Routing over Best Links is not necessarily Better in Wireless Multi-hop Networks

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***Abstract*—The conventional approach of choosing the best route to carry network traffic in wireless multi-hop networks does not maximize the overall network throughput and can lead to short-term instabilities in network state with dire consequences. To date, wireless network route selection considers mainly network or link metrics, always picking the best links, thus channeling all packets through a subset of all available links. This leaves weaker links under-utilized although such links can in fact be used to carry smaller packets or packets with less stringent requirements and free up bandwidth on the better links for larger packets or traffic with higher service requirements. As network traffic volume and heterogeneity increase in future networks, we need to maximize the usage of available network bandwidth and distribute the network traffic load. We combine network link metrics and packet attributes to determine the successful packet transmission probability, and then use this outcome to pick suitable links to forward the packet, which is not necessarily the link with the best metric. To validate the efficacy of our proposed approach in routing performance and energy efficiency, we applied it in routing for wireless multi-hop networks. More importantly, we are able to spread the traffic across nodes in the network, thus achieving better network load-balancing and higher network resource utilization.**

***Index Terms*—packet attributes, link quality, routing metrics, wireless multi-hop networks**

I. Introduction

Routing metrics, which quantify the cost of getting across a link from one network node to another, are used by routing protocols to select the "best" routes for sending packets over the network. Link cost and hop-count are common metrics for routing in wired networks, like the Internet, while link quality metrics like Expected Transmission Count (ETX) have been designed for use in wireless mesh networks [1]. Ultimately, the aim is to select routes made up of the strong links with the best routing metrics (values) to send network traffic [2] because weak links are generally viewed as a hindrance to successful packet delivery [3]. This is intuitively correct as it improves the probability of successfully delivering packets to their desired destinations.

However, an undesirable side effect emerges when network traffic increases or during temporal bursts of network activity, namely, these "best" links become congested bottleneck links leading to packet loss while other links are under-utilized [4]. Higher layer protocols like the Transmission Control Protocol (TCP) will take remedial action by reducing the transmission rates and re-transmitting lost packets (introducing more network traffic) while protocols like the User Datagram Protocol (UDP) will continue to transmit unabated and, in fact, increase the transmission rates to consume more bandwidth.

The design of wireless networks, especially, mesh networks has become increasingly important to network operators [5]. While routing metrics have been extensively researched [6] when wireless multi-hop networks was proposed more than a decade ago, the emergence of new networks, applications and services has introduced significant new traffic types that were not previously considered. Besides a growing emphasis on the use of relaying and multi-hop transmission even in cellular networks to extend coverage and accommodate more connected devices [7], emerging applications like drone networks are motivating research in novel routing metrics too [8]. Nevertheless, the design approaches for wireless routing have predominantly concentrated on network conditions [9] and link attributes [10]. Other than possibly Quality of Service (QoS) requirements [11], packets in the network are not differentiated by their attributes, like size, coding scheme, etc.

In this paper, we first show how weaker links can be used to carry smaller packets and still provide reliable packet delivery, thus freeing up bandwidth on better links for larger packets or those with higher QoS needs. By adding packet attributes to link quality metrics, we propose a Network and Packet Attribute Aware (NPA^2) routing approach which can identify different routes for packets with different attributes (e.g., packet size) to spread the traffic load over more nodes in the network. This seemingly simple consideration, especially in the case for wireless multihop networks, is able to achieve better load distribution, alleviate the occurrence of bottleneck nodes, and reduce packet loss as well as overall packet transmission delay. By applying NPA^2 in a wireless multi-hop routing protocol, we show that our approach can increase the utilization of network resources by spreading the traffic across the network, thus achieving better load distribution and consequently improves overall network performance. This approach also improves the network's operational lifetime.

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II. Related Work

Routing metrics remain the focus of many performance and optimization studies in wireless multi-hop networks, given the important role that the routing metric plays on routing. Routing metrics are critical in optimizing the performance of routing protocols because they determine the data path from a source to a destination [12]. It must be carefully designed such that the chosen path provides optimum performance. Commonly used metrics include minimum hop count, bandwidth, delay, load, energy, bit error rate, expected transmission count, etc.

Hop count is suitable for mobile ad hoc networks (MANETs) because nodes are moving and routes need to be established quickly, while link quality-aware metrics are more suitable for non-mobile multi-hop wireless networks [13]. ETX [14] and its latter variants have been designed for use in wireless mesh networks where nodes are non-mobile and do not fit into the design assumptions of MANET protocols.

When designing routing metrics, it is also important to consider the network performance. Metrics that provide optimized routing from the packet perspective may not result in global optimal utilization of network resources. One approach to improve the utilization of links in wireless multi-hop networks is to route packets through links that have less traffic by adopting metrics that account for link occupancy (Link Occupancy Metric) and available capacity (Residual Link Capacity) [15]. These metrics can also accommodate links of different capacities in the routing decision and were shown to outperform ETX via experimental validation on a testbed. The spatial reusability of wireless links has also been noted as an important factor that can improve the throughput and proposed for use in routing [16]. While the broadcast nature of wireless links provides spatial reusability benefits, it is also the source of transmission interference among nodes in close proximity. Route selection that considers interference, link bandwidth, and probability of transmission failure, has been shown to improve overall network performance significantly [17].

It has been noted that small packets have a higher chance of being successfully transmitted and does not accurately reflect the link quality for transmitting larger packets, pointing to the small probe packets used by ETX [15]. Despite the observation, and to the best of our knowledge, there has been no attempt to differentiate packet sizes and take advantage of the fact that small packets, unlike large packets, can still be successfully sent over poorer quality links. With the increase in volume and heterogeneity of traffic brought about by new applications and the Internet of Things, in particular large volume of small packets from sensors and other devices, it makes more sense to send small packets with lower QoS requirements over weaker links and leave the better links for large packets or those with higher QoS requirements.

There has been a large amount of research done in wireless networks routing, including single routing, multi-routing and load balancing routing. The majority of these route discovery studies rely heavily on network conditions such as link quality, node density, interference, node energy, and node current load. In addition, there are studies that focus on packet attributes, where Quality of Service (QoS)-aware routing methods distinguish packets based on the data they carry (e.g., video, audio) and the associated requirements and constraints. Some research efforts have focused on packet attributes at the link layer of IEEE 802.11 networks, aiming to optimise the transmission performance of arbitrary packets [18]. At the same time, related studies suggest considering packet size when evaluating links in order to better assess link quality for optimal route selection [19]. However, to date, there has been no research that considers the use of packet attributes to intelligently distribute network traffic. Our work represents the first comprehensive study to take a network perspective, demonstrating that not all packets need to traverse the same network path composed of the "best" links. This makes it possible to naturally distribute network load while maintaining a high packet delivery rate, thereby improving overall network performance.

III. Packet Attributes In Route Selection

In this section, we present our approach of including packet attributes in the routing and forwarding decision, in addition to typical network metrics like wireless link quality, link bandwidth, etc. To the best of our knowledge, considering the packet attributes has not been done before in wireless multi-hop routing although radio resource allocation schemes in cellular networks do consider the traffic type. While different packet attributes can be used, we shall only use packet size to illustrate our proposed concept. Similarly, among various network link characteristics, we use bit error rate (BER) to illustrate our concept. Let us assume the simple network as shown in Fig. 1, where node S attempts to send a series of packets of size 20 octets and 128 octets to node D.

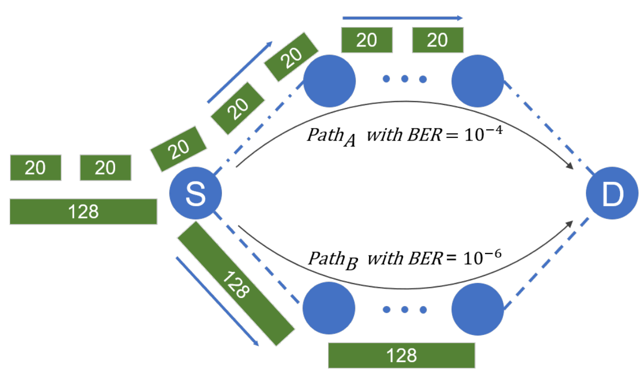


Fig. 1: Multi-hop Wireless Network Example

In wireless networks, when choosing an appropriate path between the source node and the destination node, the BER of the link between two adjacent nodes needs to be considered. Simply put, the link BER is the average number of bits received in error divided by the total number of bits received. BER is usually expressed as 10 to a negative power. For the links in Fig. 1 with BER of 10^{-4}, this means that of 10,000 bits transmitted, 1 bit had an error. Such links have poorer quality than those with BER of 10^{-6}, and if used to send packets can result in higher packet loss. We extend the notion of BER to paths as follows: we say that a path has BER b if all links along the path has BER $\leq b$.

A typical link quality aware routing protocol would pick $Path_B$ with lower BER of 10^{-6} (i.e., better quality) to send all packets. At the network routing layer, a packet is successfully transmitted if all the bits arrive without error. Therefore, the chances of a packet encountering a transmission error, denoted as the Packet Error Rate (PER), is related to the BER as follows:

$$PER = 1 - (1 - BER)^N \quad (1)$$

where N is the size of the packet in bits [20]. If we set a performance criterion of PER $< 5\%$, then the small packets of size 20 octets, with PER=1.59%, can be sent over the $Path_A$ with higher BER of 10^{-4}, leaving more bandwidth on the better route ($Path_B$) for larger packets. In fact, packets up to 64 octets in size can be sent over the weaker links while still satisfying the PER $< 5\%$ criterion. In this way, load is more evenly spread across the network naturally. With the envisaged increase in traffic from Internet of Things devices that comprise mostly small packets, this approach would have a significant positive impact on the network.

In the above discussion, we have not addressed interference issues caused by the link layer because relevant studies have shown that, in high-traffic scenarios, the majority of packet losses originate from the data packet buffering queues within nodes, while losses caused by interference at the link layer can be considered as negligible (<0.2%) [21].

IV. Network And Packet-Attribute Aware Routing

In reactive routing, a source node only searches its routing table for a route to the target/destination node when it has packets to send. A node further maintains routing information for an active node in the network only if there are data packets to be sent to that node. If there is no route to the target node in its routing table, it must send out a route request (RREQ) message that contains both the addresses of the initiating (source) node and the target (destination) node. A node receiving the RREQ first assesses whether it is the target node, and if it is, sends a Route Reply (RREP) message to the initiating node. If not, it then checks whether there is a route to the target node in its routing table and if a route exists, it also responds by sending an RREP to the source node; otherwise, it forwards the RREQ to its neighbours to continue searching for the target node and records the node that it received the RREQ from, in order to relay the corresponding RREP back to the initiating node later. This simple exchange of RREQ and RREP messages forms the basis of many reactive ad hoc routing protocols.

The core idea of NPA^2, unlike conventional routing approaches that consider only network-centric metrics, is to treat each packet differently based on its size and assign packets different transmission routes based on the PER. The PER with respect to different packet sizes is computed with Eqn. (1) using the BER that can be derived from measurements at the physical layer [22]. NPA^2 first assesses whether the PER threshold for transmission of packets can be met by the best routes in the network, which would be the ones with the lowest BER. The larger packets would be assigned to these routes. Other routes with higher BER, i.e., poorer link quality, may still be able to satisfy the PER threshold when used to send smaller packets, as shown in Section III. If all the available routes are unable to meet the PER requirements, then the packets will be sent by the shortest route. In this instance, PER is a pre-defined QoS threshold. However, it can also be an objective variable that the network aims to minimize/optimize to achieve the best packet delivery.

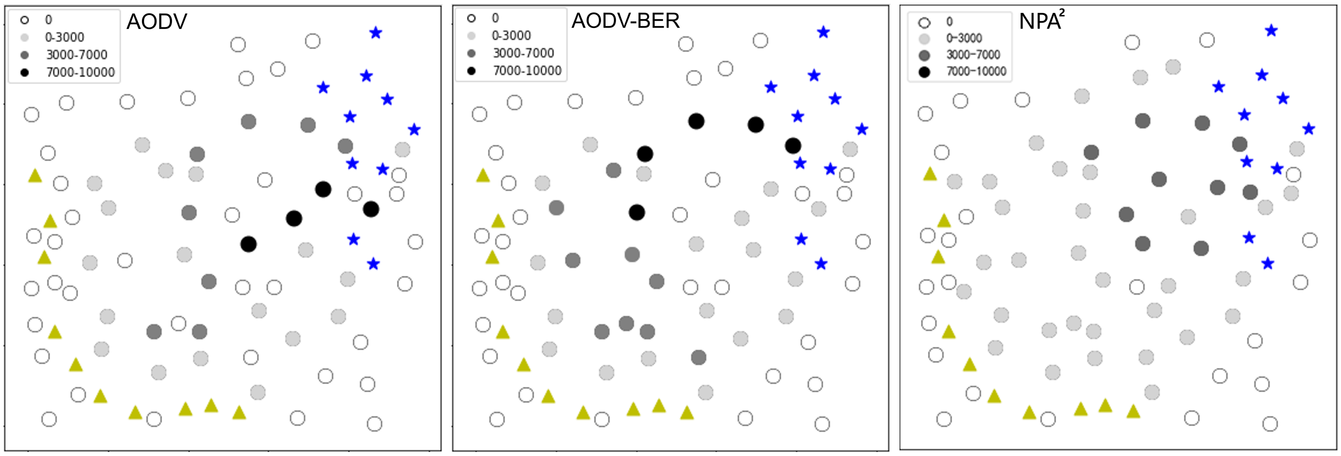
TABLE I: Simulation parameters

Parameter	Value
Simulated duration	600 seconds
Network area	1500m $\times$ 1500m
Number of nodes	$\{100, 200, 300, 400, 500\}$
Number of senders	10
Number of receivers	10
MAC protocol	IEEE 802.11
MAC data rate	2 Mbps
Transmit power	15 dBm
BER	Randomly chosen from 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8}

V. Performance Evaluation

To evaluate the efficacy of NPA^2, we used simulations implemented with the OmNet++ Simulator (version 5.4.1). Table I lists the key parameters used in the simulations. We used two packet sizes, viz. small packet of 32 bytes and large packet of 2048 bytes, which are less than the IEEE802.11 maximum transmission unit and fit within a single frame. Nodes transmit packets once every 0.25 seconds. Each simulation runs for 600 seconds with multiple runs to average the results. The PER threshold is a user-defined parameter, e.g., acceptable loss for streaming video traffic, and we used 5% as an indicative value of acceptable packet loss that can be tolerated without severe degradation of video quality [23].

We compared NPA^2 with the basic AODV routing protocol (as a baseline because it has been studied extensively by the wireless networking community) and a link-aware extension of AODV. The link-aware extension of AODV is a modified version of the MAODV-BER protocol [24] which selects routes based on BER and bandwidth. For a fair comparison with our scheme which does not consider link bandwidth and our simulations assumed a fixed bandwidth of 2Mbps, we disabled the bandwidth criteria of MAODV-BER and refer to this variant as AODV-BER. This comparator has been selected because it is the most recent among many similar approaches that have been integrated into AODV and validated using network simulations, unlike others e.g., [9] [10] that were only validated in limited scenarios without realistic routing protocols.



(a) (b) (c)

Fig. 2: Traffic Load Comparison where green triangles are source nodes and blue stars are destination nodes.

A. *Traffic Load Distribution*

One of the key problems that our packet-attribute aware routing aims to address is congestion arising from large volume of traffic being carried by the "best" routes as defined by network-centric routing metrics. For clarity, in Fig. 2, we show only the results for a 100-node network and categorize the intermediate relay nodes into four classes based on the traffic load handled by the nodes, viz. zero load (did not participate in packet transmission at all), light load (relayed less than 3000 packets), moderate load (relayed 3000 to 7000 packets) and heavy load (relayed more than 7000 packets.)

For AODV, traffic is routed via the most direct paths from source to destination nodes resulting in four nodes having to take on heavy traffic loads; these heavily loaded nodes are potentially taking on excessive loads that result in higher packet losses, as noted in the packet loss analysis later. In the AODV-BER case the selected routes are made up of the best quality links, which may not necessarily be the shortest. Nevertheless, this will also route all traffic over high-quality links, leading to heavily loaded nodes. NPA^2 spreads the traffic over more routes across the network, utilizing lower quality links that can still transmit smaller packets with the stipulated reliability. In this way, the benefits of the different schemes are exploited based on the packets' attributes.

B. *Packet Loss Rate*

As network traffic increases (due to increased node density or application traffic) or during temporal bursts of network activity, links selected by the routing protocols to send traffic become congested leading to packet loss while links that have not been chosen as routes become under-utilized. This is especially evident when routing metrics are entirely network centric. In our study, we increased the density of nodes by deploying more nodes in the same network area. Nodes will have more neighbours which will inevitably increase the wireless link contention especially when traffic is sent through a small of nodes resulting in significant loss. Spreading the

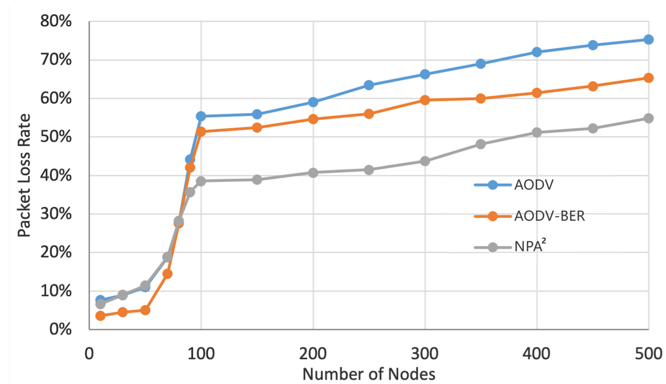


Fig. 3: Packet Loss Rate

traffic across the network helps to alleviate the congestion and reduces loss.

When the network is sparse, there are few alternative routes to choose from. Hence, as Fig. 3 shows, NPA^2 has the same loss rates as AODV for networks up to 80 nodes. AODV-BER chooses routes with best link quality and is able to achieve lowest packet loss. As the number of nodes increases, so does the packet loss. The number of available routes increases with the number of nodes, giving NPA^2 more choices to select and spread the network traffic load. Hence, as the network grows beyond 80 nodes, NPA^2 performs better than both AODV and AODV-BER. The use of higher quality links by AODV-BER also enables it to incur lower packet loss than AODV.

C. *Packet Delivery Delay*

For sparse networks, the number of available routing options to choose from is limited regardless of the criteria for choosing routes. This is evident from the results, in Fig. 4, for networks up to 100 nodes where the average packet delays among the protocols are not significantly different since the number of hops from source to destination do not differ much. AODV has the lowest delay because it picks the direct route with the least number of intermediate hops.

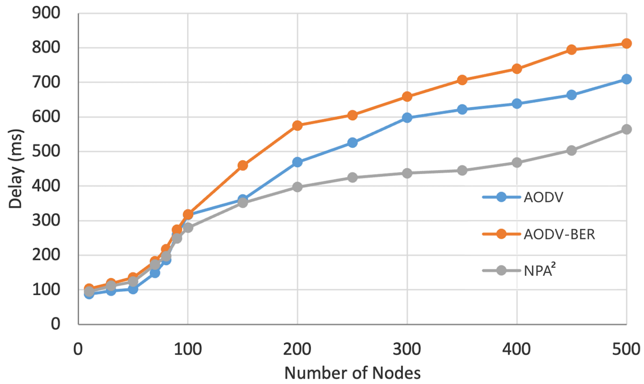


Fig. 4: Packet Delivery Delay

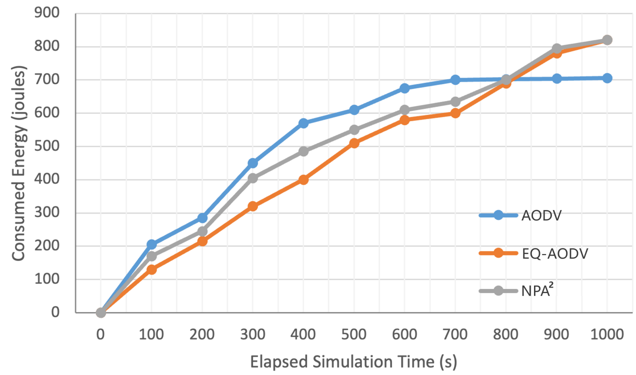


Fig. 5: Total Energy Consumed by Network

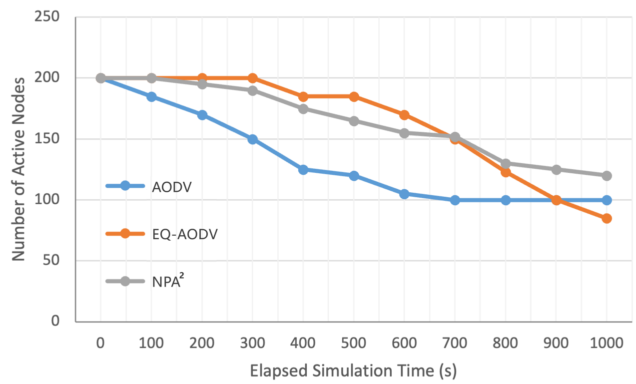


Fig. 6: Number of Active Nodes

As the network grows, there are more alternative paths to choose from. AODV and AODV-BER do not fully exploit this and send traffic through the few selected routes based on the network attributes. As a node relays more packets, the queue at the network interface grows in length and packets need to wait longer. Worse, as traffic increases, contention-based MAC protocols suffer from link level collisions that require packets to be retransmitted, incurring additional packet delays. The routes picked by AODV-BER which comprise better quality links can also traverse more intermediate nodes, resulting in AODV-BER having the highest delay.

On the other hand, NPA^2 chooses different routes for packets depending on their size. This spreads the routing load across more nodes in the network and reduces the number of heavily loaded nodes, as shown in Fig. 2. Most importantly, packet queues at the nodes would be shorter, translating to shorter waiting times for packets. Spreading traffic over the network also alleviates congestion and packet collisions at the link layer. Consequently, the overall packet delivery delay is reduced.

D. Energy Efficiency

To reduce the number of heavily loaded nodes and the overall packet delivery delay, our proposed approach spreads the routing load across more nodes in the network which may make the network less energy efficient since more nodes are now involved in the packet transmission. In order to assess the energy efficiency of our approach, we compared with EQ-AODV [25] which is an energy-efficient variant of AODV designed for wireless multimedia sensor networks; for fair comparison, the simulations ran for 1000s using the same parameters and network sizes comprising 200 nodes with limited power supply [25]. We added 1024-byte packets to align with EQ-AODV scenarios and included AODV as a baseline while AODV-BER was omitted since it was not designed with energy efficiency in mind.

The energy consumption of the whole network, as shown in Fig. 5, increased steadily over time as nodes transmit packets, with EQ-AODV consuming the least as per its design. NPA^2 distributes the traffic across the network which may result in longer paths and higher energy consumption; however, this is offset by energy savings from less contention and fewer collisions, hence fewer packet retransmissions. Overall, NPA^2 only consumes slightly more energy than EQ-AODV. Despite that, Fig. 6 shows that NPA^2 with better load-balancing kept more nodes alive and active than EQ-AODV, after the 700s epoch. The ability to find the right routes to suit the size of the packets not only increased the transmission success, which NPA^2 achieved much lower end-to-end delay, as shown in Fig. 7.

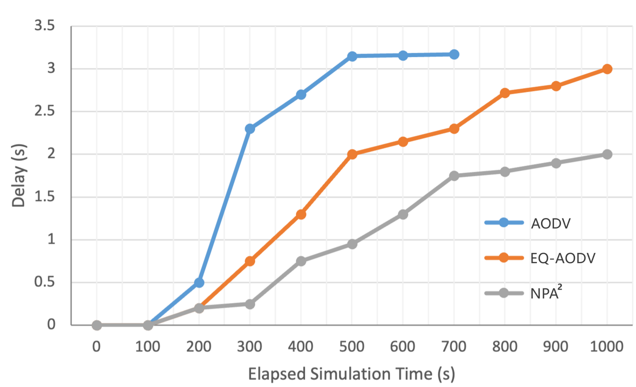


Fig. 7: Packet Delivery Delay with Energy Considerations

AODV, as a baseline comparison, picks the shortest paths from source to destination creating congested routes that result in more collisions and retransmission of packets, thus consuming more energy. Furthermore, as the traffic load is carried by a small subset of nodes in the network, these nodes expend their energy sooner than the rest. By the 700s epoch, half the network, i.e., 100 nodes, have exhausted their power supply and become inactive, as shown in Fig. 6. Furthermore, the network became partitioned and no further packet transmissions could take place. Hence, the surviving nodes that were still alive (after 700s) only consumed minimal energy thereafter without transmitting any packets.

VI. Conclusion

In this paper, we proposed a new approach to route selection in wireless networks that aims to maximize the utilization of available network resources. Unlike conventional methods where routes are picked based primarily on network and link characteristics, our approach also incorporates a packet's attributes to select the route for that packet. Traditionally, weaker links are avoided as the chances of successfully transmitting packets over them are low, without considering the fact that packet attributes such as size have a significant influence on the success factor. We show that these weaker links can still be used for transmitting small packets, and by doing so, free up the better-quality links for larger packets.

To illustrate our concept, we implemented it on a wireless ad hoc routing protocol and validated the efficacy of our approach using simulations. With the increase in volume and heterogeneity of traffic to be carried over future networks, our approach can significantly enhance overall network resource utilization as well as other aspects of network performance. While our approach may consume slightly more energy from the overall network perspective, this is offset by energy savings from lower contention and packet retransmissions.

Ongoing research will first explore the use of other packet attributes. Future research includes studying the weightage among different network and packet attributes, and optimizing the weightage to suit different network scenarios and application requirements.

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References

[1] P. Owczarek, M. Piechowiak, and P. Zwierzykowski, "Analysis of Routing Protocols Metrics for Wireless Mesh Networks," in *Proc. of 37th International Conference on Information Systems Architecture and Technology–ISAT 2016–Part II*. Karpacz, Poland: Springer, 18-20 September 2017, pp. 177–186.

[2] E. Alotaibi and B. Mukherjee, "A survey on routing algorithms for wireless ad-hoc and mesh networks," *Computer networks*, vol. 56, no. 2, pp. 940–965, 2012.

[3] L. Wenxing, W. Muqing, Z. Min, and L. Peizhe, "The impacts of weak links on routing process in large scale multi-hop networks," *IEEE Access*, vol. 5, pp. 12 125–12 134, 2017.

[4] R. Laufer, P. B. Velloso, L. F. M. Vieira, and L. Kleinrock, "PLASMA: A new routing paradigm for wireless multihop networks," in *Proc. of the IEEE INFOCOM*, Orlando, FL, USA, 25-30 March 2012, pp. 2706–2710.

[5] G. Khanna and S. K. Chaturvedi, "A comprehensive survey on multi-hop wireless networks: milestones, changing trends and concomitant challenges," *Wireless Personal Communications*, vol. 101, no. 2, pp. 677–722, 2018.

[6] Y. Yang and J. Wang, "Design guidelines for routing metrics in multihop wireless networks," in *Proc. of the IEEE INFOCOM*. Honolulu, HI, USA: IEEE, 16-19 April 2008, pp. 1615–1623.

[7] A. BenMimoune and M. Kadoch, "Joint path relay selection in 5G multi-hop relay networks," in *Proc. of the 17th International Telecommunications Network Strategy and Planning Symposium (Networks)*, Montreal, QC, Canada, 26-28 September 2016, pp. 233–237.

[8] O. Bautista, K. Akkaya, and A. S. Uluagac, "Customized novel routing metrics for wireless mesh-based swarm-of-drones applications," *Internet of Things*, vol. 11, p. 100265, 2020.

[9] J. Cheng, P. Yang, K. Navaie, Q. Ni, and H. Yang, "A low-latency interference coordinated routing for wireless multi-hop networks," *IEEE Sensors Journal*, vol. 21, no. 6, pp. 8679–8690, 2021.

[10] K. Mathews and R. Gotzhein, "Ob-ewma: A link metric for reliability-constrained routing in wireless networks," in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC)*. Nanjing, China: IEEE, 29 March - 1 April 2021, pp. 1–7.

[11] Y. Yu, Y. Peng, X. Li, J. Gao, and X. Cong, "Distributed packet-aware routing scheme based on dynamic network coding," *China Communications*, vol. 13, no. 10, pp. 20–28, 2016.

[12] V. K. Quy, N. T. Ban, V. H. Nam, D. M. Tuan, and N. D. Han, "Survey of recent routing metrics and protocols for mobile ad-hoc networks," *Journal of Communications*, vol. 14, no. 2, pp. 110–120, 2019.

[13] M. E. M. Campista, P. M. Esposito, I. M. Moraes, L. H. M. Costa, O. C. M. Duarte, D. G. Passos, C. V. N. De Albuquerque, D. C. M. Saade, and M. G. Rubinstein, "Routing metrics and protocols for wireless mesh networks," *IEEE network*, vol. 22, no. 1, pp. 6–12, 2008.

[14] D. S. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proc. of the 9th annual international conference on Mobile computing and networking*, 2003, pp. 134–146.

[15] C. Houaidia, H. Idoudi, A. Van Den Bossche, T. Val, and L. A. Saidane, "Towards an optimised traffic-aware routing in wireless mesh networks," *International Journal of Space-Based and Situated Computing*, vol. 4, no. 3-4, pp. 217–232, 2014.

[16] T. Meng, F. Wu, Z. Yang, G. Chen, and A. V. Vasilakos, "Spatial reusability-aware routing in multi-hop wireless networks," *IEEE Transactions on Computers*, vol. 65, no. 1, pp. 244–255, 2015.

[17] Y. Chai and X.-J. Zeng, "Delay-and interference-aware routing for wireless mesh network," *IEEE Systems Journal*, vol. 14, no. 3, pp. 4119–4130, 2020.

[18] M. Arisoylu, "An initial analysis of packet function-aware extension to dijkstra algorithm for wireless networks," *EURASIP Journal of Wireless Communications and Networking*, vol. 65, 2016.

[19] D. Passos and C. V. N. Albuquerque, "A joint approach to routing metrics and rate adaptation in wireless mesh networks," *IEEE/ACM Transactions on Networking*, vol. 20, no. 4, pp. 999–1009, 2012.

[20] M. Jacobsson and C. Rohner, "Estimating packet delivery ratio for arbitrary packet sizes over wireless links," *IEEE Communications Letters*, vol. 19, no. 4, pp. 609–612, 2015.

[21] H.-S. Kim, H. Kim, J. Paek, and S. Bahk, "Load balancing under heavy traffic in RPL routing protocol for low power and lossy networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 4, pp. 964–979, 2016.

[22] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, "Predictable 802.11 packet delivery from wireless channel measurements," *ACM SIGCOMM computer communication review*, vol. 40, no. 4, pp. 159–170, 2010.

[23] S. Laine and I. Hakala, "Network Capacity Estimators Predicting QoE in HTTP Adaptive Streaming," *IEEE Access*, vol. 10, pp. 9817–9829, 2022.

[24] R. S. Dahal and T. Sanguankotchakorn, "QoS routing in MANET through cross-layer design with BER and modifying AODV," in *Proc. of the Second Asian Himalayas International Conference on Internet (AH-ICI)*, Kathmundu, Nepal, 4-6 November 2011, pp. 1–4.

[25] S. Hamrioui and P. Lorenz, "EQ-AODV: Energy and QoS supported AODV for better performance in WMSNs," in *Proc. of the IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, 22-27 May 2016, pp. 1–6.