A Novel Strategy for High Throughput in Ad Hoc Networks using Potential transmission Count (PTC) Metric

ARUN KUMAR SINGH
CSE/IT
Ph.D. Scholar
Shobhit University, Meerut-10, UP
INDIA
arunsinghiiita@gmail.com

DR. NEELAM SRIVASTAVA
ECE
GBTU, Lucknow, India
IET Campus, Sitapur Road, Lucknow, UP
INDIA
neelam.srivastava@ietlucknow.edu5454

Prof. J. B. Singh
CSE/IT
Shobhit University, Meerut-10, UP
INDIA
jbsingh@shobhituniversity.ac.in

Abstract: - A multi-hop wireless network is a network of computers and devices (*nodes*) which are connected by wireless communication *links*. The links are most often implemented with digital packet radios. Because each radio link has a limited communications range, many pairs of nodes cannot communicate directly, and must forward data to each other via one or more cooperating intermediate nodes. The PTC of a route is the total number of packet transmissions and retransmissions required to send a packet across the route, assuming that each link in the route retransmits the packet until it is successfully received across the link. PTC is designed for links with link-layer acknowledgments (ACKs) and retransmissions, as provided by IEEE 802.11 radios. The PTC metric for a route is calculated using measurements of the lossless of each link in the route. Routing protocols select routes with the minimum PTC. For short routes, the minimum- PTC route is the maximum-throughput route; for longer routes, the minimum- PTC route is still a high-throughput route. The design of the PTC metric does not depend on a particular routing protocol; PTC improves the throughput of both Dynamic Source Routing (DSR), an on-demand source routing protocol, and Destination-Sequenced Distance-Vector (DSDV) routing, a proactive table-driven distance-vector routing protocol. We also present a set of design changes and implementation techniques that allow DSR and DSDV to work well with PTC.

Key-Words: - Multi-hop, Ad-Hoc, Hop Count Metric, 802.11b, PTC, Radio Packets.

1 Introduction

This paper describes how to find high-throughput routes in multi-hop wireless packet networks. Using the *Potential Transmission Count (PTC)* metric presented here, routing protocols can find multi-hop routes that have up to twice the throughput of those found using the minimum hop-count metric. Most routing protocols minimize the hop-count1 metric, which is the number of wireless links in a route, regardless of the performance of each link. Since multi-hop wireless networks likely contain many losses links, routes preferred by the hop-count metric also often contain lossy links, which reduce throughput.

A source node transmits a packet to a neighboring node with which it can communicate directly. The neighboring node in turn transmits the packet to one of its neighbors, and so on until the packet is transmitted to its ultimate destination. Each link that a packet is sent over is referred to as a *hop*; the set of links that a packet travels over from the source to the destination is called a *route* or *path*. Routes are discovered by running a distributed *routing protocol* on the network. A multi-hop wireless network can be expanded by incrementally adding nodes to the network, typically at the edges as its physical area grows. In this sense it is self-expanding: since the network nodes using the network cooperate to provide connectivity to each other, the network exists wherever there are nodes. This is in contrast to a cellular network, where data travels directly from wireless nodes to fixed base stations.

Data typically travels from a base station to its destination over a wired network, as shown in Figure 1. Since each base station provides a fixed amount of network coverage to a fixed geographical area (the ‘cell’), there is only network connectivity where base stations have been redeployed. Cellular base station locations and radio configurations are carefully chosen not to interfere with adjacent cells, while avoiding coverage gaps between cells. Although cellular networks can be incrementally deployed and expanded, the overhead and planning required to setup a base station is much larger than required to deploy a few extra new nodes in a multi-hop wireless network.

Multi-hop wireless networks have a very rich design space, and designers must make choices in many dimensions when building these networks. We make several assumptions about the underlying network those constrain the design space.

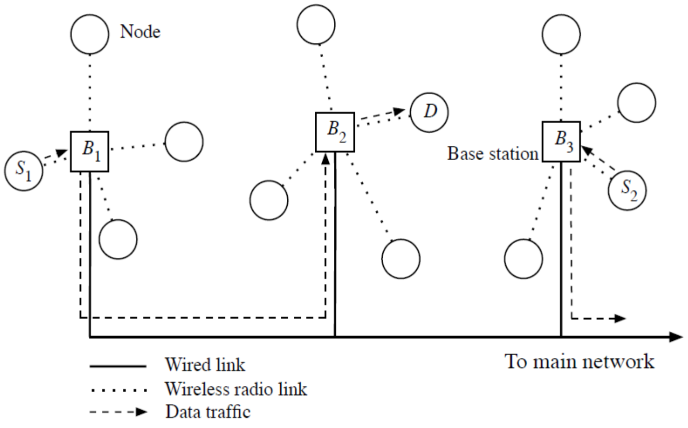

Fig. 1: Wired/Wireless Link

As discussed above, we assume that the network uses omnidirectional antennas, as they are cheaper and more convenient. This is one traditional way of operating data networks, and fits in well with current practice. However, it precludes techniques like network coding [5, 6 and 7], which make more efficient use of the underlying network capacity.

2 Network Model

However, the protocols and experiments described in this work do *not* use the radios in infrastructure mode. Instead, the radios are used in a *peer-to-peer* mode where they can directly send and receive packets from any radio which might be in range. This mode is also sometimes called *ad hoc* mode. The 802.11 standard refers to radios operating in this mode as an Independent Basic Service Set (IBSS).

TABLE I

IEEE 802.11b bit-rates and their associated modulation.

Bit-Rate	**Modulation**	**Bits/ Symbol**	**Chips/ Symbol**
1 Mbps	DBPSK	1	11
2 Mbps	QPSK	2	11
5.5Mbps	CCK	4	8
11 Mbps	CCK	16	8

+1, −1, +1, +1, −1, +1, +1, +1, −1, −1, −1

Fig. 2: Barker spreading sequence

Retransmissions and Packet Timing

The 802.11 MAC supports two kinds of data packets: broadcast and unicast. Broadcast packets are intended to be received by any radio which hears them, and are delivered to the networking layer on that radio's node. Figure 2 shows the formats of data and ACK packets. If a unicast sender does not receive an ACK packet after a specified period of time (SIFS + DIFS time after sending the data packet), it marks the transmission as failed. The sender then increases its back-off window, enters back-off, and tries to resend the packet.

Figure 4 shows the packet exchanges and timings for broadcast and unicast packets at 1 Mbps, assuming that every packet transmission is successful and that there is no contention. The figure shows the average expected back-off time of 310 microseconds. In the absence of contention, the back-off window should be at its minimum size of 620 microseconds, and the average expected random backoff is one-half of that. The maximum broadcast and unicast throughputs of a given packet size can be calculated in packets per second by inverting the time required to send a single packet. For example, for the 134-byte payload used throughout this work, the unicast throughput *B* can be calculated as

$$B = \frac{1}{1{,}146 + 8X134} = 451$$

Packets per second.

(a) 802.11 data frame, 59 + *n* bytes over the air.

Preamble (18 bytes)	Physical layer header and CRC (6 bytes)	802.11 and Ethernet headers (31 bytes)	Ethernet Payload (*n* bytes)	Data CRC (4 bytes)

(b) 802.11 ACK frame, 38 bytes over the air.

Preamble (18 bytes)	Physical layer header and CRC (6 bytes)	ACK frame (10 bytes)	Data CRC (4 bytes)

Fig. 3: Packet formats for 802.11 data and acknowledgment packets.

(a) Packet timing for 802.11 broadcasts.

802.11 Data (*n* data bytes) (8× [*n* + 59] µs)	← DIFS → (50 µs)	← Backoff → (≈310 µs)	802.11 Data

(b) Packet timing for 802.11 unicasts.

802.11 Data (*n* data bytes) (8× [*n* + 59] µs)	← SIFS→ (10 µs)	802.11 ACK (304 µs)	← DIFS → (50 µs)	←Backoff → (≈310 µs)	802.11 Data

Fig. 4: Packet timing diagram for 802.11 data traffic, assuming no contention for the radio channel.

3 Throughput Phenomena With PTC in Ad- Hoc N/W

Most existing wireless routing protocols use the minimum hop-count route metric: they select routes with the fewest links. The minimum hop-count metric implicitly assumes that links either work well, or do not work at all and that all working links are equivalent. Furthermore, most protocols assume links that deliver routing control packets such as DSDV route updates or DSR route queries will also successfully deliver data packets.

Given a broad variation in link loss ratios, hop-count will choose links poorly. This is because minimizing the hop-count of a route maximizes the distance traveled by each hop, which reduces the received signal strength and increases the loss ratio. Even if the best route is a minimum hop-count route, there may be many routes with the same minimum hop-count, but with widely varying qualities. The arbitrary choice made by minimum hop-count is not guaranteed to be the highest-throughput route.

3.1 Experimental Test

All the data in this paper are the result of measurements taken on a 29-node wireless test. Each node consists of a stationary PC with a Intel processor 2.4 GHz (Core 2 Duo) PCI/PCI-X 802.11b card, Server with a Geon Processor (Core 2 Duo-4 Processor) Intel Pro/1000 MT PCI/PCI-X 802.11b card and an omnidirectional 2.2 dBi dipole antenna, also called a ‘rubber duck’ antenna. Each PC runs the Linux operating system. The nodes are placed in offices and cabins on four consecutive floors of an office building. Their positions are shown in Figure 3.

The 802.11b cards are set to transmit at one megabit per second (Mbps) with one milliwatt (mW) of transmit power. RTS/CTS is turned off, and the cards are set to ‘ad hoc’ (IBSS, DCF) mode. Each data packet in the following measurements consists of 24 bytes of 802.11b preamble, 31 bytes of 802.11b and Ethernet encapsulation header, 134 bytes of data payload, and 4 bytes of frame check sequence: 193 bytes in total. An 802.11b ACK packet takes 304 microseconds to transmit, the inter-frame gap is 60 microseconds, and the minimum expected mandatory back-off time is 310 microseconds, resulting in a total time of 2,218 microseconds per data packet. This gives a maximum throughput of 451 unicast packets per second over a loss-free link.

While the test itself carried only the data and control traffic involved in each experiment, interference of various kinds was inevitably present. In particular, each floor of the building has four 802.11b access points, on various channels.

3.2 Path Throughputs

Figure 6 compares the throughput of routes found with a minimum hop-count metric to the throughput of the best static routes that could be found.

Minimum hop-count performs well whenever the shortest route is also the fastest route, especially when there is a one-hop link with a low loss ratio. A one hop link with a loss ratio of less than 50% will outperform any other route. This is the case for all the points in the right half of Figure 7. Note that the overhead of DSDV route advertisements reduces the maximum link capacity by about 15 to 25 packets per second, which is clearly visible in this part of the graph.

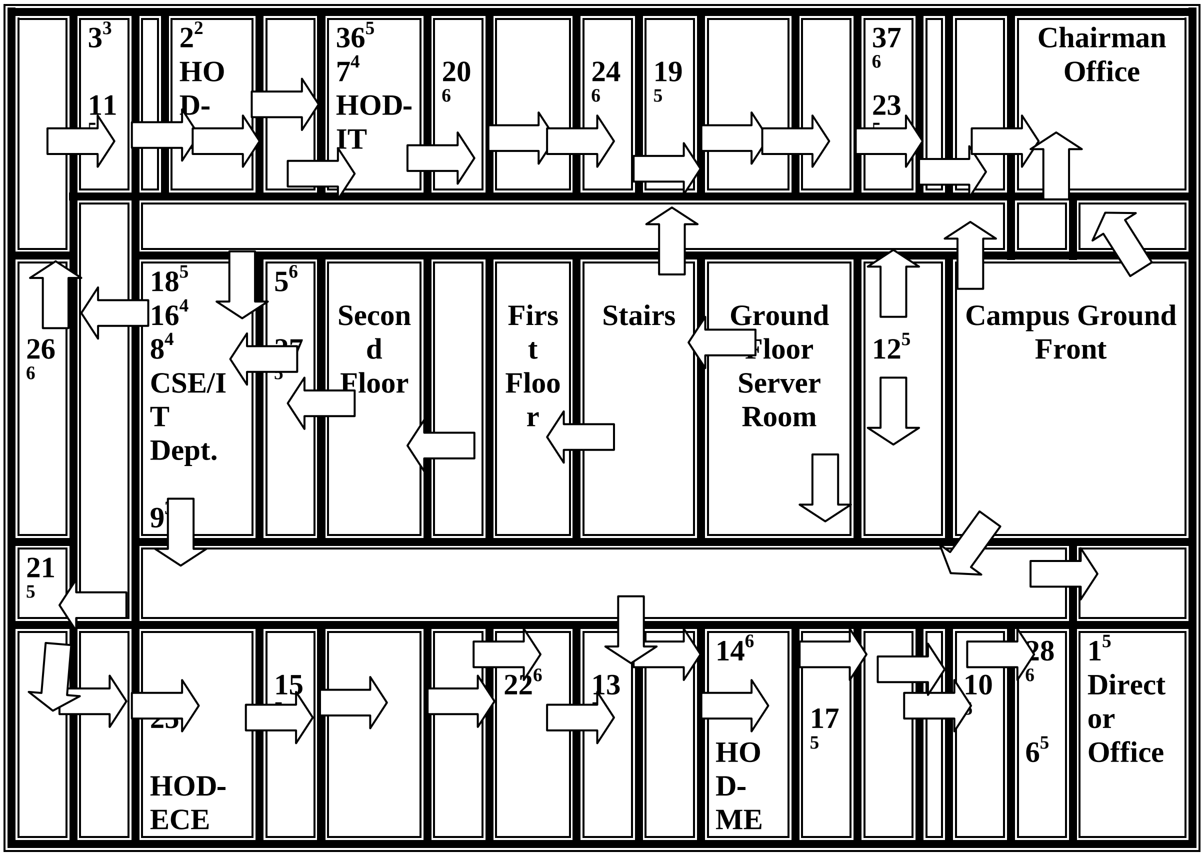

Fig. 5: A map of the test. Each circle is a node; the large number is the node identifier, and the superscript indicates which floor of the building the node is on.

3.3 Distribution of Path Throughputs

Figure 7 illustrates a typical case in which minimum hop-count routing would not favor the highest-throughput route. The figure shows the throughputs of several static routes from node 23 to node 36. The routes are the eight highest- throughput routes between 23 and 36 which were found in the 'best' static route. The graph shows that the shortest path, a two-hop route through node 19, does not yield the highest throughput. The best route is three hops long, but there are a number of available three-hop routes which provide widely varying performance.

4 Potential Transmission Count (PTC) Model

4.1 PTC Intuition

The main intuition behind the PTC design is that because links in a route share the wireless spectrum, protocols can increase throughput in packets per second by decreasing the amount of time each packet uses that spectrum. One way to do this is for protocols to choose routes with fewer links, that is, find minimum hop-count routes. This time reduces route throughput in the same way that adding links to a route reduces route throughput.

The second intuition behind PTC is that these two criteria can be combined into one: the extra transmissions due to adding links can be lumped with the retransmissions on lossy links, producing a total number of transmissions for a path. Protocols should find routes that reduce that total number of transmissions per packet. Routes with fewer total transmissions per packet have higher throughput, because they take less time to send a packet.

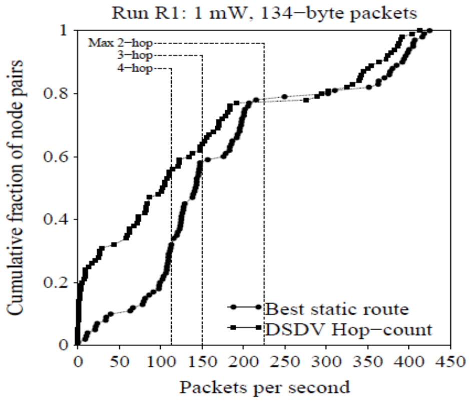

Fig. 6: When using the minimum hop-count metric, DSDV chooses paths with far less throughput than the best available routes

4.2 The PTC Metric

The PTC of a link is calculated using the forward and reverse delivery ratios of the link. The forward delivery ratio, d_f is the measured probability that a data packet successfully arrives at the recipient; the reverse delivery ratio, d_r is the probability that the ACK packet is successfully received by the data sender, given that the data packet was received successfully. The probability that a data transmission is successfully received and acknowledged is $d_f \times d_r$. The expected number of transmissions for a link is approximated as:

$$PTC = \frac{1}{d_f \; X \; d_r}$$

This equation assumes that the probabilities d_f and d_r are constant for a given link, or are at least constant for the duration of link measurements.

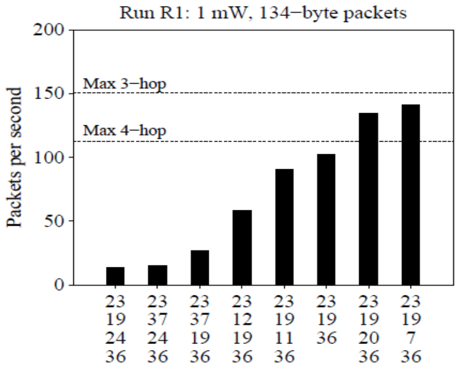

Fig. 7: Throughput measurements from node 23 to node 36

The delivery ratios d_f and d_r are measured using dedicated link probe packets. Each node broadcasts link probes of a fixed size, at an average period τ (one second in the implementation). To avoid accidental synchronization, τ is jittered by up to ±10% per probe. Because the probes are broadcast, they are not acknowledges or retransmitted. Every node remembers the probes it receives during the last w seconds (ten seconds in our implementation), allowing it to calculate the delivery ratio from the sender at any time t as:

$$\mathrm{d(t)} = \frac{\mathrm{count}(t \; - w, t)}{w/\tau}$$

Count $(t - w, t)$ is the number of probes received during the window w, and w/τ is the number of probes that should have been received. In the case of the link $X \rightarrow Y$, this technique allows X to measure d_r, and Y to measure d_f because Y knows it should receive a probe from X every τ seconds, Y can correctly calculate the current loss ratio even if no probes arrive from X.

5 PTC Evaluation

5.1 Routing Protocol Tests

The routing protocol tests show well PTC improves the throughput of a complete routing system. As a result, they include protocol-specific behavior and overheads. We tested PTC with both the DSDV and DSR routing protocols.

5.2 Experimental Setup

The protocol performance data presented below were collected during a few separate 'runs'. An entire run takes anywhere from 21 to 68 hours, depending on the experiment parameters. A run considers each pair of nodes in turn. For each pair, one experiment is performed for each routing protocol variant. As described the heavy load causes the MAC protocol to become extremely unfair, distorting the PTC measurements. To minimize the effects of MAC unfairness, every node routes packets using a snap- shot of its route table taken at the end of the warm-up period, before any data is sent. The snapshot also makes the DSDV results more comparable to the 'best' static route results, since the static route tests are not allowed to switch routes in the middle of testing a particular route.

5.3 DSDV Performance

Figure 8 compares the throughput CDFs of paths found by DSDV using PTC and minimum hop-count, between 100 randomly chosen node pairs.

Figure 9 shows the throughput CDF for TCP traffic routed using DSDV with PTC and minimum hop-count. The figure also shows the 'best' static route TCP throughput found for each pair. All experimental parameters were the same as for the UDP tests, except that the packet size was varied by TCP according to its congestion control algorithm. Hop-count does particularly poorly for TCP. First, since TCP traffic requires good routes in both directions in order to send back end-to-end TCP acknowledgments, there are twice as many chances for hop-count to select a bad route: once in each direction. Second, the TCP back-off algorithm amplifies the effects of any errors in the underlying route.

5.4 DSR Performance

DSR uses link-layer transmission failure feedback to avoid bad routes. To isolate the effects of using PTC with DSR, we evaluated DSR performance both with and without link-layer feedback enabled.

Figure 10 illustrates the performance of PTC with DSR's link-layer feedback enabled. PTC provides a small benefit to some pairs in the intermediate and low throughput ranges However, failure feedback alone allows DSR to perform almost as well as DSR with PTC.

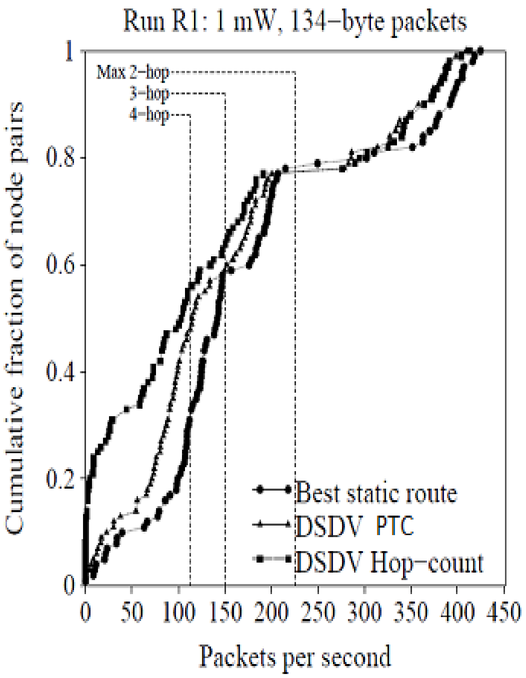

Fig. 8: PTC finds higher throughput routes than minimum hop-count.

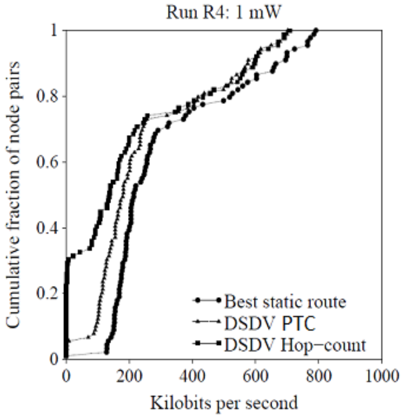

Fig. 9: PTC finds higher throughput routes than minimum hop-count for TCP traffic.

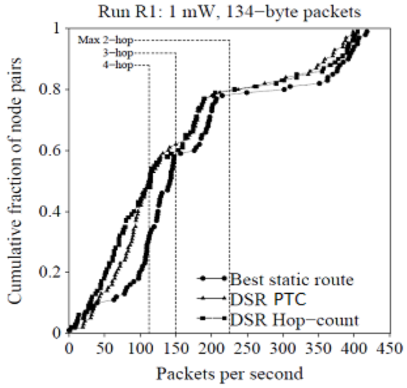

Fig. 10: DSR PTC compared with DSR hop-count, with link-layer transmission feedback enabled.

6 Simulation Result

This paper showed how PTC with protocols increases the throughput performance of the networking. It also used more focused static throughput and single link experiments to understand the gaps between the throughputs of routes found using PTC and the 'best' routes found using static routes. We identified two main causes of the discrepancy. First, PTC mispredicts the transmission count of links because it measures the reverse ACK delivery ratios using the wrong packet size. Second, underlying time variations in link delivery ratios and throughputs make it hard for PTC to make accurate predictions.

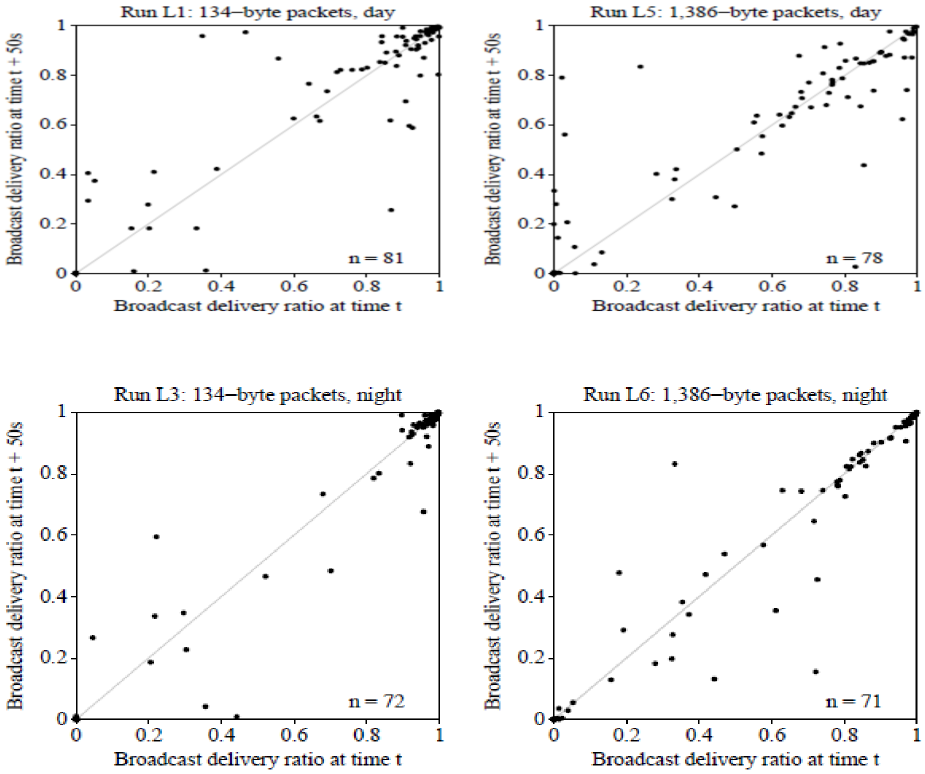

Fig. 11: The broadcast delivery ratio of a link can change significantly over time.

7 Conclusion

The main contribution of this work is a simple way for multi-hop wireless routing protocols to choose high-throughput paths in networks with link-layer retransmissions. This work also characterized the delivery ratios and asymmetry of the test-bed network, and showed how lossy and asymmetric links affect route throughput. Lossy links require more retransmissions, and therefore have lower effective throughput. However, a route with few lossy links can be preferable to a route with many higher-quality links, since contention between links also reduces route throughput.

Finally, this work proposed a simple model for how link delivery ratios vary with packet size.

The packet delivery P_p for a packet with n data symbols is

$$P_p\,(n) = P_f \times P_s^n$$

Where P_f is the per-packet probability that a receiver successfully acquires and synchronizes to a packet frame, and Ps is the per-symbol probability that the receiver successfully decodes that symbol. Measurements on the test show that this model can accurately predict the delivery ratios at many packet sizes using measurements at two packet sizes over each link.

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Authors

Arun Kumar Singh is a PhD scholar, under the guidance of Dr. Neelam Srivastava and Prof. J. B. Singh, in the School of Computer Engineering & Information Technology at Shobhit University, Meerut, UP, India. He received his M.Tech. (IT-WCC) degree from Indian Institute of Information Technology (IIIT-Allahabad), Allahabad, India in 2005 and B.Tech. (ECE) in 2002 from Agra University, Agra, UP, India. His research interests are routing metrics in wireless networks, mobile and pervasive computing, throughput control and resource allocation in MANETs and VANETs.

Dr. Neelam Srivastava is currently working as an Associate Professor and Head of Electronics Engineering at IET, Lucknow constituent college of Gautam Buddh Technical University, Lucknow, India. She received her Ph.D. degree in Electronics and Communication Engineering from IET of Lucknow University at Lucknow, India in 2004. Her research interests include self organizing sensor networks, Basic Electronics, Electromagnetic Field theory, Microwave Engineering, Digital Integrated Electronics, Antenna & Wave Propagation, Microprocessor Design &its Application, Digital & Logic Design, Switching Theory, Network Synthesis, Computer Organization and Management System, Optical Communication, Optical Instrumentation, Opto-Electronics, Computer Data Networks mobile computing, network security, wireless networks, reliable and dynamically reconfigurable distributed systems, complex distributed systems, mobile and distributed databases, and performance measurement and analysis. She has published widely in journals and conferences in these networking and distributed systems areas. She is a subject area editor of the International Journal of mobile and computer Networks. Her work had been supported by the IEEE (M90773749), IETE (F080648) and IEE (M-134084-5).

Prof. J. B. Singh is working as Senior Professor of Statistics, Dean of Students Welfare Shobhit University since Feb., 2008 and worked as Director of the School of Computer Engineering & Information Technology as well Principal Coordinator UPTU, SIET Meerut from August 2008 to Oct 2009. He has also over 42 years of experience of teaching and conducting interdisciplinary research, advising and mentoring graduate & post graduate students. Prior to joining Shobhit University, Professor Singh had a long career in teaching, research and administration at G. B. Pant University of Ag & Tech, Pantnagar. Dr. Singh was awarded the Ph.D. degree in statistics in 1986. He is a member of several Professional Societies and University Academic bodies. Dr. Singh has to his credit of 58 papers published in several scientific journals and proceedings. He has also developed lab manuals in statistics and standard computer programs for publication. He has visited University of Illinois, Oregon State University, University of North Texas and University of Chicago, University of Tennessee, Knoxville, USA. Dr. Singh has been thesis advisor for seven M.Phil Mathematics at Shobhit University, eight Masters' students in Agricultural Statistics and three M.Tech. Students in Cold Region Science and Engineering at Pantnagar University. At present he is also supervising two Ph.D. Students of Statistics and nine students of Computer Engineering and Information Technology of Shobhit University, Meerut.