Throughput of Wireless Multi-Mesh Networks: An Experimental Study

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Abstract

To overcome the capacity and interference problem of Wireless Mesh Network (WMN), we explore the possibility of increasing the coverage area of WMN by running multiple WMNs in parallel and interconnecting them. Theoretical achievable capacity from [3] to every node in a random static wireless ad hoc network with ideal routing is estimated as $O(1/\sqrt{n \log n})$, where n is the total number of nodes in the network. Therefore, with increasing number of nodes in a network, throughput capacity becomes unacceptably low. In this work we report our throughput measurements that show throughput in a WMN for different path length is almost the same, with nodes across two WMNs of the same path length. We propose to interconnect the networks by using multiple wireless adapters in gateway node configured with the SSID of the networks in operation. To achieve our goal we exploited the DSR protocol feature of assigning locally unique interface indices to its adapters.

Keywords :MR-LQSR, ETX. PktPair, RTT, ETX, WCETT, ARQ and MCL

1. Introduction

IEEE 802.11 standard provides infrastructure-less operating mode called as ad hoc mode. Absence of infrastructure and self-configuration capability makes ad hoc networks suitable for low-cost applications, but results in wireless medium instability and low connectivity. Hence WMN is proposed to increase the ad hoc connectivity because WMN extends the coverage area of communication by using multi-hop communications. WMN is a communication network made up of radio nodes organized in a mesh topology, wherein each node in the network may act as a router, regardless of whether it is connected to another network or not. Nodes allow continuous connections and reconfigurations around the broken or blocked links/paths by hopping from node to another node until data in the form of packets/frames reach the destination from the source node.Mesh Routers/Clients and Mesh Gateways are the components of WMN. Mesh clients are often laptops, cell phones, desktops and other wireless devices. WMN is a special type of wireless ad hoc network where each user node operates not only as host but also a router. Traffic is forwarded to and from internet connected gateways in a multi-hop fashion. WMN nodes usually do not have strict power constraint, because it is assumed that all the nodes are almost stationary, but this need not be so. Networking infrastructure is decentralized and simplified because each node needs only to transmit as far as the next node. Each node is connected to several other nodes with redundant routes and if one drops out of the network, its neighbors find another route unlike WLAN access points, which can relay messages on behalf of others. WMNs are dynamically self-organizing and self-configuring, with the nodes in the network, thus increasing range, stability and the available bandwidth.The reminder of this paper is organized as section-2 presents the existing technology and motivation to carry out this work, section-3 describes the methodology of the work, section-4 presents the results and observations, and finally section-5 concludes our work and future directions.

2. BACKGROUND

Off-the-shelf IEEE 802.11-based wireless interfaces has made easy and inexpensive to setup WMNs with mobile and PDA devices and be used as a private network. The performance of the WMN is based on the routing protocol and routing algorithm that is used. Hence research is active in the field of routing protocols and routing metrics to improve the WMN performance. Most of the routing protocol is evaluated based on simulation. One more issue on which performance of WMN improve is by using multiple interfaces in a node instead of a single interface. But limitation with using multiple interfaces in a node are several like, in conventional network for each physical network interface used, should be assigned with different IP addresses, but a node should have a single unique address irrespective of number of interfaces being used to communicate in the network. Therefore a suitable protocol with mechanism for communication between nodes equipped with single and multiple interfaces or mixture of single, multiple interfaces nodes. Routing metric worth should be used, which is directly responsible for the throughput performance. Board crosses talk, radiation leakage and an adequate distance required to separate multiple antennas in a node are some of the issues with use of multiple interfaces, hence using multiple interfaces in a node without taking proper measure would yield less performance in WMN.

i) **MR-LQSR Protocol**

Protocols for multi-hop routing in ad-hoc and WMNs proposed are DSDV, OLSR, TORA, and AODV DSR etc. Protocols are mainly of two types i.e. on-demand/link state routing protocol better for mobile nodes and table-driven routing protocols for static nodes. Link Quality Source Routing (LQSR) is a source routed link state routing protocol which supports link quality metrics. LQSR implements all basic Dynamic Source Routing (DSR) protocol [5] functionality including route request, route reply, route maintenance and feature of using one IP address as nodes home address for all communication while in the ad-hoc network, in-turn each node independently assigns locally unique interface index to each of its network interfaces. MR-LQSR is a combination of LQSR protocol with metric called WCETT. From [6] MR-LQSR has following four components.

- Neighbor Discover
- Link Weight Assignment
- Link weight information propagation
- Path finding

The main difference with DSR and LQSR is DSR always tries to route through shortest path, whereas MR-LQSR uses WCETT to assign the weights to links and does not follow shortest path. Shortest path routing performs worse many times. Since MR-LQSR is used in layer 2.5 architecture which does not require to modify the protocol of layer above, uses 48-bit virtual Ethernet address in its headers including source route, source reply and route error packets instead of 32-bit IP address. Mesh Connectivity Layer (MCL) from [7]which operates as layer 2.5 is a driver which generates LQSR packet by inserting an additional LQSR header into Ethernet packets received from the network layer as illustrated in fig.1+

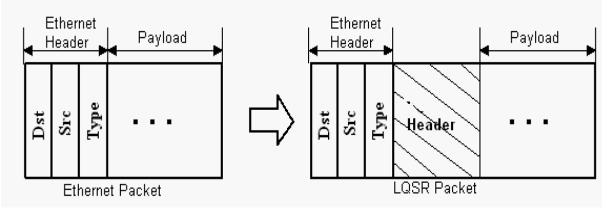


Fig.1 Ethernet Packet from IP layer , LQSR Packets generated by MCL

ii) Routing Metrics

Various routing metrics for operation in WMN is proposed and evolved from Hop Count (Hop) to Per-hop Round Trip Time (RTT), Per-hop Packet Pair Delay (PktPair), Expected Transmission Count (ETX) and Weighted Cumulative Expected Transmission Time (WCETT) with different intuitions in the way of improving network performance. We have implemented ETX, PktPair and WCETT on our testbed and observed the throughput performance.

Expected Transmission Count (ETX)

ETX is the expected number of MAC layer transmission that is needed for successfully delivering a packet through a wireless link. This metric is good in judging paths [8] by assigning large weights for long and lossy paths. ETX is derived as packet loss rate in both the forward and reverse direction denoted by $p_f$andp_r respectively and then computes the expected number of retransmission required to deliver the packet successfully to the destination as the IEEE 802.11 MAC retransmits a packet whose transmission is not successful.. The equation 1 below illustrates the computation of ETX.

$$ETX = \frac{1}{(1-p_f)(1-p_r)} \quad \text{--------------}1$$

The equation also implies that ETX metric is bi-directional, that is the metric from node x to node y is same as metric from node y to node x. The weight of a path is defined as the summation of the ETX's of all links along the path.ETX does well in homogeneous single-radio, but does not perform well in environments with different data rates.

Per-hop Packet Pair Delay (PktPair)

PktPair metric concept was thought off to correct the problem of distortion of RTT measurement due to queuing delays. To calculate this metric, a node sends two probe packets back-to-back to each neighbor every second. First probe packet is small and second one is large. The neighbor calculates the delay between receipt of first and the second packets and reports this delay back to the sending node. The sender maintains an exponentially weighted moving average of these delays for each if its neighbors. The objective of Pktpair routing algorithms is to minimize the sum of these delays, if due to high loss rate second probe packet requires retransmission by 802.11 ARQ then delay measured by the neighbor increases. The disadvantage of this metric is overheads is even greater than RTT and not completely immune to self-interference.

Expected Transmission Time (ETT)

From [4] ETT of a link k is defined as expected MAC layer duration required for a successful transmission of a packet at link k. The weight of a path p is simply the summation of the ETTs of all the links on the path. This routing metric improves the WMN performance by considering the differences in link transmission rates. The relationship between the ETT of a link k and ETX can be expressed as shown in equation 2.

$$ETT_k = ETX_k \frac{s}{b_k} \text{ ------------------------2}$$

Where b_k is the transmission rate of link k and s is the packet size. The drawback of ETT is that it still does not capture the inter-flow and intra-flow interference in the network completely. i.e. ETT may choose a path that only uses single channel, even though a path available with more diversified channels with less interference or higher throughput.

Weighted Cumulative Expected Transmission Time (WCETT)

WCETT metric was proposed to reduce the intra-flow interference, means to reduce the number of nodes operating on same channel on the path p, that is used to transmit the packets. Thus obtain high throughput in a multi-radio, multi-hop WMN. This metric does not consider the effect of inter-flow interference. One of goal of MR-LQSR protocol design is path weight should increase as more number of links are added to an existing path and that is fulfilled by this metric by adding/increasing the ETT as the links are added. It is as well as end-to-end delay experienced by a packet travelling along the path. Thus, for a path of n hops

$$WCETT = (1-\beta) * \sum_{i=1}^{n} ETT_i + \beta * \max_{1 \le j \le k} X_j \text{ ---3}$$

In equation 3 β is a tunable parameter subject to $0 \le \beta \le 1$ and X_j is the maximum number of times the channel j appears along the path p, which captures the intra-flow interference, because WCETT metric assigns lower weights to the paths that have more diversified channel assignments on their links.

We can interpret the equation 3 in two parts. First term is the sum all transmission times of all hops in the network, which reflects the total resource consumption along this path. The second term reflects the set of hops that will have mostimpactinthe throughput of this path. The weighted average can be viewed as an attempt to balance the two terms. WCETT selects links based upon their loss rate and bandwidth, without regard to channel diversity if β =0 is set. It can also be observed that WCETT is only metric that selects links based on both loss rate and bandwidth and considers channel diverse paths unlike ETX.

3. Methodology

Since it is found suitable that the combination of LQSR protocol, WCETT metric for a multi-hop, multi-interface WMN along with MCL which creates an ad-hoc routing framework is used in our experimental setup

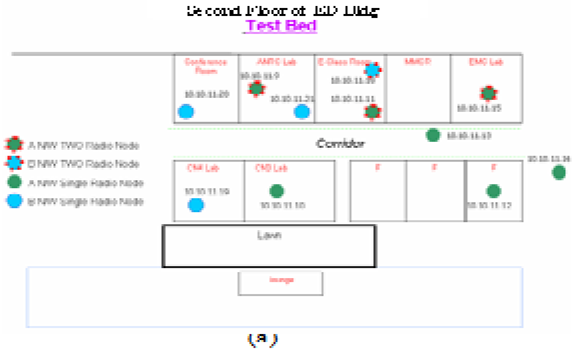
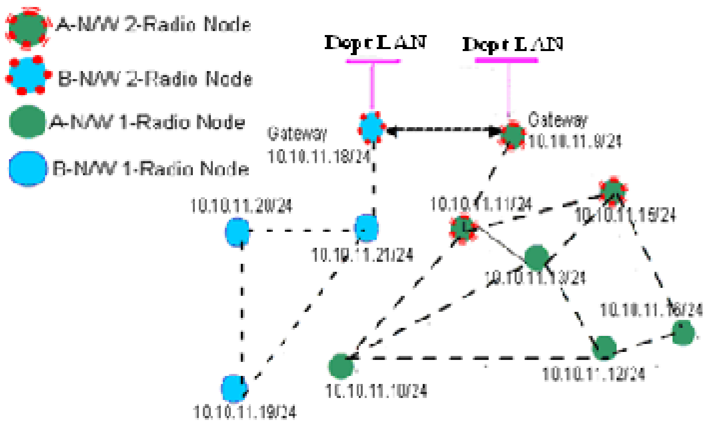


Fig.2(a) Topology of the WMN



(b)

Fig.2(b) Schematic view of the testbed.

Fig. 2(a) shows a 10-node WMN testbed setup, located on the second floor of ED building with nodes placed in the offices, conference rooms and labs. Unlike wireless-friendly cubicle environments, the building has rooms with floor-to-ceiling walls and solid wooden doors. All the nodes were placed in fixed locations and never moved during testing. Node density was kept fairly high to enable variety of multi-hop path. Our testbed spans 37 meters (120 feet approx) in length and 15.5 meters (50 feet) in width.Desktop PCs used in the testbed are 1.87 GHz Intel Core Duo processors with 2 GB memory with XP SP2 OS. All the experiments were conducted on IPv4 using statically assigned addresses. Combination of single and two radio nodes is used in our testbed, i.e. 4 nodes with two radios and 6 with single radio, with an intent to test the behavior of the network with the combination of single and two radio nodes.Each node is equipped with combination of two 5 GHz and 2.4 GHz operating band wireless adapters or with any one adopter such as D-Link DWL-520+ of IEEE 802.11*b*, Netgear WG-311 v3, D-Link DWA-510 of IEEE 802.11*g* and Proxim Orinoco gold, ZyXEL AG-225H v2 of dual band that can operate on IEEE 802.11*a*& IEEE 802.11*g* standards.Our testbed comprises of two networks (groups of nodes) i.e. nodes are grouped into ***N/W-A*** colored with green and *N/W-B*colored with blue.Consider fig. 2(a) nodes with just circle either green or blue color is with single interface and nodes with circle either green or blue with dots outside the circle is nodes with two interfaces.SSIDs for wireless adapters belonging to nodes of *N/W-A* is configured as *MyMesh* for first adapter and *MyMesh9* for second adaptor and for nodes having single adapter, SSID configured is *MyMesh*. In *N/W-B* network all nodes are equipped with single wireless adapter, configured with SSID *MyMesh3,* only gateway node of *N/W-B* is installed with two radios one configured as *MyMesh3,* second adapter configured as *MyMesh9.* It can observed that adopter with SSID *MyMesh9* is present in both the gateway nodes of *N/W-A* and *A/W-B* which is responsible to bridge two networks here.

The static IP address for the nodes is assigned as given below

N/W-A - Starting from 10.10.11.9 to 10.10.11.16
N/W-B - Starting from 10.10.11.18 to 10.10.11.21

This IP address for a node is used to identify a node in the network, irrespective of the number of hardware adapters used as part of the mesh network. Also following static address was assigned for the MAC of Virtual adapters of the nodes for better monitoring while testing.

N/W-A - Starting from 74-99-99-99-AA-00 to 74-99-99-99-AA-06
N/W-B - Starting from 74-77-77-77-AA-00 to 74-77-77-77-AA-03

Fig.2 (b) illustrates the connectivity between the nodes of twonetworks. Since the nodes are combination of single and two radios, nodes in the testbed is so arranged, such that any node of one network can communicate with any node of other network.

Except configuring to ad hoc mode and fixing the frequency band & channel number, default configuration for the radios is used. In particular, all the cards perform auto rate selection and have RTS/CTS disabled. It was ensured that there were no other 802.11*a/b/g* users during the experiments.

4. Results

The software tools used in the testbed for measurement of throughputs between nodes with path lengths of one, two, three and more hops were *Iperf*, *Microsoft Network Monitor*. *Ping* to check the connectivity and *GNU-Plot* to plot the obtained results.

Single-Radio Experiment

Firstly the experiments with single radio on a best one hop path length with IEEE 802.11*g* and IEEE 802.11*a* was conducted. Both the standards are of specification 54 Mbps data rate fig.3 shows a plot which illustrates the behavior of the adopters. Procedure of the experiment is,a three minute tcp transfer was carried out between selected nodes first between a pair of nodes with IEEE 802.11*g* adopters then with a pair of nodes with IEEE 802.11*a* adopters.

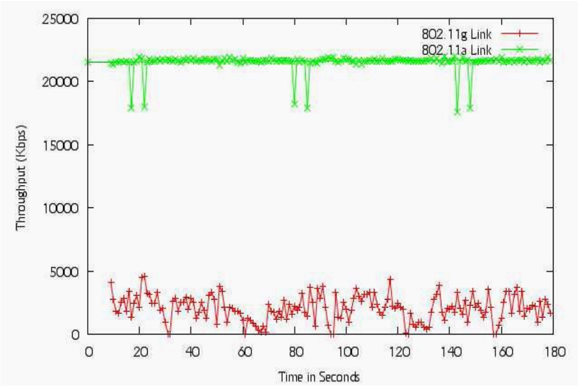


Fig.3 Comparison of throughputs between 802.11*a* linkand 802.11*g* link

It is observed that 802.11*a* link has offered a maximum throughput approx. 21 Mbps and transferred 314 MB of data whereas 802.11*g* link has given only 4.5 Mbps approx. as maximum throughput and had transferred only 44.8MB of data. Though both the standards are of same data rate, 802.11*g* tends to be slower link compared to 802.11*a* link.

Impact of Band and Channel Assignment

An assumption while designing the MR-LQSR routing protocol is, if multiple radios used in a node then they should be configured to on-interfering channels. Though it is done we can observe that performance is poor in the first set of experiment. Table 1 show that data obtained from the experiment.

	Receiver (NR Lab) Orinoco ZyXEL	Sender-1 (Average Throughput) Adapter tuned to ch 64	Sender-2 (Average Throughput) Adapter tuned to ch 36
Individually	**Two 802.11*a***	**21514 Kbps**	**12275 Kbps**
Simultaneously		**6206 Kbps**	**7970 Kbps**
Drop in Throughput		**71%**	**35%**

Table1. Comparison of throughput between nodes with 802.11*a* interfaces

i) First Set of Experiment

Procedure of the experiment is three nodes all with IEEE 802.11*a* adopters are used. As shown in fig.2 (a) first node is placed in conference room and second in NR lab and third in e-class room. All rooms are adjacent to each other. First (Sender-1) and third (Sender -2) node is used always to send packets and second node which is in the middle at NR lab is used always to receive the packets from the other two nodes. Both the sender receiver pairs of adopters in the nodes are configured to non-interfering channels as shown in table 1.

Firstly tcp traffic was transferred for two minutes from first node only and received by NR lab and it was noted that 21514 Kbps was received. Secondly same experiment was done with third node with first node made idle and traffic received at NR lab node and noted that 12275 Kbps of average throughput received. Finally from both first node and third node tcp traffic was transferred for two minutes simultaneously and packets received at NR lab node. Now from table 1, it can be observed that at the first sender the average throughput is only 6206 Kbps and from second sender it was 7970 Kbps wherein the drop in throughput are 71% and 35% respectively compared to the throughputs with experiments when conducted individually.

ii) Second set of experiment

Here sender-2, i.e. node 3 is now equipped with 802.11*g* adopter instead of 802.11*a*, also receiver adopter at node in NR lab changed to 802.11*g* and configured to channel 10 as shown in Table 2

Again same set of previous experiments was carried out and results are noted as shown in table 2. It is observed that drop in throughput is reduced significantly to 10% and 6% respectively.

	Receiver (NR Lab) ZyXEL D-Link	Sender-1 (Average Throughput) Adapter tuned to ch 36	Sender-2 (Average Throughput) Adapter tuned to Ch 10
Individually	**802.11*a* 802.11*g***	**12345 Kbps**	**4698 Kbps**
Simultaneously		**10990 Kbps**	**4387 Kbps**
Drop in Throughput		**10%**	**6%**

Table 2. Comparison of throughput between nodes with 802.11*a* and 802.11*g* a interfaces

Above two sets of experiments illustrates that though we use multiple interfaces with non-interfering channels, even then they interfere and performance is very poor. This drawback is overcome in the second set of experiment by using multiple interfaces but of different bands operating in 2.4 GHz and 5 GHz respectively in a node.

Experiment with Single/Two Radio with WCETT, ETX and PktPair Metrics

Test on WCETT, ETX and PktPair a shortest path routing was conducted to judge which metrics could be suitable for wireless mult-mesh network.Procedure of the experiment is, firstly tcp traffic transfer for 180 seconds for a path length of 3 hops with all the four nodes equipped with single 802.11*g* adopter was conducted. Secondly all the nodes are equipped with 2 interfaces one with 802.11*a* and another 802.11*g* was used and same experiment was repeated. Results are tabulated in table 3.

From this experiment it can be observed from table 3 that WCETT metric even in single radio scenario does well getting 20% and 65% more throughput compared to ETX and PktPair metrics respectively. This is because WCETT metric considers not only loss rate but also link bandwidth while assigning weight to the links. Due to this WCETT sometimes may select longer paths than ETX, even then results in better throughput. Nodes with two radios, no-doubt WCETT metric along with LQSR meant for multi-radio scenario does better then single radio performance getting 140% and 540% throughput more than ETX and PktPair metric in two radio scenario. Fig 4 shows the behavior of WCETT metric with ETX and PktPair both in single radio and two radio scenario graphically.

	Single Radio Experiment Median Throughput	Percentage Increase	Two Radio Experiment Median Throughput	Percentage Increase
WCETT	1240 Kbps	20% increase than ETX, 65% increase than Pkt Pair	2523 Kbps	140% increase than ETX, 540% increase than PktPair
ETX	992 Kbps		1031 Kbps	
Pkt Pair	434 Kbps		394 Kbps	

Table 3 Throughput with metrics WCETT, ETX and PktPair on Single/Two Radio nodes

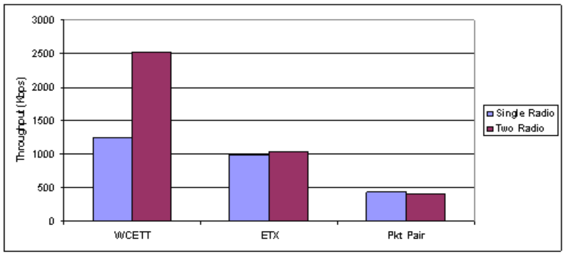


Fig. 4 Comparison of median TCP throughput with WCETT, ETX and PktPair on Single/Two radio nodes

Fig. 5 & 6, illustrates the behavior of metrics ETX and WCETT with single radio and two radio node on path length of one, two and three hops.

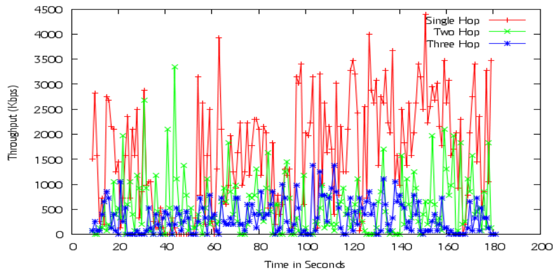


Fig. 5(a) ETX Single radio throughput comparison for single, two and three hop length

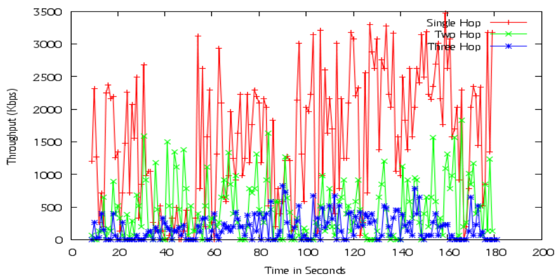


Fig. 5(b) ETX two radio throughput comparison for single, two and three hop length

From fig. 5(a) and 5(b) it can be observed that single hop throughput is almost the same, whereas the two hop path performance has reduced and the three hop performance also has no significant increase in performance. This is because ETX tries to route packets through 802.11*g* links which is longer range slower link even though higher throughput paths are available. Hence ETX uses the second interface in sub-optimal manner.

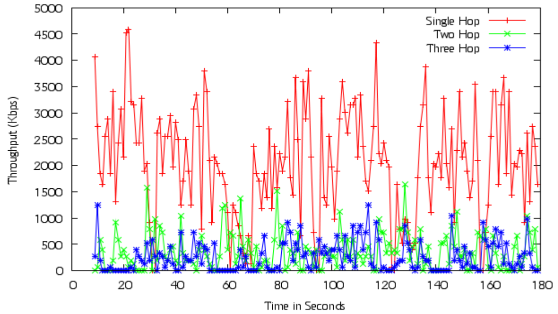


Fig.6(a) WCETT single radio throughput comparison for single, two and three hop length

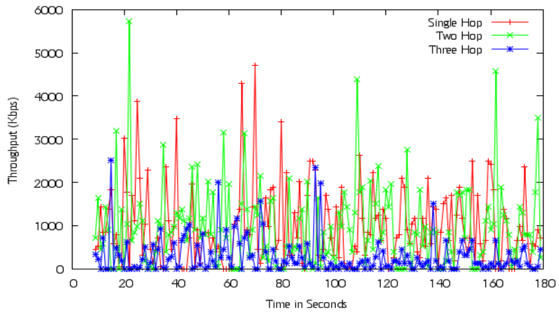


Fig. 6(b) WCETT two radio throughput comparison for single, two and three hop length

From fig 5(a) and fig. 6(a) when compared the throughputs are almost same. i.e. in single radio ETX does well but in multi-radio scenario ETX performance is worse but WCETT metric, from fig. 6(b) the two hop path length performance is almost double when compared to single radio performance. This is because WCETT uses always 802.11*a* link and uses 802.11*g* link only when it is beneficial to it and WCETT uses the second interface as an additional resource given unlike ETX using it in sub-optimal manner. Comparing fig. 6(a) and 6(b) three hop length performances has improved with two radio node compared to single radio. Fig.7 shows performance improvement in percentage compared to single radio performance with WCETT metric for various paths.

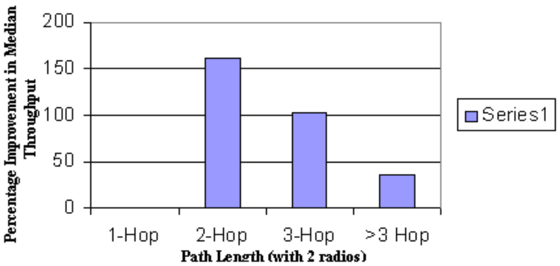


Fig. 7 Improvement in median throughput of two radio nodes over single radiofor various path lengths with WCETT as the metric.

Single hop length performance improvement is not considered because of no channel diversity. Path length greater than 3 hop, has only 30% improvement in performance, this is because on longer paths TCP performs poorer because of the following reason.

- Increase in round trip time
- Higher probability of packet loss due to channel errors
- Contention between hops that are on the same channel.

Impact of Channel diversity (β)

WCETT metric is the weighted average of following two quantities

- Sum of ETTs of all hops along the path with a weight of (1- β)
- Sum of ETTs on the bottleneck channel, with a weight of β

Experiment with path length of two, three and more hops were conducted by transferring TCP traffic for 180 seconds with the value of β = 0, 0.1, 0.5 and 0.9 set and readings are as noted in table 4 to measure the impact of channel diversity.

	2-Hop	3-Hop	>3-Hop
$\beta = 0$	66 Kbps	66 Kbps	43 Kbps
$\beta = 0.1$	1016 Kbps	262 Kbps	83 Kbps
$\beta = 0.5$	2032 Kbps	983 Kbps	671 Kbps
$\beta = 0.9$	852 Kbps	328 Kbps	272 Kbps

Table 4 Comparison of median TCP throughput for various pathlengths at various β values

Fig.8 shows β has an impact on throughput of connections of a specific path length. It is very clear that performance at β =0.5 is better for all path lengths. At β =0 the performance is poor for all path lengths. The reason could be links used by the metric at β =0 may be 802.11*g* link which yields lower throughput as seen in previous experiment and for paths longer than 3 hops the channel diversity does not provide significant benefit.

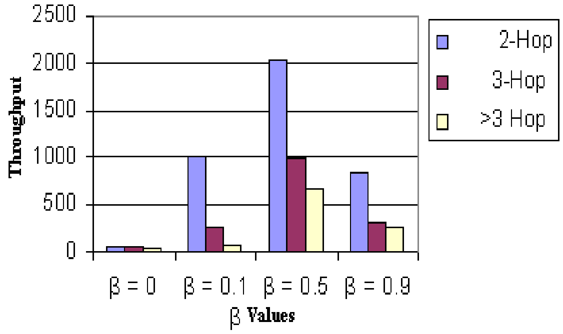


Fig. 8 GraphComparison of median TCP throughput for various pathlengths at various β values

Parallel WMN

From previous experiments it is observed that in case of using multiple interfaces then if same band interfaces are used then lot of interferences occur to extent that throughput drops to approximately 70%. This is because from [1] it is seen that activating multiple radios in a node lead to degradation in performance due any of the following reason.

- Board Crosstalk
- Radiation leakage
- Inadequate distance separation between several antennas.

[1] Shows that by taking appropriate measure like shielding of wireless cards to reduce radiation leakage, custom made platform to cancel crosstalk and adequate distance of 1 meter between the antennas, the performance can be improved to as much as 100%. [2] has shown that throughput increases as we use more number of interfaces, but limits to 5. Using more than five interfaces in a node leads to degradation of performance.

Impact of Throughput performance on parallel networks

In fig. 2(b), two mesh networks are set to operate in parallel i.e. *N/W-A*and N*/W-B*. The testbed consists predominantly single radio nodes, with a few two radio nodes used. To test transfer flow behavior between two networks, three minute TCP traffic transfer was conducted with path length of single, two, three hop lengths and also same experiment on a single WMN for comparison was done. Results are as tabulated in Table 5.

Fig.9 shows the behavior of throughput performance between nodes in a single network and across two networks. It is observed that both throughputs are almost same and closely follows except a small difference

Path Length	Median Throughput Between nodes in Single Network	Media Throughput Between nodes in Two Network	Difference in Throughput
Two-hop	**2032 Kbps**	**2228 Kbps**	**196 Kbps**
Three-hop	**583 Kbps**	**712 Kbps**	**129 Kbps**

Table 5 Comparison of throughputs between nodes in a single network nodes and nodes across two networks

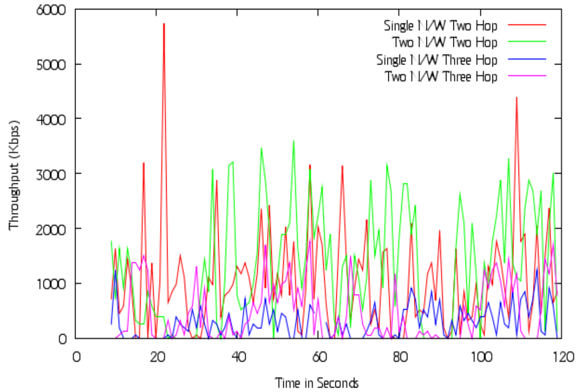


Fig. 9 Comparison of throughput between nodes in single network and nodes across network for a path length of single, two and three hops

5 Conclusions

Routing protocol that can operate with multi-radio concept like LQSR and efficient metric that utilizes the multi-radio resources beneficially like WCETT routing, also routing metric should consider both inter-flow and intra-flow interferences while routing the packets. Here WCETT does not consider inter-flow interference and hence can transmit packets to the congested route also, otherwise WCETT is the best suited metric for atmosphere like multi-hop, multi-interface and multi-mesh wireless network.As per [2] if maximum of 4 physical network interfaces can be used in a node with the measures taken to shield the network interfaces and by using custom made box to avoid crosstalk and adequate separation between antennas, thenwith multiple radios of different bands in a nodecan perform best without interference and is possible to set up multiple, say 4WMNs that can operate in parallel, such that we can extends the coverage area of Mesh network, thus enhancing the capacity of WMN.

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