QoS Enhancement and Performance Evaluation of Ad-hoc Routing Protocols for Rural Public Safety

Chad Bohannan, Li Zhang, Jian Tang, Richard S. Wolff, Shen Wan, Neeraj Gurdasani and Doug Galarus

***Abstract*—In this paper, we explore the feasibility of using Mobile Ad-hoc Networks (MANETs) for rural public safety. First, we discuss a QoS enhancement to a standard routing protocol, Dynamic Source Routing (DSR). By incorporating a new routing metric and the available bandwidth and delay estimation algorithms with DSR, we design a new routing protocol, QoS-Aware Source Routing (QASR), to meet the QoS requirements specified by Statement of Requirements (SoR) for public safety communications. We then evaluate the performance of QASR and the well-known standard routing protocols including Ad-hoc On-demand Distance Vector (AODV) and DSR based on real public safety scenarios using the OPNET modeler at the 4.9GHz public safety spectrum band. Simulation results show that QASR significantly outperforms DSR and AODV in terms of various performance metrics.**

***Index Terms*—Mobile ad-hoc networks, routing, QoS, public safety, rural areas.**

I. Introduction

Providing responsive and effective public safety is particularly challenging in rural and sparsely populated areas, where the lack of communication infrastructure, large distances and difficult terrain contribute additional complexities. A Mobile Ad-hoc Networks (MANET) is a self-organizing, and highly dynamic wireless network composed of mobile nodes. Such a network can be formed on the fly without requiring any fixed infrastructure and each node can act as a router to forward packets for other nodes. MANETs are considered as a promising solution to connect vehicular and hand-held nodes with fixed infrastructure and with each other for public safety communications in rural areas.

According to the Statement of Requirements (SoR) [11], the public safety communications have stringent end-to-end Quality of Service (QoS) requirements, which, however, have not been adequately addressed by any standard ad-hoc routing protocols. Even though these protocols vary in many aspects such as route discovery mechanisms (reactive vs. proactive), routing approaches (source routing vs. hop-by-hop routing), they share a common feature, i.e., a single shortest path from the source node to the destination node is selected for packet forwarding. A shortest path may be a cost-efficient solution however it may not able to satisfy the end-to-end QoS requirements. For example, a heavily loaded node without enough available bandwidth may still be blindly chosen by the routing protocol for packet forwarding.

In this paper, we explore the feasibility of using MANETs for rural public safety. First, we discuss a QoS enhancement to a standard routing protocol, Dynamic Source Routing (DSR) [4]. Specifically, we introduce a new routing metric which offers full consideration for available bandwidth, delay and node mobility. By incorporating the routing metric and the bandwidth and delay estimations algorithms proposed in [16], [17] with DSR, we design a new routing protocol, QoS-Aware Source Routing (QASR), to meet the QoS requirements specified in the SoR. For the evaluation purpose, we present two scenarios, the river search and the dam breach, to model the rural public safety communication environment including the effects of terrains, node mobility and traffic pattern. We then evaluate the performance of QASR and the well-known standard routing protocols including Ad-hoc On-demand Distance Vector (AODV) [2] and DSR based on these benchmark scenarios using OPNET modeler [10] at the 4.9GHz public safety spectrum band. To our best knowledge, this is the first work to address ad-hoc routing in the context of rural public safety communications and evaluate different ad-hoc routing protocols based on real-life scenarios via extensive OPNET-based simulations.

The rest of the paper is organized as follows. Section II reviews related work. Section III provides a detailed description of QASR. Two rural public safety scenarios, the river search and the dam breach, and simulation setting parameters are described in Section IV. Section V contains the results of OPNET-based simulations and performance analysis comparing QASR with DSR and AODV. The paper is concluded in Section VI.

II. Related Work

Routing is a fundamental problem in MANETs. Currently, in the IETF MANET group, four routing protocols have been finally standardized, including AODV [2], DSR [4], Optimized Link State Routing (OLSR) [8] and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [12]. Two other routing protocols, Dynamic MANET On-demand (DYMO) Routing [5] and OLSRv2 [9], are still Internet drafts. Standard ad-hoc routing protocols can be divided into two categories: reactive (on-demand) and proactive. On demand routing protocols will flood route discovery messages upon arrival of a connection request. The on-demand routing protocols include AODV, DSR and DYMO. Proactive routing protocols require the nodes to respond to changes in network topology by broadcasting updates throughout the network. OLSR and TBRPF fall into this category.

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Supporting end-to-end QoS in MANETs is very challenging. The AODV has been extended to support QoS in MANETs [3]. A resource reservation based routing and signaling protocol, Ad-hoc QoS on-demand routing (AQOR) has been introduced in [15]. In [17], Yang and Kravets presented a novel joint admission control and rate policing protocol, Multi-Priority Admission and Rate Control (MPARC) for MANETs with multi-priority traffic. They also proposed a new protocol, Distributed Delay Allocation (DAA) in [16], which provides average delay guarantees for real-time multimedia applications in MANETs. The available bandwidth and delay estimation algorithms introduced in [16], [17] are used in our routing protocol to enable QoS support.

III. QoS Enhancement

In this section, we discuss a QoS enhancement to DSR. The objective is to find a source to destination path which can satisfy the end-to-end bandwidth and delay requirements given by any incoming connection request. In addition, admitting a new connection request cannot disrupt any existing flows.

We design our QoS-aware routing protocol, QASR, based on DSR. DSR is selected as the basis for QoS enhancement because according to DSR, the whole routing path is included in each data/control packet, which is necessary for end-to-end available bandwidth and delay estimations. In QASR, an available bandwidth estimation algorithm in [17] and a delay estimation algorithm in [16] are incorporated with the route discovery process of DSR. After the route discovery, if a set of feasible paths can be found, the destination node will select the path with the minimum cost based on a routing metric (which will be introduced later), and send an Route REPlay (RREP) message back to the source node along the discovered path in the reverse direction. However, if no feasible path is available, the connection request will be rejected.

We focus on the Enhanced Distributed Coordination Function (EDCF) specified by IEEE $802.11e$ [1], which extends original Distributed Coordination Function (DCF) defined in the IEEE 802.11 to support service differentiation and QoS. In EDCF, traffic is divided into several classes and different classes are assigned different transmission parameters such as contention window size. Similarly, traffic is divided to 6 classes according to the SoR for public safety communications [11], which can be naturally supported by EDCF.

The estimation algorithms presented in [16], [17] are employed in QASR since they are considered as the best-so-far solutions for available bandwidth and delay estimation in a multihop wireless network with multi-priority traffic. These algorithms are essentially 2.5 layer algorithms which provide the QoS estimation information to the routing protocol according to the MAC protocol behavior and current traffic load. Bandwidth and delay estimations are very challenging in a 802.11-based multihop wireless network. Due to the impact of interference, in a particular node v, any transmissions in its interference neighborhood may consume its available bandwidth; and moreover, for a particular packet, node v may need to backoff and re-transmit it multiple times, which leads to a long delay. In [17], a novel bandwidth allocation model was introduced to capture bandwidth sharing between competing flows in all possible network states. Based on the model, an algorithm was designed to estimate the available bandwidth for a node based on the its state (including traffic load, traffic priority, contention window size and so on) and the states of all nodes in its interference neighborhood. Similarly, a mathematical model and a closed-form equation were presented to accurately estimate the packet delay for a node [16] according to the node state information in its neighborhood. Due to the space limitation, we omit the details of these two algorithm.

As mentioned above, a node's available bandwidth and the packet delay are related to its neighboring nodes in the interference range in a wireless environment. Therefore, in order to precisely predict the available bandwidth and delay, each node needs to collect the state information from all the nodes in its interference neighborhood periodically. The broadcasting period was set to 5s in the simulation. Since the interference range is usually 2 or 3 times the transmission range, it is not sufficient for a node to only broadcast its state information to its direct neighbors. In QASR, if each node has a GPS device (this is a reasonable assumption for public safety related mobile nodes), each broadcasting message will include the location of the node which generates this message. Once a node receives a broadcasting message, it will check its distance from the node generating the message. If it is no more than the interference range, it will re-broadcast the message. Otherwise, the message will be dropped. However, if the location information is not available, such messages will simply be broadcast within a 2 or 3 hop neighborhood. The control overhead can be reduced by using a randomized optimization scheme to select a subset of nodes in the interference neighborhood to re-broadcast the message. In this scheme, whenever a node in the interference neighborhood receives the message, it generates a random number and compares it with a given threshold. If the random number is larger than the threshold, the node will re-broadcast the message in the current period. Otherwise, it will stay silent.

A new routing metric is defined for route selection, which is the weighted sum of estimated available bandwidth, estimated delay and node speed. The cost of a node v is given by equation (1).

$$cost(v) = \alpha \times \frac{B - A_v}{B} + \beta \times \frac{D_v}{D} + \gamma \times \frac{S_v}{S} \quad (1)$$

In the above equation, A_v is the estimated available bandwidth and B is the channel capacity. Estimated delay D_v is normalized by a delay tolerance D and the average speed S_v is normalized by a maximum speed S. The values of B, D, S may vary in different scenarios and different network environments. They were set to 750kbps, 50ms and 27mph respectively in our simulation. These parameters are then mixed by the coefficients α, β, and γ, where $\alpha + \beta + \gamma = 1$. α, β, and γ are tunable parameters which are used to scale the relative weight of each term in the metric. In the simulation, $\alpha + \beta + \gamma = \frac{1}{3}$. Essentially, the cost of path is given by the sum of the costs of all nodes in the path. According to this metric, the mobile nodes with relatively large available bandwidth, small packet delay and low mobility are more likely to be selected as relay.

Similar to DSR, QASR initiates a route discovery process by flooding Route REQuest (RREQ) messages when a node has data to send. Moreover, it will start a timer. When the timer fires, the connection request will be rejected if no RREP message is received during this period. Otherwise, the source node will start data transmission along the route included in the received RREP message. When an intermediate node v receives a RREQ message, it will discard this message if it finds out its own available bandwidth is smaller than the bandwidth requirement or the cumulative delay of the partial path from source to node v is already larger than the delay requirement. However, if the requirements are not violated and the cost of the partial path included in the message is smaller than the current minimum cost stored in v (which is initialized to ∞ and is updated every time there is an improvement), the RREQ message will be re-broadcast. Note that each RREQ message includes the QoS requirement information and the delay of the corresponding partial path. The delay value in an RREQ message is updated every time it traverses an intermediate node. In addition, after the first RREQ message arrives at the destination, it will open an acceptance window, a time duration in which RREQ messages generated for that connection request will be collected. At the expiration of the acceptance window, the destination node will then select the best path from the set of feasible paths and reply with an RREP message.

IV. Rural Public Safety Scenarios

In this section, we describe the two public safety scenarios used to test the performance of QASR in comparison with DSR and AODV in rural environments with irregular terrains. The scenarios were developed according to actual rural communication problems obtained through discussions with public safety officers, and the actual terrain and roadway information given by USGS survey [13] and Google Map [6] respectively.

OPNET Modeler 12.1 [10] was used to model the protocol behavior and construct scenario configurations. The scenarios include trajectories for both vehicle and pedestrian mobile nodes, location information and communication traffic associated with voice, video and data applications. A brief introduction for the two scenarios, the river search and dam breach, are given as follows:

$1)$ The river search scenario represents a coordinated search along the Wind River (30km southeast of Dubois, Wyoming) for a missing person. The river valley is 1.6km across at its widest in the context of our simulation. Nodes in the network represent both rescue workers on foot walking along the river bank in the valley, as well as vehicles that maneuver along the adjacent roadways to overlook the search effort by visually monitoring the health and safety of the rescue workers. The terrain within the river valley causes blockage and intermittent connectivity for communications among nodes in the valley. The over-watch vehicle nodes are often positioned as relays to enable additional routes between rescue worker nodes. In this scenario, The traffic is generated by 16 nodes with 28 flows between various members of the search party.

$2)$ The dam breach scenario represents a coordinated effort to warn residents of Thermopolis WY, about 30km downstream of a reservoir on the Wind River, of an imminent flood due to the catastrophic breach of the dam. In this case, mobile nodes systematically drive along the city streets, communicating with each other and with a few fixed nodes located at the Sheriff's office and disaster control center in the police station. The model includes the grid of streets to define the node trajectories. Different from the river search scenario, the nodes in the network are connected in most of time in this scenario. In addition, the traffic is generated by 23 nodes with 22 flows between police vehicles.

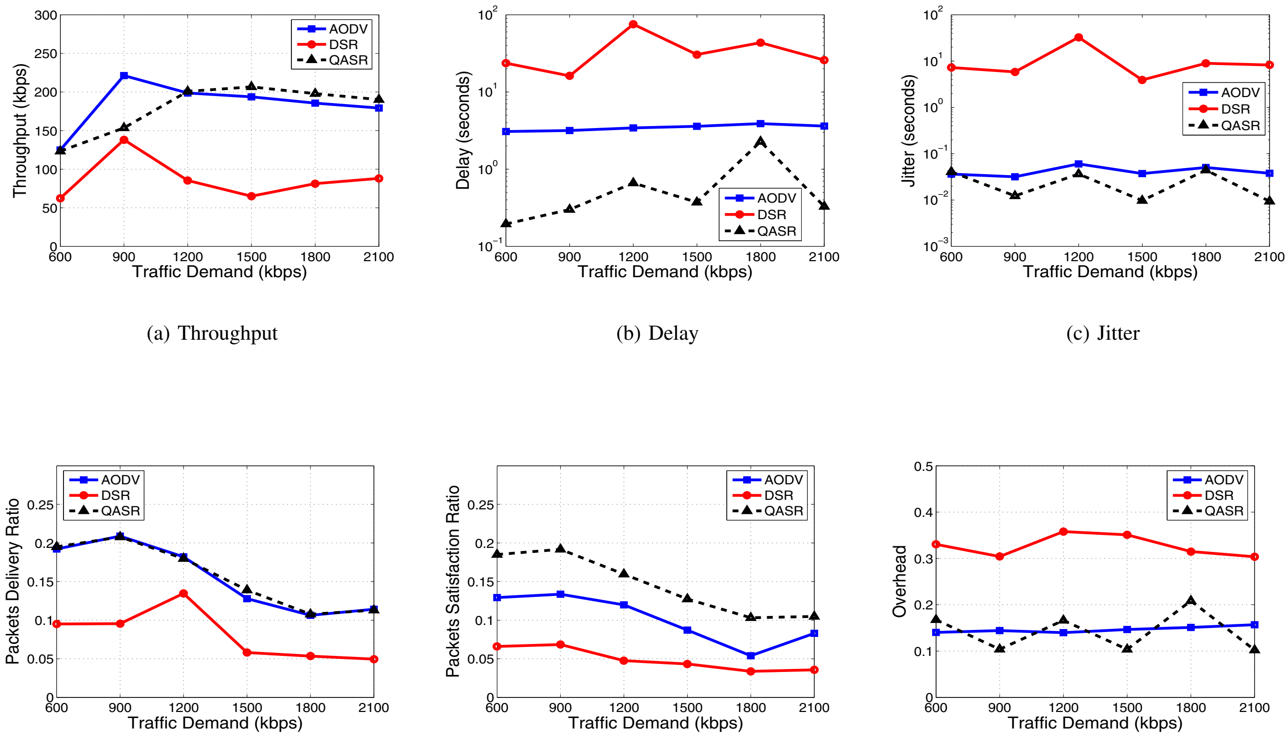
In both scenarios, the networks were operated at the 4.9GHz public safety spectrum band and the transmission power of each node was set to 5mW. The EDCF defined in $802.11e$ [1] was used as the MAC protocol. In addition, for traffic generation, a pair of source and destination nodes were also specified by the scenarios for each flow. The communication traffic included video flows, voice flows and data flows. The video flows are MS media player based video streams with a mean data rate of 320kbps [7], the voice flow is $G.726$-based Voice-over-IP (VoIP) streams with a constant data rate of 24kbps [14] and the data flows have a mean data rate of 8kbps. There are three priority levels, high, medium and low. The priority of each flow is randomly selected. For the high priority flow, both the delay and jitter tolerances were set to 50ms [11].

V. Simulation Results

In the simulation, throughput, delay, jitter, packet delivery ratio, QoS satisfaction ratio and overhead are used as metrics for performance evaluation based on the two scenarios described in the last section. The throughput is the sum of sizes of all data packets successfully delivered from each flow's source node to its destination node. The delay is the average end-to-end delay of the data packets that are successfully delivered. The jitter is the average difference of the end-to-end delay of successive packets that are successfully delivered in a particular flow. The packet delivery ratio is the ratio between the number of data packets that are successfully delivered and the number of data packets generated in the application layer. The QoS satisfaction ratio is equal to the number of data packets that arrived within the delay and jitter tolerances over the total number of data packets successfully delivered. The overhead is the ratio between the sizes of control packets transmitted for routing protocol specific operations, such as route discovery, route maintenance and information exchange, and the sizes of all the control and data packets.

The simulation results corresponding to the river search and the dam breach scenarios are presented in Fig. 1 and Fig. 2 respectively. We make the following observations.

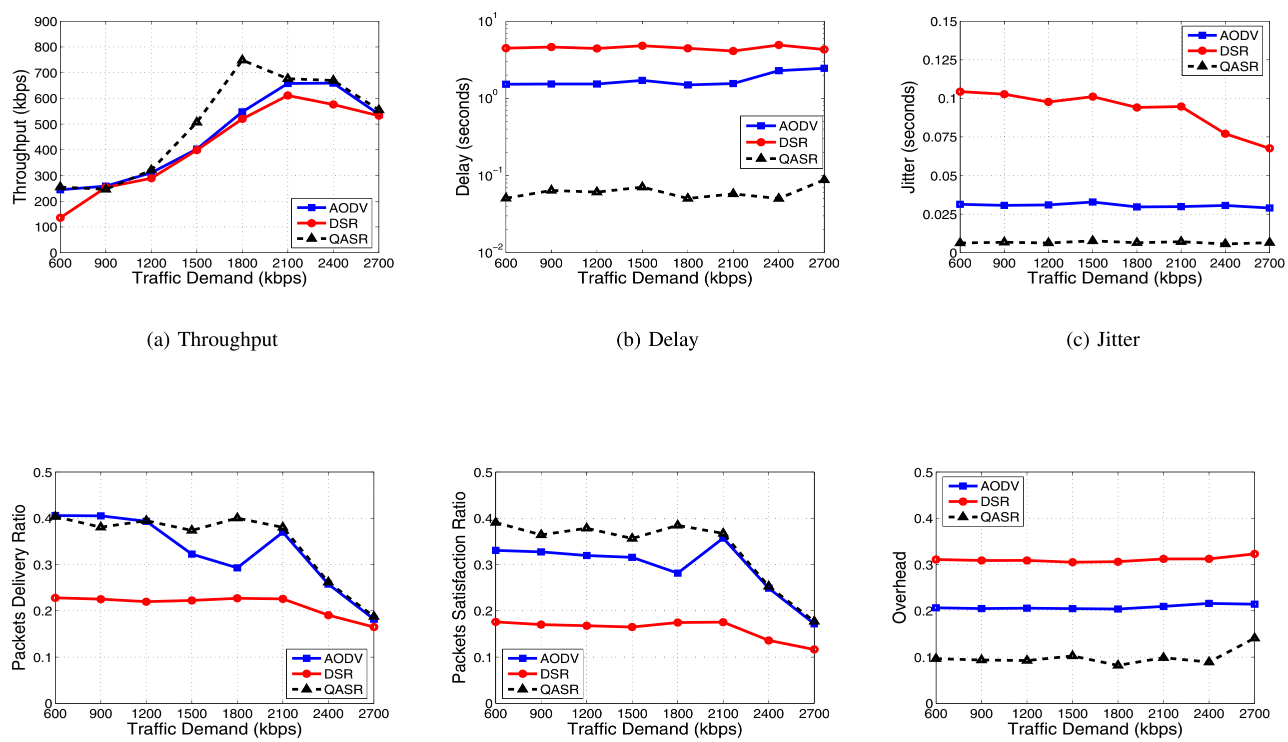
$1)$ In both scenarios, QASR performs significantly better than DSR and AODV in terms of all the metrics. The standard routing protocols always choose the shortest paths for routing without considering the bandwidth availability, traffic load status and mobility. Therefore, congestion is more likely to occur at the intermediate nodes and more retransmissions are needed for successful delivery of a packet, which will lead to poorer throughput, longer delay and larger overhead.



(a) Throughput (b) Delay (c) Jitter

(d) Packet delivery ratio (e) QoS satisfaction ratio (f) Overhead

Fig. 1. The river search scenario



(a) Throughput (b) Delay (c) Jitter

(d) Packet delivery ratio (e) QoS satisfaction ratio (f) Overhead

Fig. 2. The dam breach scenario

On average, QASR outperforms DSR and AODV by 65.7% and 4.39% in terms of throughput respectively. Moreover, the average delay given by DSR is 75 times larger than that given by QASR and the average jitter given by DSR is 233 times larger than that given by QASR. Note that the end-to-end delay and jitter are presented using a logarithm scale in the figures due to the large differences. The packet delivery ratios given by all the protocols are consistent with the end-to-end throughput. In terms of QoS satisfaction ratio, the QASR offers 145.4% improvement over DSR and 27.8% improvement over AODV on average because of its capability of estimating available bandwidth and delay. Note that the estimation algorithms can certainly improve QoS but cannot provide a 100% guarantee (achieve a QoS satisfaction ratio of 100%) since the estimation may not be accurate and more importantly, the estimation is made at the route discovery but the available bandwidth and delay may change during the actual data transmission in a highly dynamic MANET. In addition, compared to DSR and AODV, QASR reduces the average overhead from 31.8% and 18.2% to 11.8% respectively,

2) The routing protocols perform quite differently in different scenarios. In the river search scenario, they all perform very poorly due to intermittent connectivity among mobile nodes. In a poorly connected network, link breakage happens frequently. In this case, a large number of Route ERRor (RERR) messages will be generated to notify of failures, new RREQ and RREP messages need to be generated for rediscovering the routes, and more data packets need to be retransmitted multiple times to guarantee successful delivery. From 1, we can see the average end-to-end delay given by DSR is 35.86s, the average packet delivery ratio is only 8.1%. QASR and AODV perform better than DSR but still suffer from poor throughput, long delay and large overhead. In the dam breach scenario where the network is connected most of time, the network performance is significantly improved no matter which protocol is used for routing. For example, with DSR, we can see from Fig. 2 that the average end-to-end delay is reduced to 4.52s, the average packet delivery ratio is increased to 21.3%.

3) The simulation results for the two scenarios indicate several marked differences that can be attributed to the underlying connectivity characteristics and their effects on the behavior of the different protocols. In the river search scenario, the throughput does not tend to increase with traffic demand as might be expected, as the intermittent connectivity limits the overall packet delivery. In the dam breach scenario, where the network is more fully connected, the throughput increases with the traffic demand as expected, and all three protocols eventually reach a saturation level.

4) Simulation runs were also conducted to study the protocol behaviors on other spectrum bands including the ISM band at 2.4GHz (since most of previous research on ad-hoc routing focuses on this spectrum band) and the recently allocated public safety communication band at 700MHz. The selection of a lower operating frequency can provide either longer transmission range or increased link margin, which can translate into more alternative paths between a pair of source and destination nodes and a better link capacity with the use of adaptive modulation techniques. Moreover, when the terrain obstructs the Line-Of-Sight (LOS) between nodes, the use of lower frequencies is also favored, as frequency dependent diffraction effects will enable NLOS communications. However, a larger transmission range will cause stronger interference and more collisions, which eventually will counteract the gain obtained by transmitting at a lower frequency. Therefore, we find out that the performance (throughput, delay, etc.) given by the routing protocols at the 700MHz and 2.4GHz bands are roughly the same as that at the 4.9GHz band. Our QASR protocol still consistently outperforms AODV and DSR in terms of all the metrics. Due to the space limitation, we are not able to present the related results.

VI. Conclusions

In this paper, by extending the functionalities of DSR, we designed a new ad-hoc routing protocol, QASR, to meet the QoS requirements of public safety communications. Extensive simulations were then conducted to evaluate the performance QASR, DSR and AODV based on real rural public safety scenarios including the river search scenario and dam breach scenario. Simulation results showed that QASR performs significantly better than DSR and AODV in terms of various performance metrics including throughput, delay, jitter, packet delivery ratio, QoS satisfaction ratio and overhead.

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