

Topology Skewing for Improved Route Selection in Wireless Multi-Hop Networks

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Abstract—The selection of a path in a network from one node to another is performed by a routing protocol, often using the shortest path approach. However, it has been shown that in wireless networks, the shortest path approach tends to select paths with wireless links that are only intermittently available and often unstable, resulting in extensive loss of packets in the data delivery process. Instead of taking the well-trodden approach of designing a new protocol or new routing metric, we propose a method that influences the perception of the network topology for different network nodes with the aim of presenting to the routing protocol a network topology that comprises more stable wireless links. We refer to this method as the δ -scheme (“delta” scheme). We implement a proof-of-concept prototype of the δ -scheme using commercial-off-the-shelf routers and demonstrate through experimentation the viability of this scheme in a realistic scenario.

Keywords-Packet Scheduling; δ -delay; network topology;

I. INTRODUCTION

In wireless multi-hop networks, routing over multiple hops from a sender to a receiver suffers from poor performance due to various reasons, one of which is the use of a small number of hops (or equivalently, shortest-path routes) in many existing routing protocols. For example, a popular mobile ad hoc network routing protocol, the Ad-Hoc On-demand Vector (AODV) protocol [1], processes the first route request packet (RREQ) that it receives and discards latter duplicates of the same RREQ. This consequently leads to fewer number of hops in the selected route. While this approach has worked well in wired networks, its use in wireless multi-hop networks often results in geographically longer distances per hop, which are also, more often than not, the weaker and more unreliable links. When data packets are sent over weak links in such networks, retransmissions are

necessary to overcome packet loss and/or errors, thereby wasting bandwidth and energy in the process. Increasing the transmission power will not solve the problem and can lead to more interference in the network. Therefore, it has been shown, not surprisingly, that sending packets over a route with greater number of higher quality links (hops) than the shortest-path route with fewer hops gives better performance [2].

The motivation of our work is therefore to design a scheme that “influences” the network topology information presented to the routing layer so that strong links are favoured, despite that it may result in more hops from the source to the destination. We refer to our scheme as the δ -scheme (“delta” scheme), for a reason that will be apparent later. We first discuss the concept of the δ -scheme and present a design using wireless link quality as the key criteria. We then show with empirical results obtained from experimental work using commercial-off-the-shelf (COTS) hardware running OpenWRT[3] that despite more hops, performance in terms of packet delivery ratio improves significantly over multiple hops. It is inevitable that other performance measures such as average end-to-end delay may increase slightly as expected due to traversing more hops. However, this can be easily compensated by the benefits of having reliable routes that minimize packet losses and bandwidth savings from reduced retransmissions of lost packets.

II. CREATING THE DESIRED TOPOLOGY

The δ -scheme is not a medium access control (MAC) nor routing protocol. Given a network topology, a routing protocol selects the best route based on a routing metric, e.g. minimum number of hops. To produce routes with desired qualities, in this case, reliable links with good signal quality, the proposed approach aims to present to the routing protocol a network topology that is skewed toward the strong

links and excludes the the undesired links, such as those that span long distances resulting in weak signal strength.

A. δ -delay

To achieve our objective, we introduce a small delay before forwarding any broadcast-based packets. This small delay, which we call the δ -delay (“delta” delay), has an inverse relationship to a link quality metric, L_m . Hence,

$$\delta = f\left(\frac{1}{L_m}\right) \quad (1)$$

The link quality metric can be the detected Received Signal Strength Indicator (RSSI) of the packet received. It can also be the signal-to-noise ratio (SNR), the packet loss probability over a link or any other metric deemed appropriate and measurable with the hardware. For simplicity, we focus our discussion on the RSSI case:

$$\delta = f\left(\frac{1}{RSSI}\right) \quad (2)$$

The δ -delay affects all broadcast-based packets, such as RREQ in AODV routing so that such route-formation control packets are not immediately broadcasted to all potential next-hop neighbours. The next-hop nodes are therefore given a chance to accept RREQs from previous nodes that may have arrived via the stronger links (albeit along a longer route with more hops) and not necessarily always the fastest arriving RREQ (cf: Figure 1(a)). We use AODV in our discussion simply as an illustrative example. Our scheme also works with other routing protocols that employ broadcast packets, in one way or another, for their route table formation.

The δ -scheme is easy to implement, requiring only an additional (memory) buffer for packets that are associated with a certain computed delay, δ and the additional requirement of measuring the link quality in some manner (e.g. RSSI). Link qualities are already readily retrievable with many existing wireless networking hardware platforms, such as those using the Atheros chipset [4]. A packet that is associated with a δ -delay is placed in the memory buffer until the delay has elapsed or has expired. Then, the packet is processed like any other packet.

B. Implicit Backup Function

The δ -scheme provides another benefit that may not be immediately obvious. While the purpose of the δ -delay is to allow sufficient time for strong links to be established and favoured in the route formation process, it does not exclude the use of the weaker links, in the event that network topology changes (which can happen when nodes fail, channel conditions change due to temporal environmental influences, etc.) Link quality aware routing schemes that rely on specified threshold values for link selection do not have this flexibility. The δ -scheme therefore has an implicit backup design so that weak links are also eventually selected

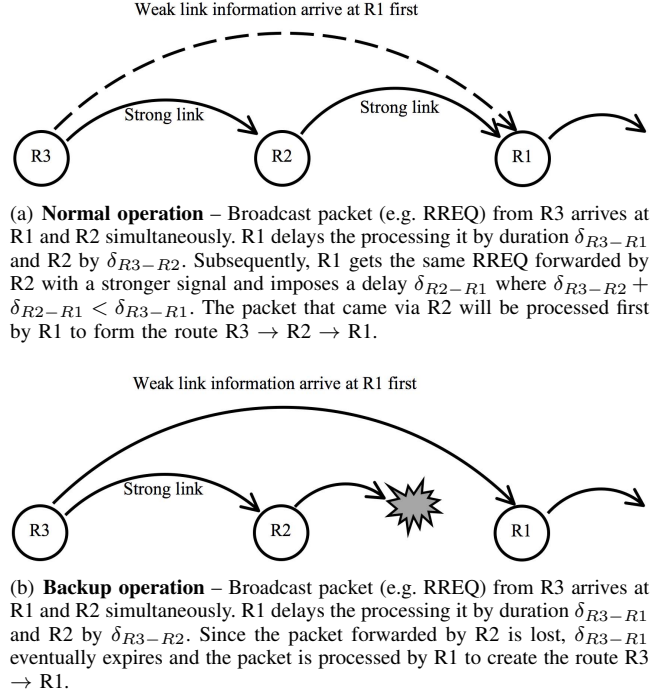


Figure 1. Operation of the δ -scheme

when strong links are no longer available (due to whatever reasons) in the network, as illustrated in Figure 1(b).

III. δ -SCHEME AND ROUTING

The δ -scheme does not explicitly select routes for packets. As such, the δ -scheme is not a routing protocol and route selection is left to the implemented routing protocol at the network layer. Therefore, the δ -scheme is not responsible for ensuring loop-free routes from source to destination. Rather, the objective of the δ -scheme is to artificially delay broadcast packets coming over unreliable paths (as if such packets are “virtually” traveling a significantly longer distance) so that nodes will get to learn of paths that are more reliable first. The reason that the δ -scheme affects only broadcast packets is that such packets are often used by protocols to discover and find routes to destinations. (This does not prevent the δ -scheme from being applied to other packet types within an autonomous administrative domain.) Besides, a unicast packet is addressed to a specific recipient node whose address is specified in the packet header and other nodes will ignore it. In the case of AODV, the δ -scheme is applied on the broadcast RREQ packets.

In this way, the δ -scheme merely attempts to “influence” the behaviour of the routing protocol by skewing the network topology in favour of the stronger links. It does not and is incapable of replacing the routing protocol. The δ -scheme only delays packets based on any measurable link quality metric, and also other network condition metrics like neighbour count, traffic load and available bandwidth, but all

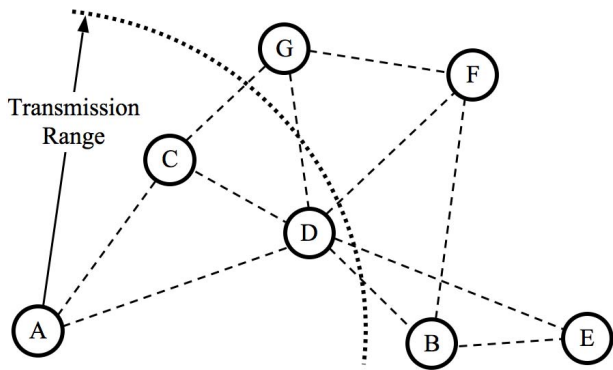


Figure 2. Arbitrary wireless multihop network

packets are eventually processed by the routing protocol for route selection and decision making.

A. δ -delay based on network conditions

We have discussed how the δ -delay can be determined based on link quality metrics, like, RSSI. Other information on network conditions can also be used in the computation of the δ -delay. We will briefly discuss a few such conditions, viz., neighbour count, traffic load and available bandwidth, using the example network in Figure 2.

Neighbour Count: Suppose node A requests a route to node F by broadcasting a RREQ. Unlike link quality, the δ -delay has a direct relation with neighbour count, N_c :

$$\delta = f(N_c) \quad (3)$$

As Node C has three neighbors while node D has six neighbors, the computed δ -delay for node C will be lower than that for node D.

In wireless networks, neighbour count is usually high for nodes at the center of the deployment field, and low near the perimeter, fringes or borders of the deployment field, assuming all nodes use the same transmission power. The δ -scheme attempts to favour the discovery of perimeter paths for routing protocols first (when possible) before the discovery of straight-through paths. Since nodes with more neighbors usually have higher probability of experiencing heavier traffic loads (assuming every node is equally likely to send data to every other node in the network), the δ -scheme can help to direct some of these traffic near the centre of the network to the perimeter of the network by inducing routing protocols to discover perimeter paths first.

Without the δ -delay, shortest path routing protocols will often select paths that are straight-through paths, resulting in heavy usage of nodes near the center, and packet collisions or losses are more prevalent at the center of the network. In this instance, the δ -scheme subtly induces the routing protocol to choose perimeter paths or paths involving nodes with small neighbour count first by presenting it with a

skewed/distorted view of the network topology. Actual route selection remains the role of the routing protocol.

Available Bandwidth: Suppose all nodes have links that are of equal bandwidth capacity, B . If the bandwidth B is large, it takes lesser time for packets to be processed at each node and the average time duration taken for packets to traverse over each hop is lesser. In this case, for any constant traffic load and constant neighbor count, the δ -delay can be small because its purpose is to delay route formation packets sufficiently for stable hops to be discovered first. Similarly, if the bandwidth B is small, it takes relatively more time for packets to be processed at each node and the average time duration for packets to traverse over each hop is more. δ -delay must be relatively larger in this case to enable route formation packets traversing through more hops but over stable links to be discovered by the routing protocol first.

As an example intended only for illustration and not to limit the scope of the scheme, the bandwidth B can affect the computation of the δ -delay through some scaling factor σ . The larger the B , the smaller the σ , and vice versa. In a network with nodes that have different link bandwidth capacities (e.g. different network interfaces), the link with the smallest capacity (bottleneck link bandwidth) can be used as the basis to determine appropriate δ -delay values or the appropriate scaling factor σ .

Traffic Load: Suppose node E requests a route to node F and both nodes B and D receives this request. Assuming that node D is experiencing higher traffic loads than node B (which is not unreasonable as D lies in the centre of the network and is more likely to be on more routes), then the δ -delay at node D should be longer than at node B (ignoring link quality and neighbor count factors). Like neighbour count, δ -delay also has a direct relation with traffic load. In this way, any new traffic from node E to node F is more likely to go through node B (than node D) because the δ -scheme favours the discovery of the path $E \rightarrow B \rightarrow F$ first, before the path $E \rightarrow D \rightarrow F$ or any other paths going through node D, thereby achieving load balancing in the network.

B. Dropping packets instead of delaying

There may be cases where some of the δ -delayed packets are dropped:

- Packets with large δ -delay values are dropped when a node's packet buffer is full to make space for newer arriving packets. If packets are queued according to their δ -delay values, those with larger δ -delay values are naturally queued further back. When the queue becomes full, it is natural for packets at the rear of the queue to be dropped; similarly, buffer management policies also tend to drop packets that have been queued the longest.
- In some routing protocols, the identification (ID) of route formation packets are cached for some finite time duration (Cache Time) for identifying duplicate

route requests. Duplicate route formation packets (of the same ID) received by a node are dropped within this Cache Time and not processed a second time. Therefore, it makes sense to drop packets with δ -delay values larger than the routing protocol's Cache Time since such packets will still be discarded by the routing protocol.

The main difference brought about by the δ -scheme is that the order of arrival of broadcast packets (or more specifically, route-discovery packets) is more RSSI-based (i.e., link quality based and/or network condition based) rather than the original shortest hop-count based and/or time-of-arrival based.

IV. IMPLEMENTATION

To demonstrate the viability of the δ -scheme, we implemented it using COTS hardware and open-source software. We used Linksys WRT54G 2.4GHz 802.11b/g routers which are low-priced wireless networking devices and they are also equipped with transmit power adjustment capabilities from 1mW to a maximum allowable power of 84mW. The routers are flashed with the open-source OpenWRT firmware and AODV-UU (an implementation of the Ad-hoc On-demand Distance Vector Routing, from Uppsala University). Unfortunately, the Broadcom chipset used in the Linksys routers do not provide per-packet RSSI information. This can be easily overcome by measuring other link quality information required by the δ -scheme, as discussed in Section IV-B.

A. Outdoor Testbed Setup

All experiments are conducted outdoors to reflect a realistic environment, and a string topology of five nodes is used. The string topology is a common deployment strategy adopted in practical applications, such as structural integrity monitoring of scaffoldings during excavations of tunnels for underground railway lines and subway systems [5]. It is also common for the deployment of nodes for monitoring of bridges, underground pipes, coastline environmental and security monitoring to be in a linear topology. Besides, the topology also facilitates the measurement and data analysis process which is crucial in the experimental study.

Figure 3 shows the network topology used in our experiments, with nodes labelled R1 to R5 spaced approximately 100m apart (with GPS positions marked as shown; GPS location information is not a requirement of the δ -scheme, but is included only to serve as marker points on the deployment site where the experiments were conducted.) All the routers are setup and configured as shown in Table I. Routers R2, R3, R4 and R5 are configured to transmit data to R1 at 4 packets per second (512 bytes per packet) at the beginning of every minute for 30 seconds, and subsequently, rests for the next 30 seconds. Each set of experiments lasts 10 minutes.

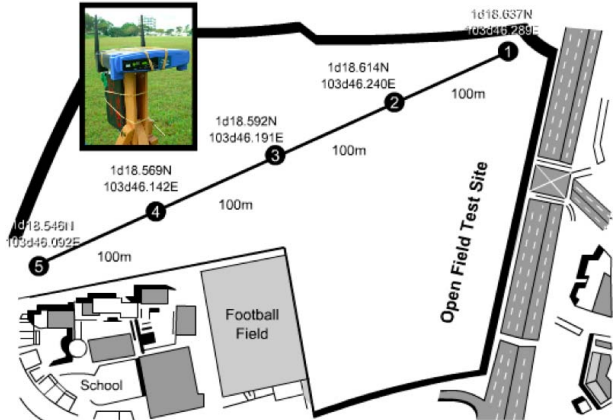


Figure 3. Network Topology at Test Site

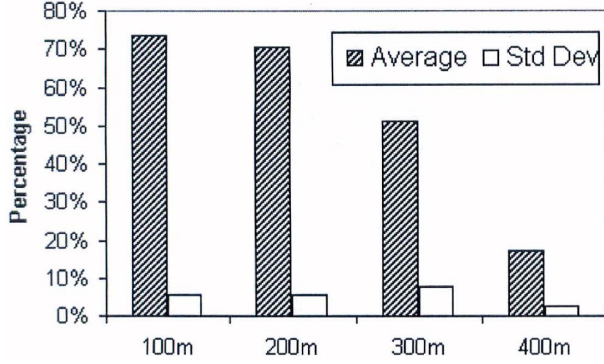
Table I
LINKSYS ROUTER CONFIGURATION

Antenna height	≈ 0.5m above ground
Antenna orientation	vertical upright
Transmit power	21mW and 84mW
Power source	12V batteries
Packet size	512bytes and 1400 bytes
Data rate	11Mbps (fixed)
Packet rate	CBR 4 packets / sec
Inter-node distance	≈ 100m
Transport layer protocol	User Datagram Protocol (UDP)
OpenWRT version	White Russian RC5
AODV Version	AODV-UU 0.9.3
AODV Gratuitous mode	Disabled
AODV Route table dump	Yes, every 1 sec
AODV HELLO interval	1sec (default)
AODV Route expiry	12sec
Weather conditions	fair weather with slightly moist ground

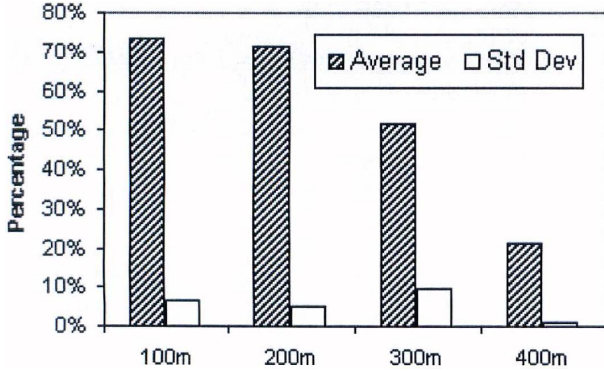
Time is synchronized amongst the routers using the Network Time Protocol (NTP); time synchronization is not a requirement of the δ -scheme, but merely serves to simplify interpretation of results. Data packets are sent from the various routers to R1 at a constant packet rate using the User Datagram Protocol (UDP). Packet tracing software (such as tcpdump) is not installed to avoid unnecessary bias to the experimental results. Instead, we dumped the AODV route table every second to analyze the routes that have been set up and used to forward the packets.

B. Using HELLOs instead of RSSI

Without hardware-provided RSSI information, we derived the link quality metric by counting the number of periodic beacons from all nodes that can be heard. In the case of AODV, these regular beacons are the HELLO packets that are, by default, broadcasted every second by each node. Tests are conducted to count the HELLO packets received by nodes at different distances from the transmitting node. Figure 4(a) summarizes the results across all power levels



(a) All power levels



(b) 21mW

Figure 4. % HELLOs received at different inter-node distances

while Figure 4(b) shows the results when the transmit power used is 21mW.

From the results, it appears that the initial granularity offered by this approach is about 200m (inter-node distance) for an open space scenario. Beyond the first 200m, finer granularity (e.g. 100m granularity) can be achieved. For the 21mW case, to distinguish between a 200m inter-node distance and a 300m inter-node distance, there is a difference of about 1200 packets within a 10-minute period, giving an equivalent difference of about 2 packets per second, which is measurable. However, for nodes within a 200m radius of the transmitter, the HELLO packet probability is not distinguishable.

V. EXPERIMENTAL VALIDATION

We choose a simple implementation of the δ -scheme to show that even with such simplicity, a notable improvement in results can be achieved. In our experiments, link quality (LQ) is measured by counting the HELLO beacon packets that are broadcasted by the AODV routing protocol; in this way, no additional overhead is incurred by the δ -scheme. AODV HELLO beacon packets are broadcasted in regular one-second intervals from every router, and LQ (in our case) is defined as the total number of such HELLO beacon packets within the most recent 50-second window. We have

Table II
LQ-TO- δ -DELAY MAPPING

Link Quality (LQ)	Pure AODV	AODV with δ -scheme	AODV with Aggressive- δ
	Set 0	Set 1	Set 2
	δ_0 (s)	δ_1 (s)	δ_{agg} (s)
>85%	0	0	0
75–85%	0	0.1	0.1
65–75%	0	0.2	0.2
55–65%	0	0.3	0.3
45–55%	0	0.4	0.4
<45%	0	0.5	DROP

also implemented the option of dropping packets if the LQ falls below a specified threshold and we refer to this option as the “Aggressive Mode δ -scheme” or, in short, Aggressive- δ . As the goal of the δ -scheme is to produce reliable routes, the ability to deliver packets successfully is our key metric. We define the Packet Delivery Ratio (PDR) of router R_X as the fraction of packets successfully delivered to router R_1 (destination node) compared to those originally sent by router R_X .

A. Link Quality to δ mapping

There are many ways in which LQ can be mapped to a δ -delay value. We have selected a simple heuristic mapping based on the estimated processing overhead of the router platform and the conceptual model of the RSSI-based δ -delay presented in Section II. The LQ-to- δ -delay mapping is shown in Table II where, for convenience, we label the experiments using pure AODV as “Set 0”, AODV with δ -scheme as “Set 1”, and AODV with Aggressive-mode δ -scheme as “Set 2”.

The LQs fluctuate significantly across time, but can be approximately summarized by their average values. A very likely cause of fluctuations is the presence of numerous other WiFi access points in the vicinity of the experiment site; at any one time, we were able to detect between 10 and 20 active WiFi access points. The measured LQs over time from the perspective of each router and the network-wide summarized average LQs are shown in Figure 5.

B. PDR using 21mW transmit power

Figure 6 summarizes the PDR results from the numerous experiments conducted with pure AODV (without any δ -scheme extension), AODV with δ -scheme, and AODV with Aggressive- δ , using transmit power of 21mW.

The PDR results reveal that the δ -scheme consistently enhances the performance of the network by influencing the AODV routing protocol to set up routes with stronger links. The results are encouraging because only a very rudimentary implementation of the δ -scheme has been used. At router R_5 (which is 400m from the destination router R_1 , and have traversed multiple hops to reach R_1), the PDR achieved with the δ -scheme is about three times better than the original

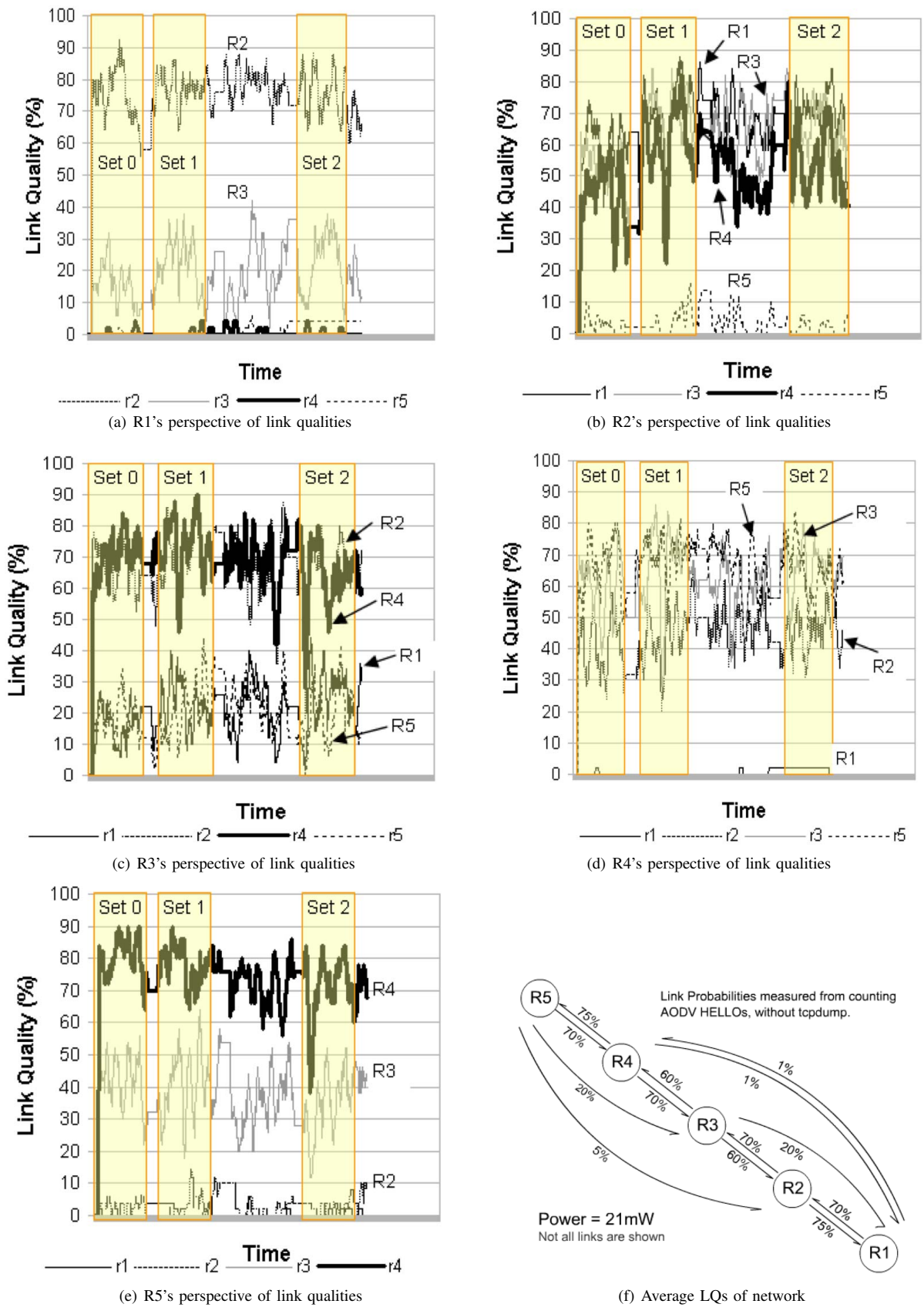


Figure 5. Link Quality (LQ) measured from counting HELLO packets

AODV protocol. Aggressive- δ performs well up to router R3 (about 200m away from the destination) but is not as effective as the source-destination distance increases. One reason is the lack of available links for Aggressive- δ in an overall poor link condition environment. Aggressive- δ drops all links with LQs that are poorer than 45%. In a fluctuating LQ environment with transmitting data, the dropping of such links may result in complete loss of data if these links are the only next-hop links.

To explain the poor performance beyond R3, we analyze the results of experiment “Set 2” (Aggressive-mode δ -scheme). We note that only router R4 is a possible next hop for packets from R5. When we consider the connectivity of R4 to/from the other nodes, we note the link between R4 and R3 exists consistently (cf: R4’s LQ in Figure 5(c)) but the link between R4 and R2 only exists intermittently (cf: R4’s LQ in Figure 5(b)). R4 is completely invisible (unreachable) from R1. As packets traversed through R5 \rightarrow R4 \rightarrow R2, packets are lost when the intermittent link R4 \rightarrow R2 goes down. This problem also arises because both the R4 \rightarrow R3 and R4 \rightarrow R2 LQs are fluctuating drastically and have approximately the same average values.

Now, the improvement provided by the δ -scheme (Set 1) is significant compared to pure AODV (Set 0), and it can be explained by the average LQs (or equivalently, also termed *link probability*) over time. For instance, the two-hop link probability from R5 \rightarrow R4 and from R4 \rightarrow R3 is $70\% \times 70\% \approx 49\%$, which is twice better than the single hop from R5 \rightarrow R3 directly with a link probability of only 20%. The same is true for the R3 \rightarrow R1 paths. In our results for the δ -scheme (Set 1), PDR of packets from R5 is more than 45%, compared to only 15% achieved by pure AODV.

Table III shows the percentage of routes of different lengths (measured in hops) from the respective routers to R1, derived from the dumps of the routing tables of each router, measured every second. The data is interpreted as follows: for example, if we consider R3, pure AODV uses a direct (1-hop) route about 42.16% of the time, a 2-hop route about 54.66% of the time and on some rare occasions (3.19%) even a 3-hop route which went towards R4/R5 and then back towards R2 and R1; this can occur if the R3 \rightarrow R2 link was bad when R3 broadcasted the RREQ which R4 successfully received, then re-broadcasted and R2 managed to receive it, thus creating a route R3 \rightarrow R4 \rightarrow R2 \rightarrow R1. In the case of AODV with δ -scheme, almost 70% of the routes are the 2-hop R3 \rightarrow R2 \rightarrow R1 route while AODV with Aggressive- δ forces all routes to take the R3 \rightarrow R2 \rightarrow R1 route. This observation corresponds to the PDR performance of R3 shown in Figure 6.

Although the data shown in Table III have not been derived from tracking the packets that actually traverse that number of hops, the routing table dump is provided as a good inference to it. Accounting every individual packet at each router (to derive the exact hop counts) is not

Table III
% OF ROUTE LENGTHS FROM DIFFERENT ROUTERS TO R1

# of hops	R2	R3	R4	R5
Pure AODV (Set 0)				
1	100	42.156863	0	0
2	0	54.656863	66.582278	8.9005236
3	0	3.186274	33.417722	54.973822
4	0	0	0	36.125654
AODV with δ-scheme (Set 1)				
1	100	26.292135	0	0
2	0	69.887640	76.903553	0
3	0	3.820225	23.096447	79.564033
4	0	0	0	20.435967
AODV with Aggressive-δ (Set 2)				
1	100	0	0	0
2	0	100	80.25974	0
3	0	0	19.74026	83.665339
4	0	0	0	16.334661

possible because tcpdump tracing has been disabled as the program consumes significant router resources. The routing table dump is therefore used as an alternative to make this inference. The table clearly shows that our experimental setup has achieved a true multi-hop scenario over the 400m outdoor string topology.

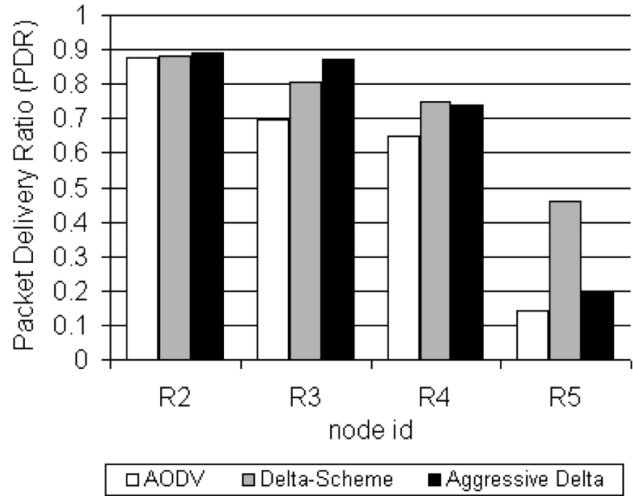


Figure 6. PDR achieved by different routers using 21mW transmit power

C. Larger packets & higher power

We repeated our experiments with different transmit power settings, and larger UDP packet sizes, as follows:

- transmit power 21mW, with 1400-byte packets
- transmit power 84mW, with 1400-byte packets
- transmit power 84mW, with 512 bytes packets

We focus on R4 and R5 as these are the routers for which we want more reliable routes, albeit across more hops. We summarize the results for routers R4 and R5 in Figure 7, comparing pure AODV against AODV with δ -scheme; AODV with Aggressive- δ is not discussed as it has

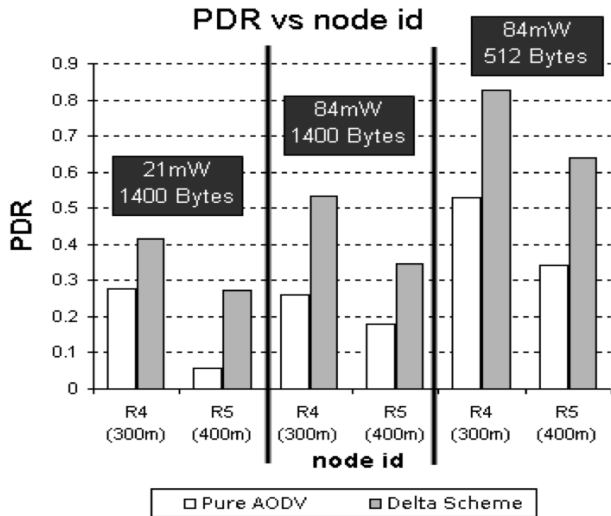


Figure 7. R4 and R5 PDR using Larger Packets & Higher Transmit Powers

not been able to achieve improved performance beyond R3. Results from our field experiments remain very encouraging with substantial improvement in packet delivery ratios over multiple wireless hops.

Router R4 is about 300m away from the destination (router R1), and router R5 is about 400m away from the destination. In all cases (for different transmit powers and packet sizes configurations), the δ -scheme consistently outperforms the original underlying AODV protocol by a significantly wide margin. The results also verify that PDR for large packet sizes is, in general, poorer compared to small packet sizes because of a higher packet collision probability of the former.

VI. RELATED WORK

An earlier effort to present a skewed network topology to the routing algorithm is the generic extension of location-based ad hoc routing protocols named Skewed Map Forwarding (SMF) [6]. SMF alters/distorts the view of the network topology from the routing protocol by mapping the physical coordinates of nodes to logical coordinates. When the routing protocol uses the logical coordinates, the resultant routes discovered appear as being skewed from the original route. It also allows multiple routes to be created depending on how much the view of the topology has been altered.

Imposing “artificial” delays on packets in order to differentiate them is a well used method in networking. Priority queuing can be viewed as a form of implicit delay imposed on lower priority packets in favour of higher priority packets. Non-work conserving scheduling algorithms have been proposed for providing quality of service support in computer communication networks, but are often criticized

for incurring higher average end-to-end delays [7]. The δ -scheme can be considered as a form of non-work conserving scheduling as a packet that has been imposed a δ -delay will not be processed/transmitted, even if the wireless channel is empty, until the δ -delay period has elapsed.

More recent and relevant to wireless multihop networks, the Transparent Biased Route Discovery (TBRD) method adopts the approach of introducing a delay in forwarding RREQs in AODV to discourage the routing protocol from picking routes that traverse nodes with limited resources [8]. This scheme addresses heterogeneous networks of nodes with different capabilities and resources, where it is less desirable to choose nodes with limited resources as they are more likely to run out of resources and fail; TBRD does not take into account the wireless link quality. In order for TBRD to be effective, certain network-wide knowledge is needed, e.g. a node that does not want to be selected must know the length of alternative routes in order to introduce a delay that is sufficiently long for the RREQ via those routes to reach the destination node. This makes the scheme hard to implement in a real system.

In ExOR [9], an opportunistic routing protocol for wireless multihop networks, a similar delay-based approach is used to coordinate the forwarding of packets by a group of candidate relay nodes. All candidates are first ordered based on a predefined metric. The order is generated by either the source node or the immediate sender, and included in the packet header. After a data packet is broadcasted (all packets are sent in broadcast mode in opportunistic routing), candidates will respond in the order specified in the packet header, i.e. i -th priority candidate will respond at the i -th time slot. A candidate responds at its turn only when it does not hear any responses from others. Therefore, before a candidate responds, it can confirm that all higher priority candidates failed to receive the data packets. Once a candidate responds, the candidate is selected as the next relay and the response will prevent others from responding.

The shortest path (or minimum hop count) approach has been extensively applied in mobile ad hoc network (MANET) protocols, like AODV, as node mobility is a dominant factor in MANETs, and sending packets through routes with fewer hops may be the best approach to overcome a constantly changing network topology. Furthermore, it has also been shown that mobility can improve the connectivity of wireless networks by moving nodes closer to one another at some point in time [10]. In static wireless ad hoc networks, the nodes’ locations rarely change, if at all, and the network topology is determined by the connectivity of the wireless links. The shortest path approach will result in the selection of long links that can be slow and lossy. This led to the development of link-quality metrics for use in wireless ad hoc networks, of which, the most well-known ones include *Expected Transmission Count* (ETX) [11] and *Expected Transmission Time* (ETT) [12]. These metrics have

been validated experimentally and shown to be able to achieve significant performance improvement as compared to using minimum hop count in wireless multihop networks. Comparative studies of link-quality metrics can be found in [13] and [14].

Key issues with most, if not all, the proposed schemes for routing in wireless multihop networks are the need to exchange channel state information (increasing communication overheads), modify the routing protocol logic and the introduction of new protocol messages, all of which hinder widespread deployment. On the other hand, schemes that rely on setting link-quality thresholds for accepting packets need to be tuned for the specific environment that they are deployed in, again limiting their deployment flexibility. Even with the use of variable transmission power control [15], [16], the problem of routing protocols selecting weak links still exists if minimum hop count is used as the basis for route selection.

It is therefore highly desirable to have a scheme that can subtly influence the route selection without having to modify any routing protocols or introducing new messages, and be able to adapt to the changing wireless link quality and network conditions. Another feature of the desired scheme should be the ability to apply it to portions of the network without the need for it to acquire network-wide state information. The δ -scheme aims to achieve these goals by presenting to the routing protocol a network topology that works best with the route selection metric(s) in use.

VII. CONCLUSION

Many routing protocols for ad hoc networks have adopted minimum hop count as a routing metric despite it having been shown to result in poor performance, especially for static wireless multihop networks. Instead of designing a new routing protocol or proposing a routing metric for use in wireless multihop networks, we have proposed the δ -scheme, which subtly influences the route selection process of the routing protocol in use without the need to modify it; the routing decision is still performed by the routing protocol. The δ -scheme can be implemented in any part of a network or the entire network without any changes to the incumbent routing mechanisms.

Instead of explicitly exchanging channel state information between nodes, which contributes to routing overhead, we adopt an implicit approach by introducing a delay, which adds no additional packet overheads. The δ -scheme operates by changing the routing protocol's perception of the network topology through the introduction of appropriate delays (δ -delays) to route formation packets so that the perceived distance between nodes appear changed based on the link quality and/or one or more of other criteria related to network conditions, such as, neighbor count, traffic load and available bandwidth. In its fundamental form, the δ -scheme favours the discovery of paths with high link qualities first,

with extensions to also include nodes with smaller neighbor counts and low traffic nodes. The δ -scheme can be easily configured to account for node and network resources, e.g. a lower δ -delay if available bandwidth is large and vice versa. The viability and efficacy of the δ -scheme have been demonstrated through outdoor field experiments using a simple prototype implemented on commercially available wireless routers and open-source software.

Ongoing and future work on the δ -scheme include its use with different routing protocols and the integration of multiple criteria into the computation of the δ -delay. A key issue to be studied is the effect of the δ -delay on average packet delay and jitter. The reduction of jitter by non-work conserving scheduling schemes [7] are highly beneficial to realtime multimedia traffic and can also reduce the need for more buffering at the receivers. In addition, cognitive networking [17] and machine learning techniques [18] will also be studied to explore the possibility of the δ -scheme autonomously evolving with changing network conditions.

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