QoSBR: A Quality Based Routing Protocol for Wireless Mesh Networks

Amitangshu Pal, Sandeep Adimadhyam, and Asis Nasipuri

Electrical & Computer Engineering,
The University of North Carolina at Charlotte, NC 28223-0001
{apal,sadimadh,anasipur}@uncc.edu

Abstract. In this paper we present a QoS based routing protocol for wireless mesh networks that tries to maximize the probability of successful transmissions while minimizing the end-to-end delay. The proposed routing protocol uses reactive route discoveries to collect key parameters from candidate routes to estimate the probability of success and delay of data packets transmitted over them. To make sure that it estimates these quantities for the flow of data packets and not control packets, we propose a new route quality metric that uses performance models of data packet transmissions that are obtained from offline experiments. We present simulation based performance evaluations of the proposed QoS based routing protocol and show its benefits in comparison to some other known routing protocols.

Keywords: Wireless mesh networks, on-demand routing, QoS.

1 Introduction

Wireless mesh networks (*WMNs*) consist of mesh routers and mesh clients, where the mesh routers have minimal mobility and form the backbone of the network using multi-hop transmissions. *WMNs* are dynamically self-organized and self-configured, enabling the nodes to automatically establish and maintain mesh connectivity among themselves [2]. These networks have low installation and maintenance costs, and provide reliable service. They can also be scaled up easily by installing additional routers to increase geographical coverage and service, if required.

A number of multimedia applications such as voice over IP (*VoIP*) and video on demand (*VOD*) are becoming increasingly popular in mobile wireless devices. But unlike traditional data applications, these applications require *QoS* guarantees to support user service requirements. In this paper, we present a *QoS* based routing protocol that tries to optimize the end-to-end throughput and delay by using an interference based routing metric. Although a lot of work has been reported on *QoS* based routing for multi-hop wireless networks, most of the proposed approaches rely on the usage of control packets to estimate route quality. But control (broadcast) packets differ from actual data packets as they are smaller in size and are sent at a lower transmission rate than data packets. This

K. Kant et al. (Eds.): ICDCN 2010, LNCS 5935, pp. 497–508, 2010.

leads to unexpected problems, such as the communication *"gray zone problem"* [8], and consequently, the data transmission performance may be poorer than expected. To address this issue, we propose a scheme that tries to obtain *predicted route quality* by developing appropriate interference models using off-line measurements. Our predictions are based on actual data packet transmissions, thus eliminating the gray zone problem.

The rest of the paper is organized as follows. In section 2, we discuss previous works on routing and *QoS* support in mesh networks. In section 3, we discuss the network model that is assumed in this work. In section 4, we describe our quality metric based on probability of success (*POS*) and delay. Section 5 describes our proposed *QoS* based routing protocol (*QoSBR*). In section 6, we present performance evaluations of *QoSBR* and its comparison with a popular shortest-path based routing protocol (*AODV*) and another QoS based routing protocol *MARIA* [4]. Conclusions are presented in section 7.

2 Related Work

Several routing protocols have been proposed that try to improve QoS by estimating parameters related to wireless interference. In [4], the authors use conflict graphs to characterize interference. They propose an interference aware *QoS* routing protocol *MARIA*, where nodes involved in a route discovery estimate the residual bandwidth in its neighborhood and forwards the information over the route request packet (*RREQ*). The destination selects the route based on the highest minimum residual bandwidth, i.e. the least interference. An algorithm that chooses the route that has minimum commitment period of the bottleneck node is presented in [6]. Commitment period is defined as the sum of the time the node spends in transmission/reception and the time a node has to reserve to be idle for enabling the flow of interfering traffic. Thus reducing the commitment period results in reduced interference. In the *DARE* protocol [3], all nodes in a path reserve time slots for a flow and all nodes near the reserved path abstain from transmissions during the reserved time slots, thus minimizing the possibility of interference. In [9], the authors propose an algorithm where each mesh router periodically measures the *RSSI*, average *SINR*, average number of transmission rounds, average residual block error rate and the actual spectral efficiency of the transport channel. For any path, the algorithm uses this information to meet minimum tolerable levels of a set of metrics.

Other approaches to *QoS* routing have also been proposed. In [5], a *Genetic Algorithm (GA)* for *QoS* multicast routing has been defined. Every route has to guarantee the bandwidth and delay requirements. Among all the routes satisfying the *QoS* requirements, the algorithm chooses the route that has the minimum hop count. *QUORUM* [7] estimates the end-to-end delay by sending *DUMMY-RREP* packets, which have the same size, priority and data rate as the actual data packets. The source selects the route for which the average delay of the *DUMMY* packets is within acceptable bounds and starts transmitting data traffic. In *Wireless Mesh Routing (WMR)* [10] the required bandwidth and delay constraints are embedded in the route discovery message. This information is used by nodes propagating the route discovery packets to help in determining the shortest-path route to mesh router.

All the above approaches mainly use control packets for estimating the link quality. Our scheme is different from the perspective that we use heuristics to measure data transmission quality metrics of a route.

3 Network Model

We consider a mesh network that consists of mesh clients representing end users, mesh routers that communicate with the clients, and a single Internet Gateway that communicates with the mesh routers and the Internet. In this paper, we focus on routing within the mesh routers only. We consider that clients are interested to establish communication with the gateway, for accessing the Internet. It is assumed that the gateway is aware of the locations of the mesh routers, and keeps track of all active nodes and neighborhood information. Although not addressed in this paper, such neighborhood information can be obtained in a static network by employing appropriate channel probing techniques. For this work, we make use of this information to enable the gateway to play the central role in all routing decisions. Although mesh routers may have multiple radios that can be configured to operate on multiple orthogonal channels to increase throughput, in this work each mesh router is assumed to have only one radio to communicate with the peer mesh routers.

4 Development of a QoS Metric Based on Simulation

With these assumptions, we present our approach for developing a routing metric that tries to capture the *QoS* of routes from clients to the gateway in terms of the end-to-end *POS* and delay. We show that the primary factors influencing the throughput and delay in a link can be effectively captured by two measurable quantities: (a) the number of active neighbors of the sender, and (b) the number of interfering nodes of the receiver. Another key idea obtained from these studies is the notion of *dependent* interferers that do not affect the performance of a receiver in the traditional sense. We develop mathematical models to represent the *POS* and delay under these factors, which are extended to the development of an end-to-end route quality metric.

For a given test link, we term those neighbors of the transmitter of the test link that are currently transmitting on the same channel as the transmitter and fall within its carrier sensing range as its *active neighbors*. These are the nodes with which the transmitter has to compete to gain access to the channel. The channel access ratio (*CAR*), defined as the fraction of the offered load that gets access to the channel, depends on its number of active neighbors. All the transmitting nodes that fall outside the carrier sensing range of the transmitter of the test link interfere with the reception of the receiver. The interference power from these nodes get added at the receiver. As the number of interferers increase, the probability that a transmitted packet on the test link will be successfully received reduces. The probability of success at the receiver also depends on the frequency of occurence of interfering transmissions, which increase with transmitted load of the interfering nodes. Consequently, the quality of a link depends on the number of active neighbors of the transmitter and the number of interferers of the receiver along with a number of other parameters such as transmitted load, locations and interplay of neighboring nodes etc. Since these relationships are complex, we use simulations to carefully evaluate the important effects and then develop simple mathematical models to describe them.

4.1 Simulation Environment

We use the *network simulator–2 (ns2)* [1] to perform these link quality assessments for developing models that can be used to estimate the quality of a link. The parameters used in the simulations are listed in Table 1. We consider *CSMA/CA* without *RTS/CTS*, and hence, we blocked the *RTS/CTS*. To measure the exact characteristics of the channel, we also block the *ACK* packets.

Table 1. Simulation environment

Parameter	Values used	Parameter	Values used
Max node queue length	200	Data packets size	1000 bytes
Propagation Model	Two Ray Ground	Transmitter antenna gain	0 dB
Receiver antenna gain	0 dB	Transmit power	20 dBm
Noise floor	-101 dBm	SINRDatacapture	10 dB
SINRPreamblecapture	4 dB	PowerMonitor Threshold	-86.77 dBm
Modulation scheme	BPSK	Traffic Generation	Exponential

4.2 CAR vs. Number of Active Neighbors

The transmission range with the chosen simulation parameters is found to be 155 meters. We first study the variation of the *CAR* in a test link with respect to the distance between an active neighbor and the transmitter for different loads of the active neighbor. This is plotted in Fig. 1, which shows that the carrier sensing range (*CSR*) is also 155 meters. As expected, as long as the interferer is within the *CSR*, the *CAR* is independent of the distance from the interferer and depends on the load.

We next determine the effect of the number of active neighbors on *CAR* by varying the number of active neighbors and the result is depicted in Fig. 2. It is observed that the *CAR* is not noticably affected by the active neighbors for loads lower than 150 kbps, but it drops significantly and non-linearly at higher loads, especially for higher number of active neighbors.

4.3 Queuing and Access Delay at the Test Link

The queuing delay Q_d is the property of the transmitting router, which is the time that a packet has to wait in its transmission queue before it actually reaches

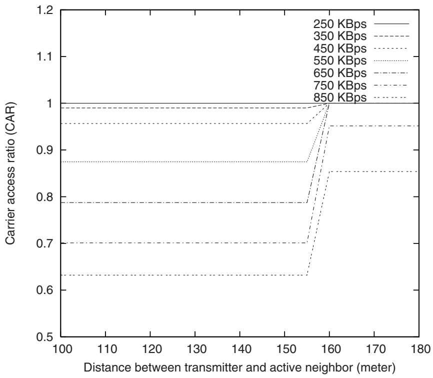

Fig. 1. Variation of CAR with respect to distance from an active neighbor

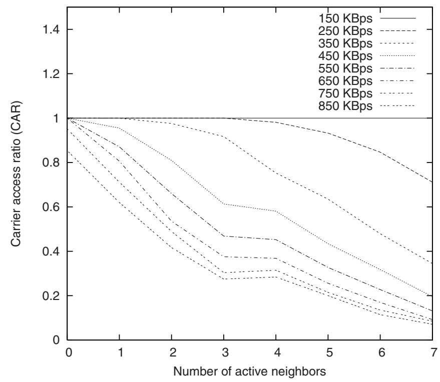

Fig. 2. Variation of CAR with the number of active neighbors

the head of the queue and starts contending for the channel. Q_d is directly related to the length of the queue and the arrival rate of the packets entering in the queue. On the other hand, the access delay Q_a is the time that a packet at the head of the transmission queue has to wait before the contention in the channel is resolved by *CSMA/CA* and the packet gets access to the channel and starts transmission. The sum of the average queuing and access delays, referred to as total delay t_d, can give a good estimate of the amount of contention in the channel for the test link. We performed simulations with different number of active neighbors. It was found that a quadratic polynomial closely describes the variation of the delay with respect to the number of active neighbors n_a as follows:

$$T_d(n_a) = An_a^2 + Bn_a + C \tag{1}$$

where A, B and C are the best fit coefficients that depend on the offered load. These coefficients were found to be $A = -3.57 \times 10^{-7}$, $B = 4.814 \times 10^{-6}$ and $C = 0.001443$ for 5 KBps; $A = 1.88 \times 10^{-6}$, $B = 9.54 \times 10^{-6}$, $C = 0.00146$ for 35 KBps; and $A = -7.023 \times 10^{-7}$, $B = 5.25 \times 10^{-5}$ and $C = 0.001425$ for 65 KBps. Delays obtained from simulations and the best fit curves described above are shown in Fig. 3, which validates the quadratic approximation.

4.4 POS at the Receiver

The variation of a test link with respect to the distance from an interfering node from the receiver for different transmission loads is depicted in Fig. 4. It is observed that the interfering range is 235m. When an interferer is within this range, its interference power causes the SINR at the receiver of the test link to drop below the minimum SINR threshold. Consequently, within this range, the *POS* is constant and depends on the load. For the rest of the paper we assume the grid spacing to be 150 meters, with which a receiver can have up to 5 interferers.

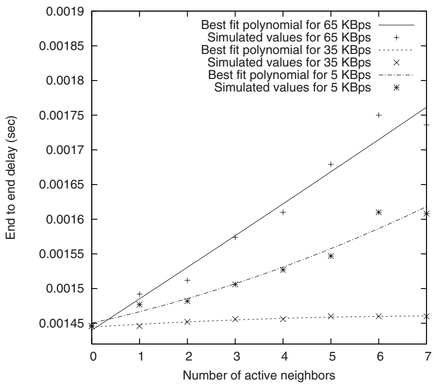

Fig. 3. Experimentally obtained model of delay versus number of active neighbors

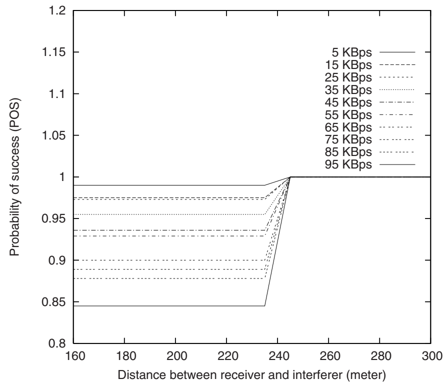

Fig. 4. Variation of POS with respect to distance from an interferer

Generally, a link in a wireless network comes under the influence of a number of interferers whose transmission may be dependent or independent of other transmitters. Independent interferers are those whose transmissions are not in any way affected by one another, i.e. each node's transmissions occur independent of those from the others. So, if S is the transmitter and D is the receiver in a test link, then the POS of the link $S \rightarrow D$ in the presense of a set of N independent interferers I with transmitted load L (L is given by $CAR \times$offered load) can be written as:

$$P_S(I) = \prod_{k=1}^{N} P_S(i_k) \tag{2}$$

where $I = \{i_1, i_2, \ldots, i_N\}$ is the set of N interferers of D and $P_S(i_k)$ is the probability of success of the test link when i_k is transmitting. Note that $P_S(i_k) = 1 - P_t(i_k)$, where $P_t(i_k)$ is the probability that a transmission from interferer i_k overlaps with the test packet from S and depends on the transmitted load L. We use simulations to determine the effect of L on $P_S(i_k)$, which is found to fit a quadratic curve as follows:

$$P_S(i_k) = Q.L^2 + R.L + T \tag{3}$$

where $Q = -1.49184 \times 10^{-6}$, $R = -0.00128499$ and $T = 0.998588$. The simulation results and the best fit curve are shown in Fig. 5.

It must be noted that although the set I can be estimated by the set of nodes that are located within the interfering range of the receiver, some additional factors affect the accuracy of equation (2). Firstly, wireless propagation can be highly non-isotropic because of shadowing, multipath reflections, and other long term fading effects. This can make it difficult to estimate the actual interference from a source from its distance from the receiver. However, because of the

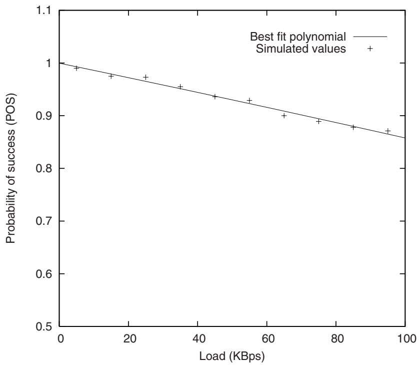

Fig. 5. Experimentally obtained model of POS versus load in the presence of one interferer

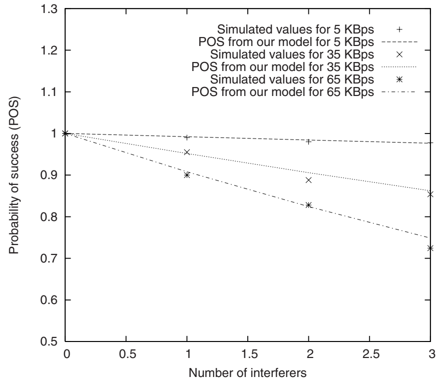

Fig. 6. POS versus number of interferers: model and simulation results

threshold effect of the interference from any source, we find that using the interfering range to identify interferers is generally acceptable. Secondly, equation (2) is based on the assumption that the set of interferers in I transmit independently of one another. The number of interferers whose transmissions are independent of each other is often hard to obtain. We discuss this issue in more detail in the next section. The above two factors need additional considerations if RTS/CTS and ACK packets are assumed, which is not discussed in this paper. Thirdly, this approximation disregards the effect of the aggregate interference of nodes that are located outside the interfering range of the receiver. This effect may cause inaccurate results in dense and highly active networks.

Fig. 6 depicts the comparison of results obtained from the approximate model in equation (2), where all the nodes have the same load, and hence, the same $P_S(i_k)$ for all i_k. The actual POS values obtained from simulations closely match the values obtained from the model, as shown in Fig. 6. So we conclude that the POS of a test link for a given load can be approximately estimated from the number of active neighbors of the transmitter and the number of interferers of the receiver using the models developed above.

4.5 Dependent Interferers and Dependencies

We now address the issue of independence of transmissions from interferers in the set I. We show with an example that not all nodes located within the interference range of a test receiver can transmit independently. For example, let us consider the scenario shown in Fig. 7, where the test link 20→21 has 3 active interferers: 16, 22, 27. However, since nodes 16 and 22 are active neighbors of each other, they cannot transmit at the same time. So, when all these nodes are active, at any point of time either 16 or 22 will transmit after resolving contention with each other, and 27 transmit can transmit independently of 16 and 22. Hence, we call 16 and 22 to be dependent interferers, whereas 27 is independent of 16 and 22.

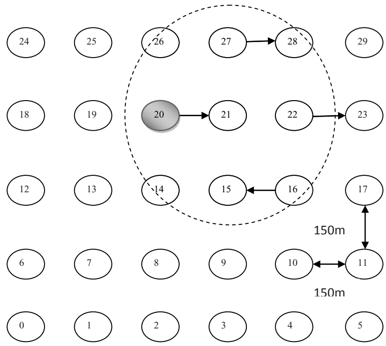

Fig. 7. 20→21 has 3 interferers and at most 2 can transmit at the same time, so dependency of D(3,2). Interference range = 235 meter is shown by dotted.

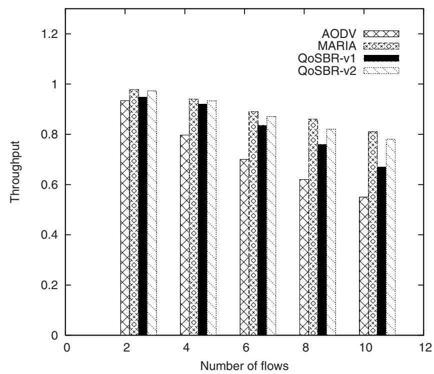

Fig. 8. Comparison of Throughput

Given a set of N_t nodes within the interfering range of a receiver, let N_a be the maximum number of interferers that can gain access to the channel simultaneously (i.e. independently). For any test link, we define the combination of N_t and N_a as a "dependency" $D(N_t,N_a)$. So, as evident from the discussion above, the dependency in Fig. 7 is *D(3,2)*. To obtain the effect of dependent and independent interferers on the *POS*, we evaluated the *POS* under different dependencies with varying loads, as shown in Table 2. It can be observed that the *POS* only depends on the effective number of interferers N_a, since the values of *POS* for *D(1,1), D(2,1), D(3,1)* are similar, and so are those for *D(2,2), D(3,2)*. So, for dependent interferers, we express the *POS* as

$$P_S(I) = \prod_{k=1}^{N_a} (P_S(i_k)) = \prod_{k=1}^{N_a} (1 - P_t(i_k)) \tag{4}$$

4.6 Route Quality Metric for Multi Hop Mesh Networks

We now extend the above models of the estimated *POS* and delay of a test link to define an end-to-end route quality metric. This is based on the objective of maximizing the end-to-end *POS* and minimizing the end-to-end delay in the route. The net *POS* is taken as the product of the *POS* of every individual link on the route and the total delay is taken as the sum of the link delays. Consequently, we define the route quality $QOS\_R(r)$ metric for route r of length v operating at load L as follows:

$$QOS\_R(r) = (\prod_{f=1}^{v} P_S(I_f)) / \sum_{f=1}^{v} T_d(n_{af}) \tag{5}$$

Table 2. POS with different dependencies

Load(KBps)	D(1,1)	D(2,1)	D(2,2)	D(3,1)	D(3,2)	D(3,3)
5	0.99	0.99	0.98	0.99	0.98	0.9776
15	0.975	0.976	0.96	0.98	0.951	0.943
25	0.973	0.953	0.915	0.953	0.9169	0.9164
35	0.955	0.938	0.888	0.9521	0.896	0.854
45	0.936	0.935	0.8886	0.94	0.878	0.829
55	0.929	0.92	0.849	0.9138	0.8522	0.794
65	0.9	0.909	0.828	0.907	0.848	0.7044
75	0.889	0.9	0.7912	0.903	0.79	0.716
85	0.878	0.879	0.752	0.869	0.785	0.685
95	0.871	0.86	0.773	0.86	0.779	0.685

Here, f is a link on the route from source to destination, $P_S(I_f)$ is the *POS* of link f, I_f is the set of interferers, and $T_d(n_{af})$ is the delay experienced by a packet with n_{af} active neighbors.

5 QoSBR Routing Protocol

In this section we describe the proposed QoS based routing protocol *QoSBR* that uses the quality metric derived in the previous section. *QoSBR* is a reactive routing protocol that tries to select routes with the highest ratio of the end-to-end *POS* and delay based on parameters collected and conveyed by *RREQ* packets. We present two versions of *QoSBR*, which differ in the contents of the propagating *RREQ* packets and how the quality metric is calculated. These are described in detail below.

When the source does not have a route to the destination, it broadcasts a route request packet (*RREQ*) to its neighbors. The *RREQ* packet contains four fields: the number of active neighbors of the sender (A), the accumulated *POS* on the current route (P_S), the accumulated delay in the current route (T_d), and a timestamp. These quantities are initialized at the source to the number of active neighbors of the source, $P_S = 1$, $T_d = 0$, and timestamp = the time when the *RREQ* packet was generated. Every intermediate node updates the accumulated *POS* and delay based on the number of active neighbors of the previous node and its active interferers before forwarding it. All intermediate nodes do the same thing until the *RREQ* reaches the destination where the destination calculates the quality metric $QOS\_R = P_S/T_d$. The timestamp is used to reduce unnecessary flooding of *RREQ* packets throughout the network. The destination waits for the first ten packets and forwards a route reply packet (*RREP*) back on the route that has the highest QOS_R value. The source then starts sending the data packets via this route. In this version, the intermediate nodes are required to calculate the *POS* and delay, for which the nodes must know its active neighbors and interferers. One way to achieve this is for the gateway to forward this information to all nodes at periodic intervals, which causes additional overhead.

In order to avoid the overhead problem mentioned above, we propose another version of the *QoSBR* routing protocol, where the *RREQ* packet simply carries the sequence of nodes that it has traversed, and the destination (gateway) uses the node location and neighborhood information to calculate the end-to-end *POS* and delay, and hence the *QOS_R* for each route. In addition to solving the problem of providing all nodes with node location information, *QoSBR_v2* can also calculate the route quality more accurately because it can use global location information to determine dependent and independent interferers based on the information conveyed by each *RREQ* packet. But the disadvantage of this scheme is that as the intermediate routers have to append its own IDs, the size of the *RREQ* packet gets larger as it propagates along the network, which can be a problem for large networks.

6 Performance Evaluation of QoSBR

We present the performance of the proposed *QoSBR* routing protocol in comparison to *AODV* and *MARIA* [4] in a general simulation scenario. We consider the same network scenario as shown in Fig. 7, which consists of 30 nodes placed in a grid. The channel bandwdith is assumed to be 2 Mbps. We have choosen 29 as the destination (Internet gateway) and all sources send packets to the gateway. The sources are selected randomly. Each flow runs *UDP* with a transmission rate of 35 KBps. Each flow is alive for 200 seconds. We have averaged the results over 10 such simulations.

We vary the number of flows and measure the average throughput, delay and jitter of the data flows using the three different routing protocols. The results are shown in Fig. 8–10. It is observed that *QoSBR_v2* performs better than *QoSBR_v1*, as *QoSBR_v2* requires the destination to measure the quality of a route after getting all the intermediate nodes in the route, while in *QoSBR_v1* the quality is calculated in the intermediate routers which only know the *existing*

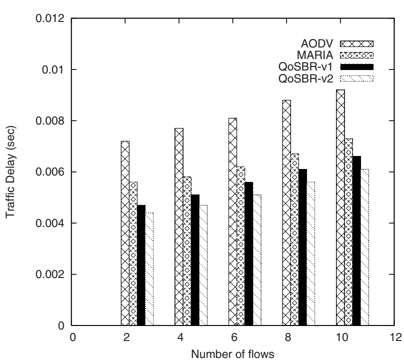

Fig. 9. Comparison of Delay

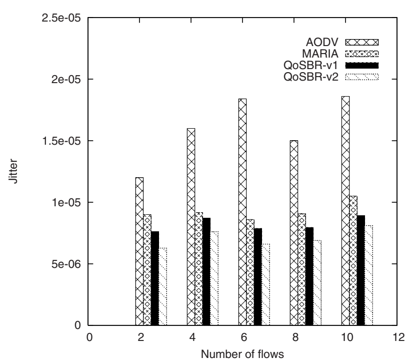

Fig. 10. Comparison of Jitter

active nodes and query packet information. But both *QoSBR_v1* and *QoSBR_v2* provide significantly better performance than *AODV* in terms of throughput, delay, and jitter. This is because the shortest path does not necessarily provide the best quality. It is observed that *MARIA* also gives better performance than *AODV*, in terms of throughput, delay and jitter. While *MARIA* gives a little higher throughput than *QoSBR-v2*, *QoSBR_v2* provides a significant improvement in delay and jitter over *MARIA*. The reason is that *MARIA* only chooses the route based on higher residual bandwidth i.e. lesser interference, without considering the delay. But the delay is an important parameter for determining a good route in many applications. While calculating the throughput, *QoSBR_v2* considers the effect of dependent and independent interferers where *MARIA* chooses routes based on only residual bandwidth without considering the dependencies among the interferers. Hence, there would be many scenarios where *MARIA* will give inferior performance than *QoSBR_v2* as *QoSBR_v2* considers both *POS* and delay. Such an example is shown in Fig. 11, where route chosen by *MARIA* for the flow 5 → 29 is much longer than *QoSBR_v2* in presence of background traffic 16 → 22 → 28 → 29. The performance of these two routes have been shown in Table 3 and Table 4 in presence of background traffic. From Table 3, we can see that the route chosen by *MARIA* gives almost same throughput compared to *QoSBR_v2*. But the traffic delay for *MARIA* is much larger than *QoSBR_v2*, as seen from Table 4.

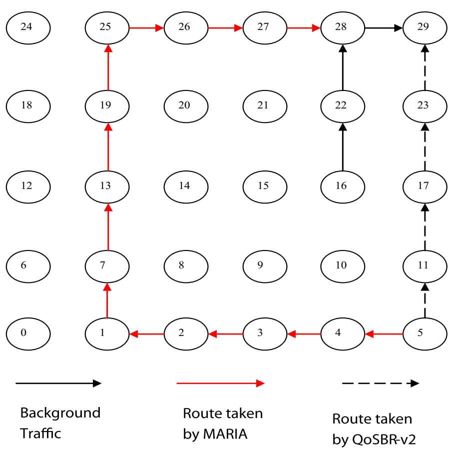

Fig. 11. Routes chosen by MARIA and QoSBR-v2 when the source-destination pair is 5→29 and 16→22→8→29 is the background traffic

Table 3. Comparison of throughput

Load (KBps)	MARIA	QoSBR_v2
5	0.988	0.9799
15	0.969	0.96
25	0.945	0.936
35	0.923	0.917

Table 4. Comparison of delay (sec)

Load (KBps)	MARIA	QoSBR_v2
5	0.0176	0.0058
15	0.0176	0.0058
25	0.01765	0.0058
35	0.01769	0.0058

7 Conclusion and Future Work

Mesh networks are a promising approach to wireless Internet connectivity for mobile users and routing remains a major concern in multi-hop wireless mesh networks. In this paper, we have developed *QoSBR*, a novel *QoS* aware routing protocol for wireless mesh networks. Specifically, *QoSBR* takes two *QoS* metrics into account: *POS* and end to end delay. Our *QoS* based routing scheme achieves encouraging results with the help of proposed quality metric for link.

There are a number of grounds to do future work on this topic. Firstly, we plan to work on the presented scheme under more general assumptions, such as usage of *RTS/CTS* and *ACK* packets. We also intend to apply this to multiple gateway nodes using anycasting. In addition, we will extend this QoS-based routing approach to incorporate multiple channels with multiple radios for each mesh routers to reduce co-channel interference.

References

1. The network simulator - ns-2 webpage, http://www.isi.edu/nsnam/ns/
2. Akyildiz, I.F., Wang, X., Wang, W.: Wireless mesh networks: a survey. Computer Networks 47(4), 445–487 (2005)
3. Carlson, E., Karl, H., Wolisz, A., Prehofer, C.: Distributed allocation of time slots for real-time traffic in a wireless multi-hop network (2004)
4. Cheng, X., Mohapatra, P., Lee, S., Banerjee, S.: Maria: Interference-aware admission control and qos routing in wireless mesh networks. In: ICC (2008)
5. Ke, Z., Li, L., Sun, Q., Chen, N.: A qos multicast routing algorithm for wireless mesh networks. In: SNPD (1), pp. 835–840 (2007)
6. Kolar, V., Abu-Ghazaleh, N.B.: A multi-commodity flow approach for globally aware routing in multi-hop wireless networks. In: PerCom, pp. 308–317 (2006)
7. Kone, V., Das, S., Zhao, B.Y., Zheng, H.: Quorum - quality of service in wireless mesh networks. MONET 12(5-6), 358–369 (2007)
8. Lundgren, H., Nordström, E., Tschudin, C.F.: The gray zone problem in ieee 802.11b based ad hoc networks. MC2R 6(3), 104–105 (2002)
9. Romdhani, L., Bonnet, C.: Cross-layer qos routing framework for wireless mesh networks. ICWMC, 382–388 (2008)
10. Xue, Q., Ganz, A.: Qos routing for mesh-based wireless lans. IJWIN 9(3), 179–190 (2002)