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Rapid and Reliable Routing Mesh Protocol (RRRMP)

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***Abstract*— In Wireless Mesh Networks (WMNs), packets are frequently lost or excessively delayed due to the failure of links and nodes, or the existence of bottlenecks along their routing paths. This often causes an outage or performance degradation for the clients. A mesh fashion topology of WMNs enables the capability to relieve this issue by using multi-path routing as a possible solution. Therefore, we propose a novel multi-path routing protocol that utilizes the mesh connectivity of WMNs in order to enhance the delay and reliability. The designed protocol discovers one primary path and multiple mini-paths between a source and a destination. Whilst the former connects the source to the destination, the latter connects pairs of intermediate nodes along the primary path. Multiple copies of packets are simultaneously routed through the mini-paths to compensate for possible outage at intermediate nodes along the primary path or their corresponding links. Routing along these mini-paths is performed in a way that redundant copies do not cause an excessive congestion on the network. The designed protocol is specifically advantageous for applications which are sensitive to delay and throughput. For evaluation, extensive simulation is carried out using the OMNET discrete event simulator and subsequent results validate the performance of our proposed protocol.**

I. Introduction

In the recent years, wireless mesh networks (WMNs) have absorbed considerable attention as a promising technology towards forming an alternative backbone to Next Generation Networks (NGN) due to their capability for providing viable advantages such as extendibility, high throughput, and cost effectiveness in terms of infrastructure and utilization [1]. The main elements of a WMN are mesh access points (APs) and its clients, where the former have minimal mobility and are interconnected in a mesh fashion forming the wireless backbone. Further, the APs with multiple interfaces provide connectivity to clients and their neighboring APs.

Naturally, achieving a satisfactory performance is the goal of any network, and WMNs are not excepted. However, owing to the wireless medium and interferences among APs, this is a challenging task as both links and nodes are subject to severe performance changes. This frequently causes packet loss and excessive delay in WMNs. For example, packets are often lost due to broken links or buffer overflow at an AP. Alternatively, they may experience excessive delay due to the existence of a bottleneck along their routing paths. This problem specially heightens for applications which are sensitive to both packet loss and delay (e.g., emergency, VoIP applications). Tackling this issue requires the design of a new routing protocol, which is capable of enhancing both delay and fault tolerance. Needless to say, such a protocol should be simple and easy to integrate with the existing protocols and other functionalities, whilst adhering to the WMN environment. In fact, since mesh fashion connectivity between nodes in WMNs provide a great capability for facilitating the above, it is unfortunate that this feature has not been exploited by most of the existing protocols.

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The mesh connectivity within a WMN implies the connectivity between a pair of APs through multiple disjoint paths. Disjoint paths refer to paths, which do not share any intermediate APs, except the aforementioned pair. The existence of multiple paths provides the capability to send multiple copies of a packet to a destination via multiple paths. This motivates us to design a novel routing protocol aiming towards enhancing fault tolerance and delay. In essence, this protocol selects a primary path from a source to a given destination, whilst copies of packets are simultaneously and cognitively sent through selected mini-paths. The selected mini-paths connect pairs of APs along the primary path, in which APs in a pair have a distance of at least two hops from each other. Redundant packets are relayed in a way that prevents excessive congestion in the WMN. The designed protocol is efficient in terms of implementation and utilization, despite its considerable effectiveness as illustrated in our simulations.

The remainder of this paper is organized as follows. In Section II, background and related works are discussed. The proposed mechanism and the utilized metric for path discovery are explained in Section III and Section IV, respectively, followed by the illustration of simulation results in Section V. Finally, in Section VI, some concluding remarks are presented.

II. Background and Related Works

In general, routing protocols in WMNs can essentially be categorized based on their QoS objectives [2]. By and large, these objectives are distance, link-level QoS, end-to-end QoS (e.g, delay and bandwidth), reliability, load balancing and so on. Accordingly, a vast range of protocols have been developed in both ad hoc networks and WMNs targeting the above

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objectives [3][4][5]. Obviously, each of these protocols are best suitable for certain networks and applications, based on their QoS objectives, complexity and so on. On the other hand, simplicity of a routing protocol is advantageous as it facilitates the integration with other protocols and functionalities. This certainly eases the utilization of multiple protocols in a network in order to serve various applications with different QoS objectives.

The idea of utilizing multi-path routing in ad hoc networks and WMNs has existed for some time, and many of the recent protocols are developed based on the same idea [6]. This is due to the range of benefits that multi-path routing provides, such as bandwidth aggregation, delay enhancement, fault resilience, load balancing and so on. In numerous reliability aware protocols in ad hoc networks [7][8][9], multiple disjoint paths are discovered and maintained between a source and a destination, where packets are sent along a primary path, and mini-paths are mainly used as a backup in the event of failure at the primary path.

Nasipuri et al. [10] propose two extensions to Dynamic Source Routing (DSR) protocol [11], where the first extension proposes multiple disjoint paths from a source to a destination, whilst the second extension supplies the source and each intermediate node with an alternate route to the destination. They find that the latter extension outperforms the former in terms of reliability and path discovery rate. Further, their modeling efforts show that longer alternate paths tend to break earlier. The use of totally disjoint paths is also argued by [12], where it is analytically proved that fully exploited mesh connectivity results in a better reliability compared to a disjoint construction for a given topology. Our approach is different from [10] as; firstly, each intermediate node along the primary path is provided with at least one mini-path to a further intermediate node along the same path. This implies the superior exploitation of mesh connectivity and existence of shorter mini-paths in comparison to the designed protocols in [10], which subsequently results in a lesser rate of breakage and superior reliability. Secondly, in our approach, copies of a packet are simultaneously sent along the mini-paths, which results in reducing the end-to-end delay in the event of failure, as retransmissions are not required.

A totally different approach from the aforementioned schemes is proposed for WMNs in the Resilient Opportunistic MEsh Routing protocol (ROMER)[13]. In ROMER, a forwarding mesh is created on the fly for each packet and multiple copies of a packet are sent to several paths from a source to a gateway. ROMER assumes there exist a method for finding the minimum cost from each AP to a gateway, and the forwarding decision is subsequently taken based on the packets' credits. Despite the interesting approach of the ROMER, it has several unresolved issues. ROMER is particulary designed for packet traversals from a client to gateways, and it does not support other scenarios. Furthermore, packets are not unicasted towards the gateways but broadcasted. This makes the scheme unreliable for high rate transmissions [2].

Our contribution in this paper lies in the design of a routing protocol for particular applications, which are sensitive to both packet loss and excessive delay. The designed scheme utilizes the concept of multi-path routing for achieving the aforementioned criteria.

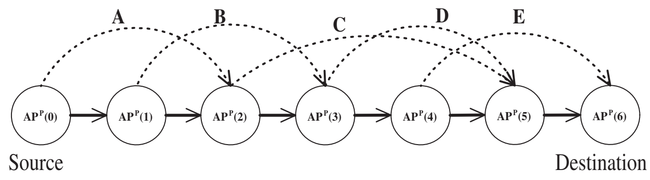

Fig. 1. Rapid and Reliable Routing Mesh Protocol.

III. Proposed Algorithm

In general, node and link failures are the most common reasons for packet loss in WMNs. The mesh connectivity of the WMNs implies the existence of multiple paths between a pair of source and destination. This characteristic is utilized in the designed protocol for immunizing the data traversal against both link and node failures. The concept behind the RRRMP is illustrated in Fig.1, where multiple mini-paths simultaneously convey backup packets for retrieving the data affected by packet loss or excessive delay in the event of failures at any intermediate AP or their corresponding links.

RRRMP selects a primary path from the source to a given destination (i.e., the path marked by solid lines in Fig.1). The selected path contains N nodes excluding the source and the destination. The nodes along the primary path are denoted by $AP^P(0), AP^P(1), ..., AP^P(N), AP^P(N+1)$, where $AP^P(0)$ and $AP^P(N+1)$ are the source and the destination, respectively. Thereafter, the source sends one copy of packets through the primary path, and other copies towards the second furthest AP (e.g., $AP^P(2)$). The mini-paths, which are indicated by dotted lines in the figure must not overlap with the primary path. For example, mini-path A connects the source ($AP^P(0)$) to ($AP^P(2)$). In the event that no mini-path is discovered, the source extends its discovery to the third furthest intermediate AP and this trend continues until the destination is reached. The intermediate APs along the primary path follow the same approach (e.g., mini-paths B, C, D and E). If multiple copies of a packet are received by an intermediate AP, the redundant copies are discarded. Since this technique aims to utilize the mesh connectivity of the WMNs to provide high fault tolerance, the primary path should be accordingly selected. To this effect, a new metric, called richness of mesh connectivity is designed for selecting a path with a richer mesh connectivity as discussed in Section. IV.

A step-by-step description of the proposed multi-path routing method is demonstrated with Pseudo-code under Algorithm 1 and explained as:

1) Source ($AP^P(0)$) selects a reliable and short path towards the destination ($AP^P(N+1)$). We refer the nodes along this path as primary nodes. The algorithm for discovering the primary path is discussed in Section IV.

Note that, it is assumed that the source routing mechanism is utilized, and sources attach the route information to the packets' header

2) Source sends one copy of packets through the selected primary path. This path may experience packet loss due to node or link failures. However, retransmissions of the lost packets may often compensate the packets loss, but impose higher delay. For securing the delay and reliability against such incidents, multiple copies of the packets are sent via the mini-paths, which connect pairs of APs along the primary path.
3) As previously stated, each primary node including the source further intends to discover M mini-paths towards the second furthest node along the same path. Unlike the primary path, which is selected based on its mesh connectivity richness and distance, mini-paths are only selected based on their distance (i.e., shortest path). Similarly, these paths should neither share a common node with the primary path nor with each other. The participating nodes along these paths are referred here to as alternate nodes. Moreover, node a along the mini-path m, which connects $AP^p(i)$ to $AP^p(i+j)$ (i.e., $j = 2$) is denoted by $AP^{A_m}_{i,i+j}(a)$. There are incidents that no further mini-path can be discovered towards $AP^p(i+j)$, in this case $AP^p(i)$ increases j by one. This iteration continues till M mini-paths are found by the corresponding AP or the destination is reached (i.e., $i + j = N + 1$). Undoubtedly, larger M results in an improved reliability, however may impose higher load to the network. The choice of M depends on the sensitivity of data and congestion status of the network.
4) Accordingly, M copies of a received packet are simultaneously sent through the mini-paths, whilst one copy is always relayed towards the next primary AP. Note that, in case of the source, the copies of originated packets are sent. Furthermore, APs along the primary path temporarily store the sequence numbers of the relayed packets, and subsequently discard those, which were earlier relayed.
5) It is further assumed that, nodes in our network periodically advertise their congestion status (i.e., buffer utilization) to their neighbors. Therefore, congested alternate nodes, which are preset to relay packets are skipped by the previous relayed node. In other words, each node checks the congestion status of the next alternate node; If it is congested (i.e., its buffer utilization is more than a certain threshold), another route discovery similar to the above is carried out, in which congested neighbors are excluded. If all neighboring nodes are congested, the packet is discarded. Note that, if the next relayed node is a primary node, the packet is relayed. This technique avoids excessive congestion due to the existence of redundant copies.

Furthermore, broadcasting feature of wireless communication implies that nodes can overhear their neighbors' data transmissions. As RRRMP may send multiple copies of packets to multiple neighboring APs, this data traversal can be done by one transmission. In other words, the sender multicasts the packets to the selected neighboring APs. On the other hand, successful reception of packets at a primary AP can be overheard by its neighboring nodes and subsequently they can discard other copies in advance. Note that, in RRRMP mini-paths are generally shorter as they are between two APs, which are few hops apart (normally two hops). Therefore, this results in minimal transmissions during the transmission of backup copies.

Algorithm 1 Pseudocode of the RRRMP

```
if (Current AP is Source) then
    Primary path discovery
    SET {AP^P(0), ··· , AP^P(N+1)}
    Send one copy of packet to AP^P(1)
    SET i = 0;
    Add discovered primary APs to Excluded List (EL)
else if (Current AP is a primary node) then
    Check the packet sequence number
    if (Packet was previously received) then
        Discard Packet
    else
        Store the packet sequence number
        SET i = AP's identifying numeral
        Send one copy of packet to AP^P(i+1)
        Add next primary APs to EL
    end if
end if
SET m = 0 and j = 2
while (m < M) and ((x+j) < (N+1)) do
    Discover shortest path to AP^P(i+j), which does not
    include APs in the EL
    Set {AP^{A_m}(1), ··· , AP^P(i+j)}
    if (Path discovered) then
        if (AP^{A_m}_{i,i+j}(1) congested) then
            Add AP^{A_m}_{i,i+j}(1) to EL
        else
            Send one copy to AP^{A_m}_{i,i+j}(1)
            SET m = m + 1
        end if
    else
        j = j + 1
    end if
end while
```

IV. Discovery of Primary Path

Traditionally, hop-count (i.e., the shortest path) is the main metric for selecting a routing path for many existing protocols [14][15]. The main advantages of this metric are its simplicity and low overhead requirements. Although shortest path provides a minimum number of intermediate APs towards a given destination, and an increased robustness against nodes' failure, it may not be necessarily rich in terms of mesh connectivity.

A path is considered to have a rich mesh connectivity, when its participating nodes have a high number of connectivity (links) with other nodes within their neighborhood. As this characteristic is exploited by the designed technique, a new metric is defined, which takes both distance and the richness of mesh connectivity into consideration. The richness of mesh connectivity (R) relates to the average number of links that each participating node contains along the path, measured by the harmonic mean as:

$$R = \frac{N}{\frac{1}{l_1} + \frac{1}{l_2} + \cdots + \frac{1}{l_n}} \quad (1)$$

where N denotes the number of participating nodes along the path and l represents the number of connected neighbors to the n^{th} node along that path. The reason behind utilizing the harmonic mean is that the mean strongly tends to be the least value of the elements. This is significant for the proposed technique, as a node with a few links may become a bottleneck, and may subsequently reduce the connection reliability. On the other hand, a shorter path is preferred as lesser nodes are involved in packet transmissions. Therefore, the metric for selecting the primary path denoted by U is related to the tradeoff of R and N, in which R and N should be maximized and minimized respectively. Therefore the path with the minimized metric of U is preferred as:

$$U = \frac{N}{R} = \frac{1}{l_1} + \frac{1}{l_2} + \cdots + \frac{1}{l_n} \quad (2)$$

Simply, the Dijkstra algorithm can be applied for discovering the primary path, where the weight of $\frac{1}{l}$ is assigned to each node throughout the WMN [16]. Therefore, for a given pair of source and destination, a path which results in a minimum U is selected as the primary path.

V. Simulation Results

We evaluate the performance of our proposed protocol using the OMNET discrete event simulator. The adopted network topology in the simulation contains sixty static APs, which are randomly distributed throughout an area of $800m \times 800m$. The transmission range of an AP is set to $100m$ and each AP generates packets towards a random destination for a random and limited period. Both the destination and the period frequently changes during the simulation. Moreover, the accessibility rate of the APs to the radio interface is modeled as a Poisson distribution, where the maximum achievable data rate is set to $17Mbps$. Each AP is equipped with a FIFO (First-In, First-Out) queue with a random buffer size (maximum 2 MB). Further APs advertise their congestion status to their one-hop neighbors every 0.1 second. The AP is assumed to be congested, when its buffer utilization is more than 60%. Since the mesh network topology is static, it is assumed that APs have full knowledge of the topology and path selection algorithms are performed at sources (source routing).

For performance comparison purposes, two scenarios are considered. In the first scenario, the shortest path is selected for relaying the generated packets from a source to a destination.

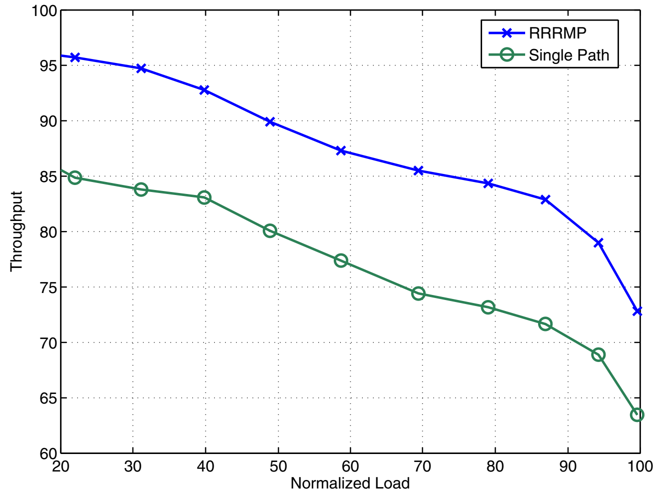

Fig. 2. Throughput comparison for the selected connections.

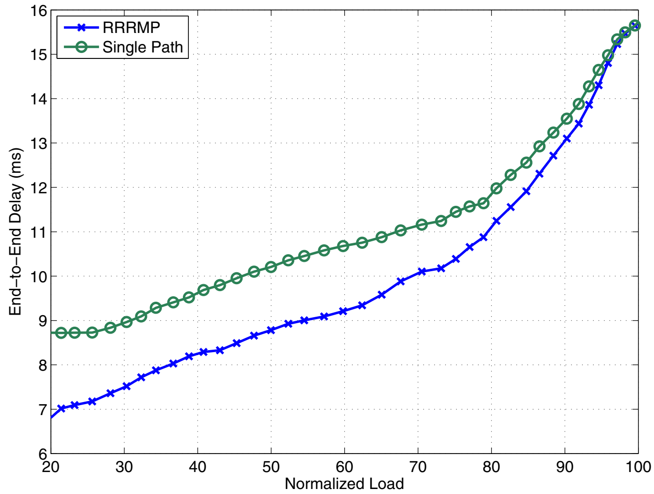

Fig. 3. Delay comparison for the selected connections.

In the results, this scenario is labeled as a Single Path (e.g., the OLSR protocol [17]). In the second scenario 10% of the connections are randomly selected to use the RRRMP, whilst the remaining connections utilize the same approach that is utilized in the first scenario. The number of mini-paths (M) for the RRRMP connections is set to 2. Note that, the performance of the system is illustrated versus the average load of the APs in the network. For an AP, this load relates to the sum of relayed traffic received from its neighboring APs and its generated traffic, against its available bandwidth. Intuitively, the average load of 100% does not necessarily mean that all nodes in the network are completely congested. In fact, it represents the condition, where some APs are overloaded and others are in less congested conditions, which subsequently results in the average of 100%.

Figure 2 illustrates the average throughput (i.e., successful packet transmission) achieved by those of connections that

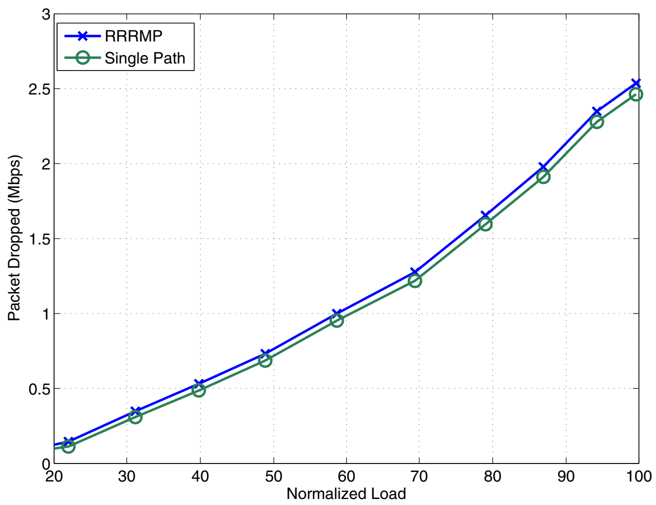

Fig. 4. Packet dropped comparison in the network.

use RRRMP in the second scenario. According to the figure, the RRRMP enhances the throughput by approximately 10% under all congestion conditions. Note that, it is assumed that links are faultless in our simulations, and packet loss only occurs due to buffer overflow. Therefore, the enhancement is resulted from the transmitted copies, which partly compensate the packet loss on the primary path. For both scenarios, the throughput decreases as load increases; this is due to the fact that an increased load intensifies the buffer utilization and subsequent throughput degradation. The throughput enhancement for RRRMP experiences a reduction for the load conditions over 60%. This is because of the RRRMP algorithm, which forces alternate nodes to drop the copies in the event that all its possible neighbors have a buffer utilization more than 60%. Additionally, many copies may be dropped due to buffer overflow on alternate APs.

The average end-to-end delay is illustrated by Fig. 3. The RRRMP improves the delay by more than 20% in non-congested scenarios, however this trend degrades under the load conditions for over 60%. This improvement is a result of the arrival of the copies prior to the arrival of the main packets as mini-paths are often quicker than the primary paths. This improvement declines in congested conditions as less copies are able to convey the mini-paths as discussed above.

Obviously, sending multiple copies results in an increased number of packets in the network, and subsequently increases the possibility of packet loss. The RRRMP intends to reduce this to a minimum by not relaying the copies to congested alternate APs in order to have a minimum impact on the performance of other connections. Accordingly, the average rate of packet loss in the network is illustrated in Fig. 4, where the cost of using RRRMP for 10% of the connections is shown. Although 10% is a considerable number of connections in the network, the packet drop rate of the network represents a slight degradation compared to the Single Path scenario. This can be considered as the drawback of the protocol against its considerable ability in enhancing reliability and delay.

VI. Conclusions and Future Works

In order to improve the throughput and delay for the end users of a WMN, a multi-path routing protocol was proposed. In the proposed technique, in addition to the primary path, multiple copies of a packet are sent through mini-paths, which connected pairs of intermediate APs along the primary path. This protocol exploited the rich connectivity of the WMN to enhance both delay and throughput. Simulation results demonstrated the validity of the proposal in improving the aforementioned goals. There are several challenges targeted to be studied in the author's future works: namely, developing RRRMP for on-demand routing scenarios and evaluating its performance through analytical modeling and more comprehensive simulations.

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