesh routers have multiple radio interfaces with multiple orthogonal channels. Utilizing the feature of multi-channel is important to improve the performance of routing over mesh networks [19]. The packet redundancy in broadcasting leads to high resource consumption, contentions, and collisions. In [20], the gossip-based algorithm is used in which the packets are forwarded based on the probability model. Thus, the optimized route discovery algorithms [21, 22] reduce the routing overhead more than the blind broadcasting mechanism. The performance of the gossip-based approach is limited when the network density or traffic is high [20]. The coverage area and neighbor-based probabilistic broadcasting are proposed in [17]. The neighbor confirmation scheme ensures the router reachability, and the re-broadcast probability is set based on the neighbor coverage area. The neighbor knowledge-based Scalable Broadcast Algorithm (SBA) determines whether the packet reaches additional nodes. However, it is difficult to determine the multiple disjoint routes between the source and gateway with optimized broadcasting [23]. For WMN, it is necessary to optimize the broadcasting technique and determine multiple disjoint routes between the source and gateway node without incurring high routing overhead and delay.

### 3 Network Model

In the network G, all the nodes have the same transmission range R. Each node is denoted as N with a unique ID, and it belongs to G. Let \( \eta(N) \) denotes a set of neighbor nodes of N. It means the nodes \( \in \eta(N) \) are within the transmission range of N, and it receives the packets transmitted by N. A node N should know the information of its direct neighbors,

![Architecture for the mesh network in smart applications](image)
including their identities. The following Fig. 1 shows the wireless communication in a mesh topology.

The following Table 1 lists the notations used in the proposed work.

Every node ∈ G obtains its 1-hop η(s) neighbor information using the HELLO message broadcasting by each node. Likewise, every sender node broadcasts RRRQ packets to identify a better route to the destination. Instead of blindly broadcasting the RREQ packets into the network, the proposed methodology attempts to reduce the number of forwarding nodes without shrinking the coverage area of a sending node s. If a node η1(s) receives a flooding message for the first time and η1(s) satisfies the forwarding condition, η1(s) is designated as a forwarding node. The necessity of control message forwarding is decided based on the uncommon neighbor list. In other words, in identifying the forwarding nodes, Fw from the neighbor list should satisfy the condition: Coverage area of node s, C(A)s must be covered by the entire forwarding nodes η(s). The C(A)s by the η(s) can be formally defined as follows.

\[
\bigcup_{i=1}^{\|\eta(s)\|} d(i) = \bigcup_{s \in G} d(s)
\]  

\[ (1) \]
For example, a node \( s \) has three neighbors, such as \( \eta(s) = \{u, v, \text{ and } w\} \). They make up the neighbor’s area of \( s \), and so a restricted forwarding list from 1-hop neighbors should be enough to cover all of \( s \)'s 2-hop neighbors if only the forwarding nodes are involved in the RREQ broadcasting. In other words,

\[
\bigcup_{f=1}^{[F_w(s)]} d(f) = \bigcup_{i=1}^{[\eta(s)]} d(i)
\]

There is no need for nodes \( \in F_w \) to broadcast the RREQ message. The following sections describe the issues in RREQ broadcasting latency and also the determination of \( F_w \) from the neighbors.

### 3.1 Problem Formulation

The main problem associated with the on-demand routing protocol is communication latency. Generally, many metrics related to the on-demand route discovery latency, such as network traffic rate, node mobility, and average one-hop neighbor distance of the network and control packet processing time at intermediate nodes, contribute to route discovery latency [21]. The blind broadcasting mechanism mainly incurs the latency of route discovery. In an on-demand route discovery process, a source node broadcasts the RREQ packet in the network. Initially, a source node broadcasts the RREQ packet to the one-hop neighboring nodes. The neighboring nodes re-broadcast the packet, including its id, to one-hop neighboring nodes. If it has seen the same packet already, the RREQ is considered a duplicate and discarded. If the intermediate nodes have a fresh route to the gateway, it sends the Route Reply (RREP) packet to the source node via the same route. Otherwise, the packet is broadcasted towards the gateway until the packet’s living time has expired and establishes the routes to the gateway.

A source node estimates the route discovery time, \( T_{\text{discovery}} \), when it broadcasts the RREQ packets. It represents that the source node takes \( T_{\text{discovery}} \) time to discover the multiple disjoint routes to the gateway. This \( T_{\text{discovery}} \) is the total route discovery latency, including broadcasting time, waiting period, and replying time. The given formula can express the route discovery latency,

\[
T_{\text{discovery}} = \{T_{\text{broadcasting}}\} + \{T_{\text{waiting}}\}_{\text{network traffic}} + \{T_{\text{reply}}\}
\]

\( T_{\text{broadcasting}} \) is defined as the total traveling time of the RREQ packet in the network. As each node broadcasts the RREQ packet to all of its neighbors, it determines the time to traverse the average hop length of the network and the maximum number of hops between the source and gateway (\( NH_{\text{max}} \)). In the worst case, consider that the source and gateway are placed on two different network edges. By default, the distance between the source and gateway as network width means the nodes are placed on two different edges.

\[
T_{\text{broadcasting}} = \left( NH_{\text{max}} \cdot \frac{R}{v} \right)
\]

where \( R \) is a communication range of a node, and it is used to represent a maximum hop length of a one-hop neighbor, \( v \) represents the packet speed, and \( \eta \) represents the number of one-hop neighbors in the communication range \( R \). \( NH_{\text{max}} \) is estimated based on the network Height (\( H \)) and Width (\( W \)).
Moreover, the $T_{\text{waiting}}$ is based on the network traffic rate, which denotes the number of source and gateway pairs in a particular interval or how many nodes access the medium ($N'$) within a particular time interval ($T_i$). If other nodes access the medium at a particular interval, a new node waits almost ‘$\beta$’ time for sending the RREP packet back to the source node, as it is a unicast routing.

Thus, instead of using the blind technique in the route discovery, in the proposed work, the MDPD mechanism employs uncommon neighbor set-based restricted broadcasting that significantly reduces route discovery latency.

### 3.2 Multiple Disjoint Routes Discovery (MDPD) Based On-Demand Routing

Disjoint ness is an important factor for discovering multiple routes to the gateway node, but the duplicate Route Request packet (RREQ) reception induces unnecessary transmissions, resulting in high routing overhead. Duplicate packets and retransmissions due to the mobility of nodes may exacerbate congestion in the network. Multiple disjoint routes are employed for data transmission to reduce the impact of unnecessary delay and congestion on the protocol performance. However, the time consumption for discovering multiple disjoint paths to the gateway node is quite large. The proposed system employs the uncommon neighbor set to limit the RREQ broadcasting. Moreover, it includes the end-to-end capacity estimation for traffic allocation among multiple disjoint routes. Thus, the proposed system reduces the determination time of disjoint paths to the gateway. The following Fig. 2 shows the block diagram of the proposed methodology.

#### 3.2.1 MDPD Mechanism

The proposed MDPD-based on-demand routing comprises two phases such as route discovery based on uncommon neighbor set and route maintenance and data forwarding [17]. The routing paths which have high capacity are selected for the data transmission. In the route discovery phase, each node estimates the uncommon neighbor set and
broadcasts the RREQ packet only to the neighbors in an uncommon neighbor set. RREQ includes a hop count as one of its fields. Each node increments the hop count in RREQ when it receives. The gateway node replies to the source node with the RREP packet through the reverse path of the received RREQ packet. Each node that receives the RREP packet measures the link capacity in available bandwidth. A node may receive more number of RREP packets from different disjoint routes. If a node receives one or more RREP packets from the gateway, it selects the RREP packet with high capacity and allows it to traverse towards the source node, and it stores the remaining routes in the route list. Thus, the proposed MDPD mechanism reduces the re-broadcast delay in the route discovery phase.

The proposed MDPD-based on-demand routing discovers multiple routing paths using fewer control messages. Instead of using a blind technique for broadcasting the RREQ packets to neighboring nodes in the communication range, the proposed work focuses on neighbor knowledge-based broadcasting. To reduce the re-broadcast latency or duplicate transmissions, exploit the restricted broadcast technique, including neighbor coverage knowledge. It avoids duplicate packet transmission and joint path usage in multi-path routing. Thus, a node that receives the RREQ packet needs to broadcast the RREQ packet only to the uncommon neighboring nodes.
The need to estimate the uncommon neighbor set is shown in Eq. (9). A source node appends its neighbor list in the RREQ packets before initiating the discovery process. A node that receives the RREQ packet estimates its uncommon neighbors with the sender node using the neighbor information included in the RREQ packet and broadcasts it if only the uncommon neighbors are high. In addition, a node discards the packet if it has seen the packet already and adjusts the uncommon neighbor set $\eta'$:

$$\eta'_i = \{\eta_i - [\eta_i \cap \eta_s] - S\}$$  \hspace{1cm} (9)

where $\eta_i$ and $\eta_s$ represent the neighbors of node $i$, and $S$ and $\eta'_i$ represents the uncommon neighbor list of node $i$ with node $S$. To sufficiently reduce the route discovery latency exploits the neighbor coverage knowledge. The main aim of the neighbor coverage knowledge utilization is not only to avoid the duplicate packets but to distribute the RREQ packet more quickly in the network. Suppose the intermediate nodes have the largest number of uncommon neighbors with the node according to the Eq. (9), the $T_{\text{broadcasting}}$ is high. If it has less number of common neighbors, $T_{\text{broadcasting}}$ and $T_{\text{waiting}}$ are small.

### 3.2.2 MDPD Initial Route Discovery Latency

In the proposed system, each node has 11 channels and four different physical layers as it implements IEEE 802.11 g standards in the Multi-Channel MAC layer in which a common channel is assigned as a control channel. In the control channel, the value of $T_{\text{discovery}}$ is estimated based on the estimated max $H_i (\eta')$ value. Thus, the Eq. (4) is rewritten as,

$$T_{\text{broadcasting}} = \left( NH_{\text{max}} \times \frac{\max H_i (\eta')}{\nu} \right)$$  \hspace{1cm} (10)

where $\max H_i (\eta')$ denotes the maximum hop length of a node in $\eta'$, instead of taking the node’s communication range, because there is a possibility for $H_i (\eta') \ll R$. Due to the reduction of duplicate packet transmission in the route discovery process, the $T_{\text{broadcasting}}$ period is reduced [24]. Thus, the value of total delays, such as $T_{\text{discovery}}$ is reduced significantly based on the restricted broadcasting mechanism in the proposed system.

### 3.3 Route Maintenance

In the route discovery process, the sender node floods the RREQ packets in the network. Each node that receives the RREQ packet is responsible for re-broadcast the packet to the uncommon neighbor set unless it is the gateway. In response to an uncommon neighbor set-based route discovery, a gateway may learn or receive more RREQ packets from multiple disjoint routes. The gateway replies to all the RREQ packets with the RREP packets, but the RREQ packets should be received within the TTL period, equal to the $T_{\text{broadcasting}}$.

The gateway node measures the modified TTL ($TTL_m$) when it receives the first RREQ packets based on the hop count included in the received packet. The RREQ packets with the $TTL_m$ expired are discarded. Otherwise, it replies with the RREP packet, including $TTL_m$. From the gateway, the RREP packets are routed back to the source node via the reverse path of the RREQ packet. Each router in the path calculates the RTT period based on $TTL_m$ for receiving further RREP packets after receiving the first RREP packet. In each path, each node retains the path for the received RREP packets.
within the estimated RTT period. Moreover, it measures the capacity for all the received RREP packets. The packet with high capacity is allowed to travel back to the source node. The alternative routes are maintained and used for data forwarding when the main route fails. This mechanism responds to the unpredictable neighbor changes to be much quicker.

In the proposed work, a gateway node sets the $TTL_m$ value for receiving RREQ packets. Each RREP receiver estimates the RTT based on the $TTL_m$ for receiving further RREP packets. In Eq. (11), the $TTL_m$ value of received RREQ packets is determined. Where $H$ represents the hop count of the first received RREQ packet, and $c$ represents the constant value.

$$TTL_m = H + R + c$$  \hspace{1cm} (11)

Each node determines the RTT based on the used $TTL_m$, shown in Eq. (12).

$$RTT = \left(2^*TTL_m\right) + T_b$$  \hspace{1cm} (12)

The source node waits for an RTT period to collect all possible communication path information to the gateway. Where $T_b$ denotes, the time is designed to boost the RTT period if an RREP is on the way to the source node. Moreover, a node, after receiving the first RREP packet, estimates the RTT using $TTL_m$. For a specific network topology, $T_b$ is constant. Therefore, the RTT period is only adapted to the used $TTL_m$ value. For example, consider the disjoint path such as A-B-K-M in Fig. 3. A node k receives RREP packets from two different disjoint paths within the estimated RTT value. These routing paths are K-M and K-L-M. It retains the available routes to the reachable gateway node M. It allows the highest capacity RREP packet, such as K-M, to travel through its path to improve system performance. A sender node initiates the data forwarding based on its estimated capacity through the discovered routes when the RTT of the first received RREP packet has expired.

![Fig. 3 MDPD route maintenance](image-url)
3.4 Available Bandwidth Estimation

Consider, each disjoint route, $D_{rt}$ to the gateway includes $L_i$ number of links ($i=1, 2, 3, 4,..., n$). The residual path bandwidth of a complete disjoint path, denoted by $D_{rt}(B)$, is the minimum link residual bandwidth of all links, $L_i$ on $D_{rt}$. The mobile clients’ link capacity estimation scheme relies on the information available at the MAC layer. The MAC layer properties such as MAC busy ($M_{busy}$), MAC idle ($M_{idle}$) period, Queue_packet waiting ($\tau$) period, and the number of successive transmissions ($T_s$) within an interval $d$ are used to measure the link capacity ($B_i$). In Eq. (13), $\alpha$ is a constant value. From Eq. (14), the minimum value of $L_i$ is set as the path residual bandwidth $D_{rt}(B)$.

$$B_i = \left\{ \alpha \ast \left( \frac{T_s \ast M_{idle}}{M_{busy} \ast d} \right) \right\} - (1 - \alpha) \ast \left( \frac{q}{d} \right)$$

$$D_{rt}(B) = \min(L_i) \text{ where, } i = 1, 2, 3, ...., n$$

A sender node initiates the data transmission when it receives the RREP packets with high path residual capacity. The traffic of the sending node is allocated based on the estimated bandwidth value. Thus, it utilizes the channel capacity efficiently without incurring congestion in the network. The algorithm of the proposed methodology is as follows.
Route Discovery Process ();
Route Maintenance Process ();
Route Selection and Data Forwarding ();

At Sender Node,

Route Discovery Process {
    Neighbor List, $\eta(N)$ Identification using Beaconing;
    Uncommon Neighbor List, $\eta'$ Generation () {
        For $i=1;i++;i<|\eta(N)|$
            For a node, $i \in \eta$(sender node)
                If Id$(i) == Id(\eta(i))$
                    Increase the count of $\eta'$ by one
        }
    Restricted RREQ Broadcasting using $\eta'$;
}

At the Destination Node,

Route Maintenance Process () {
    Measuring TTLm and RTT ;
    Establishing Reverse Path to the Source Node;
    Estimating Bandwidth of a link; }
Route Selection and Data Forwarding () {
    Selecting a path with high residual capacity;
    Initiating Data Forwarding; }  

Algorithm for Proposed MDPD

3.5 MDPD Adaptive to Heterogeneous Routers

The WMN is a particular type of MANET, and it shares the characteristics of multihop communication, scalability, and mobility-related issues as MANETs. Hence, the MANET routing protocols are suitable for WMN, but in which unnecessary latency and resource utilization is incurred due to the presence of heterogeneous nodes such as mobile clients and mesh routers or stable routers. Thus, there are significant changes in the performance of MANET’s routing protocols in WMN. The proposed MDPD mechanism is suitable for both the MANET and WMN, reducing the unwanted delay and resource utilization in the WMN.

Initially, the MDPD mechanism incurs the same delay in WMN as MANET because no route is established among the mesh routers. If the route discovery process is initialized, the mesh routers retain multiple fresh routes to the reachable gateway routers, connecting
other networks or the internet. The rediscovery of routes to the gateway from the mesh routers is unnecessary because the topology changes due to the mobility of mesh routers being very less. However, route rediscovery is necessary for mobile clients to determine the routes to the mesh routers because the mobile clients induce high link disconnections due to their mobility. To design a routing protocol to adopt these different characteristics with reduced control overhead includes the disjoint sub-paths maintenance scheme in the proposed system. If a node initiates the route discovery process to the gateway node, the RREQ packets are broadcast to the uncommon neighbor set until it reaches a mesh router with the discovered route to the gateway. Thus, it avoids unnecessary delay, routing overhead, and resource utilization in the network. The RREQ re-broadcast and reply delay are reduced due to the maintenance of established routes to the gateway node from the wireless mesh routers, and a limited \( \text{TTL}_{\text{m}} \) period is shown in Eq. (17).

\[
T_{\text{re-broadcast}} = \left\{ \alpha \ast \left( H - \left( \frac{D_{\text{mb}}}{H_l} \right) \right) \ast \left( \max H_l (\eta')/\nu \right) \right\} \tag{15}
\]

\[
T_{\text{reply}} = \left\{ \left[ N_r(H) - \left( \frac{D_{\text{mb}}}{H_l} \right) \right] \ast \left( H_l/\nu \right) \right\} \tag{16}
\]

\[
\text{TTL}_{\text{m}} = \left\{ \left( H - \left( \frac{D_{\text{mb}}}{H_l} \right) \right) \ast \left( \left( \alpha \ast \eta' \right) + \left( H_l/\nu \right) \right) \right\} \tag{17}
\]

where \( D_{\text{mb}} \) represents the Diameter of the Mesh Backbone. There is no need to take the wireless mesh backbone area for determining the route to reach the high capacity gateway node because the mesh routers retain the available disjoint routes to the gateway node in its route list. When an RREQ packet reaches the wireless mesh backbone, the high capacity routes to the gateway node are attached to the RREP packet and sent back to the source node.

For example, the final design of the MDPD process in WSNs is shown in Fig. 4. When a sender node A initiates the route discovery process, the RREQ packets are broadcasted until it reaches the first mesh router in the mesh backbone since the mesh routers retain the available routes to all reachable gateway nodes. Thus, the mesh router attaches the feasible route information to reach the gateway in the RREP packet and sends it back to the sender.
node. The route failure is intimated by the Route Error (RERR) packet. Thus, the node which maintains the route removes the failed route from the list. Moreover, a mesh router that has a route to the gateway node determines the $TTL_m$ value based on the area of wireless mobile clients’ network, but not considering the wireless mesh backbone area. The actual waiting time of a source node for receiving the high-capacity RREP packets from the gateway node before initiating the data transmission is $RTT$ [22]. The restriction of $RTT$ value based on the proposed work reduces the unnecessary delay of data transmission initiation in WMN successfully.

4 Performance Evaluation

4.1 Simulation Model

NS-2-based simulation is conducted to show the performance of the proposed MDPD based on-demand routing protocol over the wireless mesh network. The simulation is performed with different densities of nodes. The simulation model consists of randomly deployed 100/200/300 nodes, and these are randomly placed within the $1000 \times 1000$ m$^2$ area. The moving velocity of the node is 25 m per sec, and it pauses for 0-40 s. The communication range of a node is 100 m. The network is simulated for 900 s. This simulation study focuses on routing parameters such as communication latency, throughput, and

![Fig. 5 Route discovery latency versus path length](image-url)
normalized overhead to analyze the performance of the proposed MDPD based on-demand routing protocol with the MP-DSR [15] routing protocol in mesh networks.

4.2 Simulation Results

4.2.1 Route Discovery Latency

Route Discovery latency is defined as the time taken by a node to determine the shortest route in terms of a hop count to the gateway from the source node using control packets, and it is shown in Fig. 5. It describes the path length impact on the route discovery latency. The main reason behind the route discovery latency is the frequent blind broadcasting of the route discovery process. Moreover, the route discovery latency is decreased with the Node Density (ND) in the network. In existing protocols, the sender node initiates the route discovery process without applying any limitations, which leads to duplicate packet transmissions, and thus the route discovery latency is increased from 7.5 to 9 µs. However, the proposed work initiates the neighbor knowledge-based route discovery process that reduces the duplicate packet transmission during the route discovery process. Considering the uncommon neighbor set for RREQ broadcasting, the proposed protocol significantly reduces the route discovery latency range from 9 to 6 µs, even under a sparse network. The estimation of TTL and RTT values based on the source position information can define the maximum time to travel in the network, and thus, the network resource and time consumption are low. Moreover, the maintenance of available alternative shortest routes reduces the reinitialized route discovery delay due to the link disconnections. Thus, the proposed work reduces the 13% route discovery delay induced in the existing MP DSR protocol.
4.2.1.1 Throughput

Throughput is defined as the number of bits successfully delivered to the gateway per second. The throughput is shown in Fig. 6 describes that the throughput is degraded when the node disjointness is decreased. The proposed work can infer the available bandwidth and optimize network traffic using queuing dynamics for queuing delay. It provides adaptability to the dynamic bandwidth conditions and efficient diversity paths to the gateway. The node disjointness is enhanced by eliminating a common neighbor set from the neighbor list because it removes the duplicate packet reception during the route discovery process. Thus, the proposed work improves the throughput with node disjointness. However, network throughput is degraded from 29 to 16 Mbps when the numbers of source and gateway pairs (SD) increase in the network because the node disjointness is less when the number of source and gateway pairs is increased from 5 to 15. Supporting the heterogeneous nodes in the network through the restriction of RREQ broadcasting among mesh routers except the initial route discovery process increases the throughput performance by 30% more than the existing protocol under a highly dynamic network topology.

4.2.1.2 Normalized Routing Overhead

The normalized routing overhead is the ratio between the number of control packets transmitted to the number of data packets received. The normalized overhead is shown in Fig. 7, which describes that the normalized overhead increases from 0.42 to 0.5 when the node common neighbor ratio and Pause Time (PT) are decreased in the range of 10 to 0 s. Existing protocols employ blind broadcasting for the route discovery process. Thus it increases the number of RREQ packets broadcasted in the neighborhood. It increases the normalized routing overhead in the network, and it is varied based on the network traffic. However, the MDPD-based on-demand routing protocol reduces the number of RREQ broadcasted in the neighborhood by eliminating uncommon neighbor sets. The control packets used for the route discovery process are less than the total number of transmitted data packets in the network. However, it is increased slightly from
0.35 to 0.42 when a link disconnection rate is increased (10 to 0 PT) due to unpredictable node mobility. Moreover, the maintenance of available alternative shortest routes reduces the normalized routing overhead because there is no need to broadcast the RREQ packets among the mesh routers in the backbone network, excluding the first route discovery process in the network.

5 Conclusion

In this paper, a Multiple Disjoint Path Determination (MDPD) mechanism based on-demand routing in WMN is proposed that formulates the path discovery latency. By employing an uncommon neighbor set, it derives the high capacity of multiple disjoint communication routes among source and gateway. The available bandwidth aggregation and network traffic optimization using queuing dynamics in queuing delay eliminate the routing issues. In other words, the unnecessary waiting delay due to duplicate packet transmission is eliminated. Moreover, it is adaptable to the dynamic bandwidth conditions and efficient diversity paths among source and gateway. The disabled flooding of control packets across the mobile routers and available route storage system enables each mesh router to attain the benefit of heterogeneous nodes in wireless mesh networks. Thus, it reduces the route discovery delay and improves network throughput. The performance of the proposed MDPD algorithm is simulated using the NS2 simulator and analyzes the routing efficiency over mesh networks. The simulation comparison reveals that the proposed MDPD algorithm is more suitable for mesh networks than existing routing protocols.

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Declarations

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