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# GSQAR: A Quality Aware Anycast Routing Protocol for Wireless Mesh Networks

Amitangshu Pal and Asis Nasipuri
Electrical and Computer Engineering, The University of North Carolina at Charlotte
9201 University City Blvd., Charlotte, NC 28223
Email: {apal,anasipur}@uncc.edu

***Abstract*—We consider anycast routing to improve the quality of communications in multi-gateway wireless mesh networks. A centralized gateway and route selection scheme is proposed that tries to maximize the end-to-end probability of success and minimize the end-to-end delay of all active traffic flows in the network. The proposed scheme employs a novel route quality metric that is based on the effects of interference on data packet transmissions. We present performance evaluations of the proposed scheme using *ns-2* simulations.**

## I. Introduction

Wireless mesh networks (*WMNs*) are emerging as a promising technology for extending the coverage of wireless LANs in enterprises, campuses and metropolitan areas. A small fraction of the wireless mesh nodes or routers in a *WMN* may have wired connection to the Internet and serve as gateways to the rest of the network. Thus, *WMN*s also provide a cost-effective solution for extending the reach of Internet access points. In such applications, mobile clients (users) are interested to connect to any one among a set of gateways in the network, which is termed as anycasting.

Multi-gateway *WMN*s with anycast routing has several features that can be utilized for improving the *quality of service* of wireless connections. Firstly, multiple gateways provide redundancy, which help in reducing congestion on any single gateway. In addition, the possibility for *cooperative* selection of gateways for all active users and their corresponding routes enables better utilization of resources in the network. However, this leads to a *joint* gateway selection and routing problem, which is computationally hard. In addition, the network parameters may vary with time, which increases the complexity of the problem. For instance, as illustrated in Fig. 1, an user $C$ may be initially connected to $G_1$, which provides the best quality of service among a number of available gateway nodes ($G_1, G_2, G_3, G_4, G_5, G_6$) in the absence of any other active node in its vicinity. However, if user $A$ becomes active after $C$ is connected, it may be necessary to switch $C$ to $G_2$ and connect $A$ to $G_1$ so that the two active routes do not interfere with each other and the overall performance is optimized. Such decisions depend on a number of parameters that affect the quality, which are evaluated at different locations and times, making the optimization difficult. In this paper, we consider a centralized approach to address this issue, where it is assumed that the gateway nodes are connected by an infrastructured network such as an optical fiber network, and collaborate with each other for determining the optimum gateway and route selections for all active nodes in the network. We propose a *gateway selection and quality aware anycast routing protocol, GSQAR*, which tries to maximize the overall quality of all active traffic flows in the network. *GSQAR* employs a novel route quality metric that utilizes performance characteristics of data packet transmissions as opposed to control packets, and effectively captures the effects of intraflow and interflow interference. We show that *GSQAR* performs better than anycast routing schemes that are based on *random* and *nearest* gateway selection.

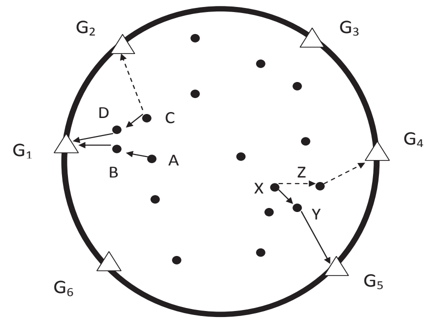


Fig. 1. Wireless mesh network architecture with multiple gateways

## II. Related Work

First, we briefly review existing research on related issues of multi-gateway wireless mesh networks. In [8], the authors propose a *multi-gateway wireless mesh network routing protocol (MAMSR)* based on the *Dynamic source routing (DSR)* protocol. The routing metric used in *MAMSR* is hop count, where gateway and route selection is performed on the basis of the first *RREP* packet received by the source. A hybrid anycast routing is proposed in [7] where the network is divided into two regions: proactive and reactive. Nodes that are very close to any gateway are in the proactive region and send packets to this gateway only. Nodes that are not in the proactive region are part of the reactive region; these nodes choose gateways that carry minimum load. Another multi-gateway association scheme is proposed in [2], where the shortest paths from any node to each gateway and the available bandwidth in all the paths are computed. The path that has the largest available bandwdith is selected in a greedy manner. In [4], the authors propose a scheme where each source keeps track of its nearest gateway as the primary and other gateways as secondary gateways. All nodes generally send traffic to their primary gateways. If the primary gateway is congested, sources with high traffic are notified by the gateway to switch their traffic to some other gateways.

In our earlier work [6], we proved that the *gateway selection problem* is *NP-hard* and proposed a quality-aware anycast routing protocol that searches through a smaller subset of nodes in the network for gateway and route selection. The proposed routing protocol in [6], which we term as *GSQAR-v1*, primarily uses hop count as a measure of route quality, which can lead to suboptimal results. Many other *QoS* routing protocols rely on control packets (such as *RREQ* and *RREP* packets) for route quality assessments, which also leads to inaccurate assessments of route quality, since control packets are much smaller than data packets and are sent at a lower transmissions rate [3]. As opposed to these approaches, here we apply a route quality metric that uses probabilistic models and characteristics of actual data packet transmissions obtained from offline simulations. This is motivated by our prior work on applying a similar approach for unicast routing [5], [6], which generated encouraging results.

## III. Problem Formulation And GSQAR Design

Consider a scenario with $n$ sources $\{S_1, S_2, ..., S_n\}$ and a group of $m$ gateways $\{G_1, G_2, ..., G_m\}$ where $1 \leq m \leq n$. The optimum gateway selection problem is to assign the $n$ sources to $m$ gateways so that the aggregate quality of all routes is maximized. This problem can be formulated as a $0-1$ *integer programming problem* as follows:

$$Maximize \sum_{i=1}^{n} \sum_{j=1}^{m} Q_{S_i G_j} X_{S_i G_j} \quad (1)$$

subject to

$$\sum_{j=1}^{m} X_{S_i G_j} = 1, \quad (1 \leq i \leq n) \quad (2)$$

$$X_{S_i G_j} = 0 \text{ or } 1 \ (1 \leq i \leq n) \ (1 \leq j \leq m) \quad (3)$$

where $Q_{S_i G_j}$ is the quality of the best route between $S_i$ and $G_j$ and $X_{S_i G_j}$ is a binary variable used for gateway selection: if the best gateway chosen for $S_i$ is $G_j$, then $X_{S_i G_j}$ =1; otherwise $X_{S_i G_j}$ =0. Constraint $(2)$ states that $S_i$ can transmit all its packets to one gateway only.

### A. Route Quality Estimation

We now describe the development of a routing metric that tries to capture the quality of multihop routes in terms of the end-to-end probability of success (*POS*) and delay. Our approach is to determine the major factors that affect the *POS* and delay in multihop wireless networks using the *IEEE 802.11 MAC* and develop models that involve a compact set of parameters. These models are then applied to develop the routing metric that can be used to estimate the route quality using parameters obtained from the network.

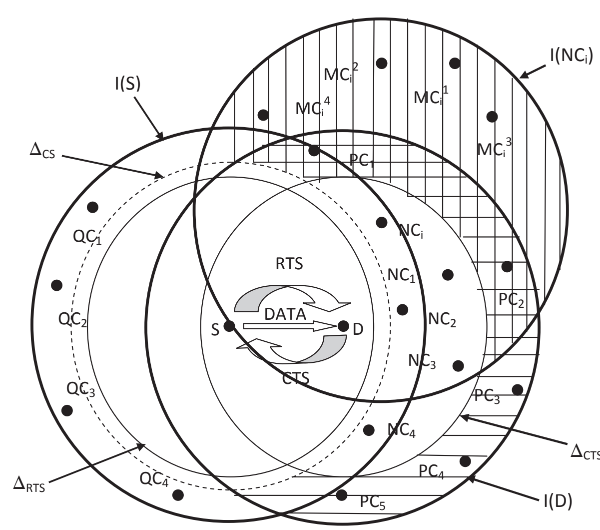


Fig. 2. Effect of interferers in presense of RTS/CTS for test link $S \rightarrow D$

*1) Probability of success (POS):* In order to model the *POS* using a simple set of measurable parameters, we analyze a test link $S \rightarrow D$ as shown in Fig. 2. Here, $\Delta_{RTS}$ and $\Delta_{CTS}$ denote the regions where the *RTS* and *CTS* packets for the test link $S \rightarrow D$ can be received, respectively. $\Delta_{CS}$ denotes the area around *S* where nodes can sense the transmission from *S*. For any node $i$, $I(i)$ denotes the area from where a transmission from any node $j \in I(i)$ can interfere with a packet being received at $i$. In the following, we determine the *POS* in the test link by analyzing the possible cases that can cause a data packet transmission in the test link to be unsuccessful.

**Case-1:** The transmitted data packet is unsuccessful due to interference from nodes that are outside the reception range of the *CTS* packet but within the interference range of $D$. These nodes are marked as $PC_i$ in Fig. 2, of which we assume $q$ and $r$ nodes are in sending and receiving states, respectively. The sending nodes can interfere by transmissions of either *RTS* or data packets. However, since the length of the *RTS* packets is much smaller than the data packets, its effect on the *POS* of the data packet at $D$ will be much smaller, and hence we only consider the interference of data packet transmissions from the $q$ sending nodes among $PC_i$. In the absence of any other interferer that can affect the reception of the test data packet, the effect of a single interfering sending node among $PC_i$ can be evaluated as follows: *P(DATA packet is received successfully* $|$ *DATA packet is transmitted) = P(DATA packet is received successfully* $|$ *RTS is received successfully at D) = P(DATA and RTS are received successfully) / P(RTS is recived successfully at D) = P(*$PC_i$ *does not send DATA in the vulnerable period (2×DLEN) of S) / P(*$PC_i$ *does not send DATA in the vulnerable period of RTS of S (DLEN))* = $e^{-2\times\lambda\times DLEN}/e^{-\lambda\times DLEN} = e^{-\lambda\times DLEN}$, where $\lambda$ is the arrival rate of data packets, which is assumed to follow a Poisson distribution, and $DLEN$ is the data packet length. For $q$ independent senders ($PC_1, PC_2, ..., PC_q$) in this region, the *POS* of the *DATA* packet is given by $e^{-\lambda\times DLEN\times q}$.

The receiving nodes among $PC_i$ can interfere by the transmission of *CTS* packets during the transmission of the test *DATA* packet; thus the *POS* in the presense of *r* such nodes is $e^{-\lambda \times DLEN \times r}$.

**Case-2:** The transmitted data packet is unsuccessful due to interference from nodes that are within the transmission range of $D$ but fail to receive the *CTS* packet from $D$. Such interfering nodes, marked as $NC_i$ in Fig. 2, do not receive the *CTS* from $D$ due to an overlapping transmission from $MC_j^i$. The probability of this event is $1 - e^{-\lambda \times DLEN}$, which is the probability that $MC_i^j$ transmits in the vulnerable period ($DLEN$) of the *CTS* transmission from *D* [1]. In general, if there are $m$ such interferers among $MC_i^j$, then the probability that the *CTS* is not received by $NC_i$ is $1 - \prod_{i=1}^{m} e^{-\lambda \times DLEN} = 1 - e^{-\lambda \times DLEN \times m}$.

The probability that $NC_i$, having failed to receive the *CTS* from $D$, interferes with the reception of the *DATA* packet at $D$ is then given by $(1 - e^{-\lambda \times DLEN})$, which is the probability that an *RTS* transmission from $NC_i$ overlaps with the test *DATA* packet at $D$. Consequently, the *POS* of the test *DATA* transmission from $S$ to $D$ in the presence of interference from any node $NC_i$ is given by $1 - (1 - e^{-\lambda \times DLEN})(1 - e^{-\lambda \times DLEN \times m})$. In the presence of $n$ such nodes $(NC_1, NC_2, \cdots, NC_n)$, the *POS* is given as $\prod_{i=1}^{n} 1 - (1 - e^{-\lambda \times DLEN})(1 - e^{-\lambda \times DLEN \times m})$.

**Case-3:** The data transmission is unsuccessful due to failure in receiving the *ACK* packet at $S$, caused by interference from neighbors of $S$. A little thought reveals that the *ACK* packet can be interfered only by *RTS* packets transmitted by neighbors of $S$. As the packet sizes of both *ACK* and *RTS* are very small, the corresponding probability of interference is also small, and we ignore this case.

By taking into account all the factors described above, the *POS* for the *DATA* packet on the test link is given as:

$$POS = \left\{ \prod_{i=1}^{n} 1 - (1 - e^{-\lambda \times DLEN})(1 - e^{-\lambda \times DLEN \times m}) \right\} \times e^{-\lambda \times DLEN \times q} \times e^{-\lambda \times DLEN \times r} \quad (4)$$

Hence, the *POS* of a link can be estimated using the above equation as long as the values of $m, n, q$ and $r$ are known, which can be obtained in a static mesh network from knowledge of node locations. The above model for the *POS* has been verified with extensive simulation experiments, which could not be included in this paper due to space constraints. We refer the readers to [5] for further details.

*2) Queuing And Access Delay:* The transmission delay in a wireless link using the 802.11 MAC depends on the complex interaction of channel access, back-offs, transmissions and retransmission attempts of multiple active nodes in the neighborhood of the test link. However, it can be shown [5] that for a given offered load, the total delay on a test link can be approximately estimated from the number of active

[1]As before, we ignore the effect of interference of the smaller *RTS* and *CTS* packets in favor of a data packet from $MC_i^j$, since those probabilities are comparitively smaller.

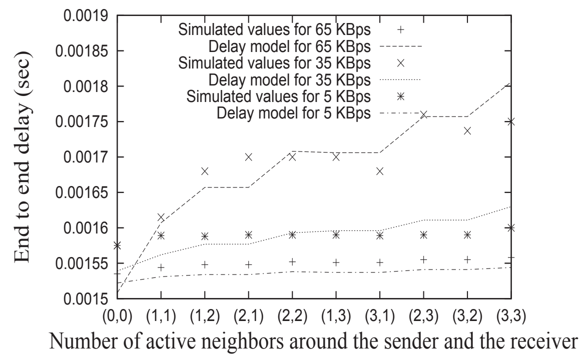


Fig. 3. Variation of delay with different number of active neighbors of sender and receiver. The terms in x axis are ($n_a$, $n_b$).

neigbors of the sender ($n_a$) and the number of active neighbors of the receiver ($n_b$) as follows:

$$T_d(n_a, n_b) = A(n_a^2 + n_b^2) + B(n_a + n_b) + C \quad (5)$$

We use simulation experiments to develop this approximate model for $T_d(n_a, n_b)$ at various offered loads, as shown in Fig. 3. In equation (5) $A$, $B$, $C$ varies with load and are obtained by best fitting the simulated values.

*3) Route Quality Metric:* With these, we propose a route quality metric with the objective of maximizing the end-to-end *POS* and minimizing the end-to-end delay in the route. For any 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 metric for route $R$ of length $v$ as follows:

$$QOS(R) = (\prod_{f=1}^{v} P_S(I_f)) / \sum_{f=1}^{v} T_d(n_{af}, n_{bf}) \quad (6)$$

Here, $f$ is a link on the route from source to gateway , $P_S(I_f)$ is the *POS* of link $f$, $I_f$ is the set of interferers. $T_d(n_{af}, n_{bf})$ is the delay with $n_{af}$ and $n_{bf}$ active neighbors at the sender and the receiver end respectively.

### *B. GSQAR design and the proposed routing protocol*

As the problem of optimal gateway selection is *NP-hard*, we propose a heuristic scheme that avoids a global search but has a high probability of improving the quality of service in the network. We assume that the gateway nodes can exchange information with one another and can collaborate to perform gateway and route selections for the entire network. We also assume that the neighborhood information for all nodes, including neighbors within carrier sensing and transmission ranges of all nodes, are known. This could be obtained from a separate scheme, such as one using probing signals from all nodes, which is beyond the scope of this paper.

When a source becomes active (i.e. needs to connect to a gateway), it broadcasts a *RREQ* packet, which carries information about the route that it traces. This information is used by the gateway node to compute the route quality using equation (6) and neighborhood and activity information for all nodes

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involved in the route. For each source $S_i$, a gateway keeps the first $N$ routes that it obtains from the arriving *RREQ* packets. These routes are called *candidate routes (CR)*. So, *CR*s from $S_i$ to $G_j$ can be written as $\{R^p_{S_iG_j}\}, p = 1, 2, ..., N$, where $R^p_{S_iG_j}$ is the route taken by the $p$th *RREQ* packet from $S_i$ to $G_j$. The qualities of $R^p_{S_iG_j}$ are represented as $Q^p_{S_iG_j}$. Table I(a) shows the *quality table (QT)* for an instance of three active sources and two gateways, where qualities of the best routes among the candidate routes for all source-gateway pairs are stored. So, $QT = \{Q_{S_iG_j}\} \quad \forall S_i \in S$ and $\forall G_j \in G$ where $Q_{S_iG_j} = max\{Q^p_{S_iG_j}\}, p = 1, 2, ..., N$ and the corresponding route is denoted as $R_{S_iG_j}$. So, gateway and route selection for the first source that becomes active is determined by the highest $Q_{S_iG_j}$ in the *QT* corresponding to that source.

When a new source becomes active, the algorithm compares the average route quality for all active sources as obtained from the following two methods for gateway and route selection: (a) *Incremental method:* where all previously assigned routes are unchanged and gateway and route selection for the new source is performed based on the best $Q_{S_iG_j}$ value for the new source by considering *interflow interference* from existing routes, and (b) *Global method:* where the best set of gateways are calculated for all active sources together, assuming that existing routes can be switched to any other route in its *CR*. This gives a better solution, but not necessarily the globally optimum one. If the average quality using the *global* solution is greater than the *incremental* solution by a significant amount, then those selections are chosen. Else, the algorithm prefers the *incremental* solution, to avoid *frequent switching*, which may lead to quality degradation. When more than one route have the same quality, the shortest route is selected.

We take an example to describe the process. Consider that $S_1$ and $S_2$ are active and connected to $G_2$ and $G_1$, respectively, when $S_3$ becomes active. Here, the *incremental* solution consists of $S_1{\rightarrow}G_2$, $S_2{\rightarrow}G_1$ and $S_3{\rightarrow}G_i$, where $G_i \in \{G_1, G_2\}$ is the gateway corresponding to the highest entry for $S_3$ in *QT* assuming the interflow interference from $S_1{\rightarrow}G_2$ and $S_2{\rightarrow}G_1$. Let us assume that $Q_{S_1G_2} + Q_{S_2G_1} + Q_{S_3G_i} = Q^{inc}_{total}$.

The *global* solution is obtained as follows: the highest entry in the *QT* table constructed without any interflow interference (shown by $Q_{S_iG_j}$ in Table I(a)) is selected first. Assume this entry is $S_1{\rightarrow}G_2$. Next the quality of the candidate routes for the remaining sources $(S_2, S_3)$ are recalculated by considering the *inter-flow interference* from $S_1{\rightarrow}G_2$, as shown by $\dot{Q}_{S_iG_j}$ in Table I(b). The highest quality among these entries is selected next, which in our example is $\dot{Q}_{S_3G_1}$. Consequently, $S_3$ is routed to $G_1$, as shown in Table I(c). This procedure is repeated (recalculating the qualities of the candidate routes with existing interference of $S_1{\rightarrow}G_2$ and $S_3{\rightarrow}G_1$), for $S_2$ as shown in Table I(d), which indicates the selection of $S_2{\rightarrow}G_2$ in the last step. All selected entries in $QT$ are indicated in larger font. Thus, the *global* method results in $S_1{\rightarrow}G_2$, $S_2{\rightarrow}G_2$, $S_3{\rightarrow}G_1$, where the average quality is $Q^{glo}_{total} = Q_{S_1G_2} + Q_{S_2G_2} + Q_{S_3G_1}$. Now, if $Q^{glo}_{total} - Q^{inc}_{total} > \tau_Q$, where $\tau_Q$ is a predefined parameter, then the selection from the *global* method are selected, otherwise those from the *incremental* method are selected. The process can be repeated for additional sources.

TABLE I
QUALITY TABLE

(a) Initially

| | $G_1$ | $G_2$ |
|---|---|---|
| $S_1$ | $Q_{S_1G_1}$ | $Q_{S_1G_2}$ |
| $S_2$ | $Q_{S_2G_1}$ | $Q_{S_2G_2}$ |
| $S_3$ | $Q_{S_3G_1}$ | $Q_{S_3G_2}$ |

(b) After $S_1{\rightarrow}G_2$ is selected

| | $G_1$ | $G_2$ |
|---|---|---|
| $S_1$ | $Q_{S_1G_1}$ | $Q_{S_1G_2}$ |
| $S_2$ | $\dot{Q}_{S_2G_1}$ | $\dot{Q}_{S_2G_2}$ |
| $S_3$ | $\dot{Q}_{S_3G_1}$ | $\dot{Q}_{S_3G_2}$ |

(c) After $S_3{\rightarrow}G_1$ is selected

| | $G_1$ | $G_2$ |
|---|---|---|
| $S_1$ | $Q_{S_1G_1}$ | $Q_{S_1G_2}$ |
| $S_2$ | $\ddot{Q}_{S_2G_1}$ | $\ddot{Q}_{S_2G_2}$ |
| $S_3$ | $\dot{Q}_{S_3G_1}$ | $\dot{Q}_{S_3G_2}$ |

(d) After $S_2{\rightarrow}G_2$ is selected

| | $G_1$ | $G_2$ |
|---|---|---|
| $S_1$ | $Q_{S_1G_1}$ | $Q_{S_1G_2}$ |
| $S_2$ | $\ddot{Q}_{S_2G_1}$ | $\ddot{Q}_{S_2G_2}$ |
| $S_3$ | $\dot{Q}_{S_3G_1}$ | $\dot{Q}_{S_3G_2}$ |

## IV. PERFORMANCE EVALUATION OF GSQAR

We now present the performance of the proposed *GSQAR* routing protocol, which we refer to as *GSQAR-v2*, and compare it with anycasting mechanisms employing other routing metrics and gateway selection policies. In particular, we consider *AODV based nearest gateway selection scheme*, which is a popular ad hoc routing protocol, and the *QoSBR based random gateway gateway selection scheme* presented in [5]. We also compare the performance of *GSQAR-v2* with *GSQAR-v1* presented in [6]. We use the *ns–2* [1] for all performance evaluations on a uniform grid network consisting of 30 nodes. We choose two gateways and keep them fixed. The active sources are selected randomly, with each source generating *UDP* traffic with a transmission rate of 65 KBps for a period of 200 seconds. All results are averaged over 10 such simulations.

The performance is measured in terms of the average throughput, delay and jitter with different number of data flows, i.e. number of active sources. The results are shown in Fig. 4. It is observed that the two *GSQAR* schemes perform better than both *QoSBR based random gateway selection scheme* and *AODV with nearest gateway selection scheme* in terms of throughput, delay, and jitter. This shows the benefits of anycasting for achieving the best overall quality. It is observed that *GSQAR-v2* provides higher throughput than *GSQAR-v1*, while the delay and jitter performances are similar for both the schemes.

Finally, we take a specific example to demonstrate the potential benefit of *GSQAR* over nearest gateway selection and random gateway selection. We consider the scenario shown in Fig. 5(a), where the sources, which are marked by shaded circles, are chosen to lie close to one another to increase the probability of contention for channel access. It is observed that when using the nearest gateway selection scheme, all sources choose the gateway 24, thereby causing heavy contention and interference that affects the throughput. On the other hand, *GSQAR* chooses gateways intelligently to give better performance. The results are shown in Fig. 5(b)-(e). Fig. 5(c)-(e) again show the superiority of *GSQAR* over nearest gateway and random gateway selection schemes in terms of throughput, delay and jitter. Fig. 5(b) confirms the fact that even if a

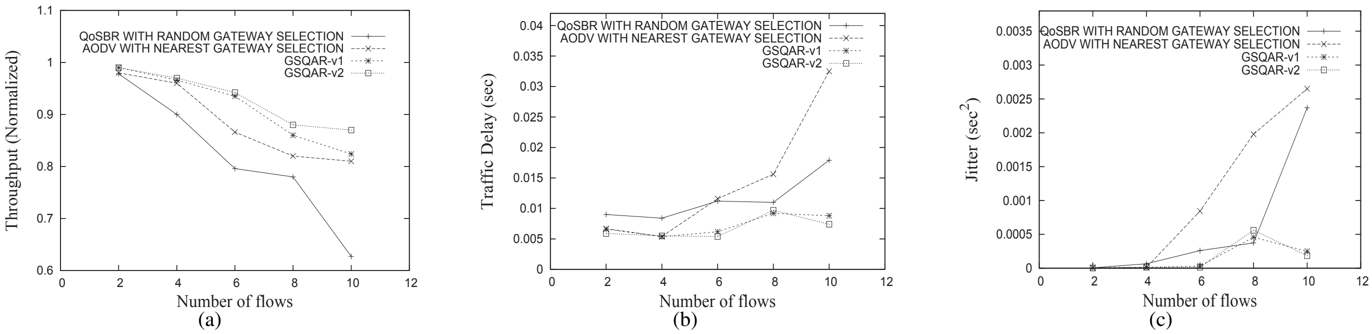


Fig. 4. Comparison of (a) Throughput (b) Delay (c) Jitter

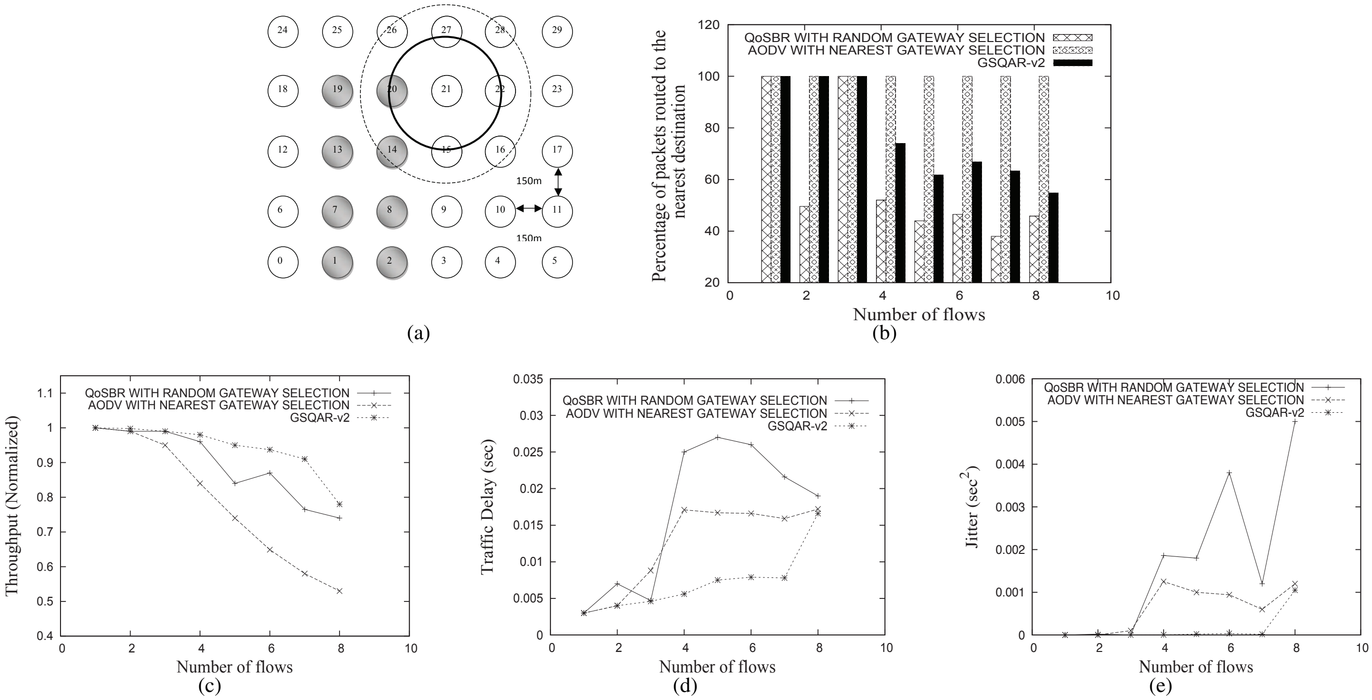


Fig. 5. (a) Simulation scenario, 19, 20, 13, 14, 7, 8, 1, 2 are actived in sequence, 24 and 29 are gateways, interference and transmission range are dotted and dark circle respectively (b) Comparison of percentage of packets routed to the nearest gateway (c) Throughput (d) Delay (e) Jitter.

large number of packets in *GSQAR* do not choose the nearest gateway, the throughput, dealy and jitter performance are still far better than nearest gateway selection scheme.

## V. Conclusion and Future Work

We develop a *QoS* aware anycast routing protocol *GSQAR*, which uses a quality metric that is built on offline measurements of characterisitics of data packet transmissions in a multihop network. Simulation experiments demonstrate that *GSQAR* is effective in improving both the throughput and delay performance in mutlihop environments in comparison to schemes using nearest or random gateway selection with shortest path routing. Future work includes application of the proposed *QoS* based anycast routing approach to incorporate multiple channels with multiple radios for each mesh router to reduce co-channel interference.

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