QoS Control in MANETs – A State-of-the-Art Perspective

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Abstract. This paper examines the state-of-the-art of Quality of Service (QoS) control for wireless Mobile Ad-hoc Networks (MANETs) based on an exhaustive literature search comprising over 70 journal papers and conference proceedings and standardization development, per the Institute of Electrical and Electronics Engineers and the Internet Engineering Task Force. Site visits to selected United States Government facilities augmented this literature search by addressing "real-world" models for a comprehensive series of follow-on simulations and analyses. This paper defines prominent QoS metrics, such as throughput, delay, packet delivery rate and jitter and then proposes that design parameters, such as data rate, packet size, transmitted power, etc., influence QoS in a way to formulate a Multi-Objective Function (from the QoS metrics) subject to constraints (from design factors) that will solve an optimization problem using evolutionary computation techniques. This research will foster improvements for data link layer and network layer protocols optimizing QoS control.

1. Introduction

This paper examines the prospects to control (define, measure, and evaluate) Quality of Service (QoS) in Wireless Mobile Ad-hoc Networks (MANETs) from a state-of-the-art perspective. It will only pertain to these wireless MANETs, herein referred to as stand-alone MANETs, and will exclude cellular radio, fixed Wireless Local Area Networks (WLANs), and Wireless Sensor Networks (WSNs), except where these MANETs may connect to a wire-based Internet.

MANETs are unique in communications in that no base infrastructure is required for connectivity. Topologies are consequently dynamic in that mobile nodes can arrive and depart the network in an arbitrary fashion. The nodes must behave as transmitters, receivers, and routers (Layer 2 for nodes on the same subnet and Layer 3 for nodes on different subnets). In typical situations, mobile communications require multiple hops (forwarding) from the source to the destination using an appropriate routing algorithm. MANETs are suitable for a variety of applications, among them first responders (emergency relief efforts), military (battlefield conditions), and other applications which all can also benefit from this research.

This paper and its follow-on research will denote these MANETs, consistent with the Institute of Electronic and Electrical Engineers (IEEE) 802.11 standard, which has received recent and considerable interest among academic, industrial, and government sectors. Designing and implementing these MANETs can be quite demanding and complex due to the nature of wireless communications. Adverse effects, such as channel capacity variations, sparse bandwidth, routing failures (due to node mobility), and erratic power control can wreak havoc with these designs and implementations. IEEE 802.11-2007 (IEEE) combined the base standard with its eight amendments, including the one that defined QoS enhancements for WLAN applications employing modifications to the Media Access Control (MAC) sublayer, into one document. In addition, numerous research efforts have spawned from the standardization work of the Internet Engineering Task Force (IETF) MANET Working Group (WG) who have established IP routing standards (IETF), such as Adhoc On-demand Distance Vector (AODV) per (Perkins et al. 2003), Dynamic Source Routing (DSR) per (Johnson et al. 2007), and Optimized Link State Routing (OLSR), version 1 per (Clausen and Jacquet 2003), et al.

Based on an exhaustive research and review of over 70 papers from recent technical journal publications and conference proceedings, this paper reveals some interesting observations. First, a preponderance of these papers (70%) related primarily or exclusively to QoS routing. The authors proposed both improvements to already existing routing algorithms (Badis and Al Alga 2004), (Brahma et al. 2005), (Chen and Heinzelman 2005), (Haghighat and Khoshrodi 2007), (Helweh-Hannan, 2006), (Perkins et al. 2004), and (Zhang and Gulliver 2005) as well as the development of new protocols (Kone and Nandi 2006), (Medidi and Vik 2004), and (Ziane and Mellouk 2007). Second, a number of papers were devoted to cross-layer approaches (Abdullah and Parish 2007), (Canales et al. 2006), (Crawley et al. 1998), and (deRenesse et al. 2007) which encompass multiple protocol layers relying on information exchanges, e.g., from the data link (for the MAC sublayer) and networking (IP routing) layers. Third, based on this review, various categories for MANETs, in addition to routing and cross-layer approaches included architectural models (Chakrabarti and Mishra 2001), (Mayhew 2007), (Sarma and Nandi), (Shenoy et al. 2005), and (Stine and de Vecina 2004) and security (Fung et al. 2005), (Heimo et al. 2005), and (Lu and Pooch 2005). Interestingly, some researchers (Kurkowski et al. 2007), (Perkins et al. 2002), and (Vadde and Syrotiuk 2004) applied a similar approach by proposing that design factors can influence QoS. However, none of these works solved the multivariate problem as proposed herein. In addition, some suggested the need to solve a Non-deterministic Polynomial-Time (NP)-complete or NP-hard problem (Kone and Nandi 2006), (Zhang and Gulliver 2005), and (Ziane and Mellouk 2007) but none adequately addressed its derivations or the details of such a problem solution.

This paper proposes a methodology to solve an NP-complete or NP-hard problem for optimizing QoS for MANETs. Follow-on efforts will documents these results and quantify just how much QoS can be controlled in real-world scenarios. This paper attempts to formulate functions, describing these QoS metrics, subject to appropriate constraints, i.e., design variables, and subsequently solve a complex optimization problem using evolutionary computation techniques. The methodology proposed herein is a value-added component to the systems engineering process, specifically systems modeling, whereby a complex problem, such as controlling QoS in MANETs, can be resolved using a combination of machine intelligence and the human cognitive properties of first responders, among others.

The remainder of this paper is organized in the following manner: Section 2 defines QoS based on established standards and appropriate QoS metrics for MANETs, namely throughput, delay, dropped packet rate, and jitter, will be measured in follow-on research, using event-driven network simulations and associated analysis software empirically highlighting the results, primarily based on ‗real-world' models gleaned from United States Government sources. Accordingly, this section also denotes relevant MANET QoS standards in context of current MANET QoS research. Section 2 also documents those vexing problems affecting MANETs when defining, measuring, and evaluating QoS through an exhaustive review of several dozens of journal papers and relevant conference proceedings involving researchers working, across the world, on various MANET problems. Section 3 cites the research premise that design variables directly influence QoS metrics. Section 4 will offer cogent conclusions and highlight how this particular research will benefit the design and implementation of QoS in MANETs. Lastly, Section 5 chronicles the future research depicting ‗real-world' models, evaluate their respective simulation results and then solve an optimization problem by formulating a QoS Multi-Objective Function (MOF) and using evolutionary computation techniques to solve that problem.

2. Background and Related Work

2.1 QoS Defined

QoS has been invoked in communications and network engineering for quite some time. Its definition and inherent characteristics (or metrics) are not universal, so some existing standards were reviewed to determine their suitability for this paper. For instance, the International Telecommunications Union–Telecommunications (ITU-T) issued Recommendation E.800 (ITU-T) which was recently updated (September 2008) and was in a pre-published format {at http://www.itu.int/rec/T-REC-E.800-200809-P/en} but not yet freely available as of March 2009. E.800 described QoS from a telecommunications and network management perspective. Explicit QoS metrics were not addressed but some terminology dealing with serveability contained references to service and connection access and delay can be associated with MANETs. Additional sources (Crawley et al. 1998) proposed a QoS-based routing framework but dealt with an Internet (wire-based) perspective and did not account for the uniqueness of node mobility in MANETs. Lacking a *bona fide* standard explicitly defining QoS, other sources were found and these relevant QoS metrics, for the purposes of this paper, were chronicled below.

2.2 QoS Performance Metrics

Relevant QoS performance metrics, excerpted from (Subbarao 1998) and the *tracegraph* help.txt file, included throughput of received packets, End-to-End (E2E) delay, and packet delivery rate and received packet jitter (or delay variance). These metrics were considered to be more widespread, useful, and consistent for MANET performance than other metrics. Regardless of the responses (metrics) employed, the approach cited herein would remain the same.

Throughput of received packets is measured by counting the number of successfully received packets at a destination over the elapsed time of the measurement. In this case, as well as with the other QoS metrics, the elapsed time was equated to the duration of simulation time. The received packet throughput (dimension in packets per second) is computed by measuring the number of ssuccessfully received packets divided by the elapsed simulation time.

To measure **E2E delay**, a packet must be time-stamped when it is generated. The packet is then sent and received at the destination. The E2E delay (dimension of seconds) is computed by measuring the simulation time at packet reception less the simulation time at packet generation.

Packet delivery rate is similar to received throughput in that successfully received packets are tallied. However, this metric also takes into account dropped and lost packets as well. The packet delivery rate (dimension in decimal or percentage) is computed by measuring the number of successfully received packets divided by the number of total transmitted packets.

Received packet jitter is the delay variation of a current event (or state) and that of the previous event. Received packet jitter (dimension in seconds) is computed by measuring the difference between the receive time of the current event and the receive time of the previous event divided by the difference between the current sequence number and the previous sequence number.

2.3 MANET Standardization Developments

MANET standards have evolved since the late-1990s. Standards bodies, such as IEEE and IETF have produced useful standards for the MAC sublayer and network (IP routing) layer, respectively. IEEE 802.11–2007 combined the base standard and eight amendments, including QoS enhancements, while the IETF has approved a variety of Requests for Comment (RFCs) related to IP routing algorithms and has issued Internet Drafts (not intended for standardization purposes). Recent developments regarding the data link, network, and transport layer communications protocols are described below

IEEE 802.11 MAC Sublayer Enhancements. To accommodate QoS-based traffic in a manner comparable to other IEEE 802 LANs, the IEEE 802.11 QoS facility required the IEEE 802.11 MAC sublayer to incorporate functionalities that differed from traditional ones. This accommodation applied to both LAN stations (mobile nodes for MANETs) and access points. Two basic mechanisms were envisioned for QoS support delivery–Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA). An improvement to IEEE 802.11e MAC EDCA by (Rhomdhani and Bonnet 2005) who proposed a Cross-Layer AODV-EDCA (CLAE) based on AODV. CLAE determined the _best‘ path for applications in term of bandwidth, delay, and route stability. The estimated average transmission delay information was inserted into Router Requests (RREQs) and corresponding Router Replies (RREPs). In addition, (Nasir and Albalt 2008) proposed an improvement to the IEEE 802.11 binary exponential backoff algorithm, labeled History-based Adaptive Backoff (HBAB), and was heralded to better manage the contention window when collisions occurred and more accurately predict the network status. Second, (Brahma et al. 2005) proposed QoS support using the MAC buffer management in lieu of access priority differential with load balancing providing service differentiation. To provide load balancing, a new IEEE 802.11 MAC message was designed containing HELP (if node is congested), OK (if node has available bandwidth), and NOTIFY (congested node chooses _best‘ node).

IETF RFC IP Routing Enhancements. The IETF MANET Working Group, under the auspices of the Internet Advisory Board, standardizes IP routing protocols through the RFC process intended to support MANETs. Pertinent improvements for these protocols (AODV, DSR, and OLSR) are denoted below.

AODV, per RFC 3561 (Perkins et al. 2003), was the most often cited routing protocol for MANETs referenced in the reviewed papers. First, (Chen and Heinzelman 2005) proposed a QoS-aware routing protocol using the RREQ-RREP mechanisms (for route discovery), but with modified header information to add a model-flag indicating whether the source node used an admission control or adaptive feedback scheme in the RREQ and a minimum bandwidth calculation from the destination back to the source in the RREP. This method increased packet delivery rates, reducing delay and energy dissipation, while not impacting end-to-end throughput. Second, (Zhang and Gulliver 2005) proposed a QoS-based AODV (QS-AODV) extension adding to the RREQ, RREP, and Router Error (RERR) packets that included application bandwidth requirements and session IDs to identify each established QoS flow. The route entry created used the session ID; in lieu of the source node broadcast RREQ, it used the destination node IP address. If the destination node did not have sufficient bandwidth to accommodate the QoS flow, then the packet was discarded improving the existing standard by finding a route based on multiple metrics, not just bandwidth. Third, (Haghighat and Khoshrodi 2007) introduced an approach, labeled Stable QoS by AODV (StQ-AODV), that included a Neighbor number (Nr) which is a value representing the probability that a node in that neighborhood can be selected for a given route and link stability (LS) in the AODV protocol. If the Nr of the selected node was greater or equal to one, then the LS is checked. If both conditions were true, then the RREQ message was sent, a new entry recorded, and bandwidth resources reserved for that route.

Although referenced many fewer times, DSR, per RFC 4728 (Johnson et al. 2007), was cited for improvements or enhancements. First, (Perkins et al. 2004) introduced QoS-sensitive Multipath Routing with Packet level Redundancy (QMR/PR) which addressed problems caused by mobility-induced route failures by combining packet-interleaving using multipath routing and packet-level forward error correction and was advertised to significantly reduce both random and correlated packet losses. QMR/PR compared very favorably to unicast DSR by reducing packet loss by 42–84% depending on the networking environment (50 mobile nodes, with limited and high node mobility). Second, (Hanzo and Tafazolli 2006) proposed a QoS routing with admission control solution, based on DSR, labeled as QoS-DSR. The DSR RREQ packet was modified to include the requesting session‘s throughput requirement. Then, each intermediate node tested whether that its channel usage was greater than that of the source node before forwarding the RREQ. Simulated results showed QoS-DSR a marked improvement, compared to DSR, regarding session completion rate, packet loss rate and average packet delay, even in highly mobile scenarios. Third, (Laboid and Quidelleur 2002) contributed an extension to DSR, denoted as QoS Adaptive Source Routing (QoS-ASR), that applied flow aggregation, provided stable paths based on link availability, and reduced complexity while improving performance.

OLSR, per RFC 5626 (Clausen and Jacquet 2003), was not cited very often in the papers reviewed, possibly due to the comparative newness of the protocol in MANET designs and implementations. Nonetheless, research efforts showcased the interest in improving and enhancing OLSR. For instance, (Badis et al. 2004) proposed the QoS routing over OLSR (QOLSR) protocol introducing metrics such as bandwidth and delay that were considered more appropriate than hop distance. As an enhancement of QOLSR, QOLSR supported multiple-metric routing criteria, per (Badis and Al Alga 2004). A theoretical analysis OLSR promised simulated results validating their research.

New Routing Protocols. For new protocols, not based specifically on an existing standard, (Ziane and Mellouk 2007) proposed a delay-oriented routing protocol labeled Adaptive Mean Delay Routing (AMDR), based on a reinforcement learning paradigm without node synchronization and compared its performance with AODV and OLSR. Their simulated results did show that for a static model, delay for AMDR was initially higher but then it reduced to the smallest amount when compared to AODV and OLSR. For packet loss, OLSR exhibited the best performance, followed by AMDR and AODV. For the mobility model (with different loads), AMDR performed the _best' for delay by adapting to network loading changes. Second, (Kone and Nandi 2006) proposed an adaptive distributed routing protocol aptly named Adaptive QoS Routing (AQR) providing a QoS-aware path from a given source-destination pair. This protocol took in account multiple QoS constraints and incorporated admission control and bandwidth reservation mechanism. A source node broadcasted its RREQ packets to all of its 1-hop neighbors. These packets contain the sequence number, source and destination identifications, and QoS parameters, such as minimum bandwidth and maximum delay. After receipt of the RREQ, admission control ensured the requested minimum bandwidth and maximum delay requirements were satisfied. Third, (Medidi and Vik 2004) proposed a QoS-aware source initiated ad-hoc routing protocol (QuaSAR) that added a QoS header, from the source to an ordinary RREQ packet which is now labeled as a QoS RREQ (QRREQ), containing information about battery power, signal strength, bandwidth, and latency during route discovery, selection, and maintenance. Correspondingly, the destination automatically sent a QoS RREP (QRREP) to the first threshold QRREQ that it received. QuaSAR compared very favorably to DSR for both fine (8 nodes) and coarse (50 nodes) grain models.

Transport Protocol Enhancements. Only one reviewed paper related its proposed improvement to the transport protocol (Transport Control Protocol (TCP) per RFC 791 (Information Science Institute, 1981). Here, (Mbarushimana and Shahrabi 2008) proposed a means to optimize TCP‘s slow-start and contention-window mechanisms by limiting the number of contention-induced retransmissions and referred to this enhancement as Resource-Efficient TCP (RE-TCP). This enhancement modified the TCP retransmission timer by compensating for those additional delays without pre-empting the delay sensitive traffic. When the medium was busy with high priority traffic, the MAC layer notified TCP, which in turn, froze its retransmission timer. The countdown resumed when TCP was notified by the MAC layer that the medium was idle again. Their results indicated RE-TCP outperformed TCP for end-end delay, ‗goodput‘, and bandwidth utilization, especially when accounting for delay sensitive (voice) traffic.

2.3 Recent QoS MANET Standard Developments

The IETF RFCs related to MANETs were cited in Section 2. The IETF has also issued Internet Drafts which are not standards, per se, but are circulated for six-month increments and are either updated, replaced or made obsolete. A number of Internet Drafts were issued by the IETF MANET WG in 2008 but only one was retained through mid-2009, cited below. Note that none of the papers reviewed mentioned any of these most recent standardization efforts. However, it is anticipated as these drafts evolve into RFCs, more interest and efforts will expended to implement these routing algorithms or enhance them. Dynamic MANET On-Demand (DYMO) is an Internet Draft, last updated on 5 December 2008 and is in its 16th iteration (Chakeres and Perkins 2008). DYMO enables reactive, multihop unicast routing among participating DYMO routers and relies on route discovery and route maintenance.

3. Discussion and Analysis

3.1 Research Premise

The premise denoting that design factors influence QoS performance (in a maximization or minimization sense) through a series of simulations and analyze that data to denote the most significant factors with those QoS metrics has been accomplished before, per (Kurkowski et al. 2007), (Perkins et al. 2002), and (Vadde and Syrotiuk 2004). However, this research extends these prior works by solving an optimization (multivariate) problem using evolutionary computation (to be documented in a future paper). This method of solution will result because it will be proven that this problem is NP-hard or NP-complete.

3.2 Design Variables

According to (Montgomery 2005) there are a number of guidelines that must be followed when planning, conducting, and evaluating experiments. First, a problem statement is required; here, the premise is that QoS in MANETs can be improved to achieve better and more reliable performance for customers. Second, the outputs are selected, i.e., the four QoS metrics (or responses). Third, the choices of factors, each with the number of levels, and corresponding experimentation are made. Fourth, the experiments (in this case, simulations) are conducted. Fifth, statistical analysis is applied to the derived data using graphical methods and/or empirical models. Sixth, conclusions are made that can include confirmation testing, e.g., follow-up runs (experiments).

Because network simulator (*ns-2*) will be the method of choice to validate which design factors are more influential than others with respect to QoS performance, the options defined in *ns-2* will be used. Herein these design factors are categorized into four different types. First, held-constant factors have some effect but are not of sufficient interest or whose variability can be ignored, respectively. Nuisance factors, to include controllable and uncontrollable (or noise), as well as those blocked, have large effects and must be accounted for in the experiment. Furthermore, uncontrollable factors can be measured and possibly controlled, at least in the experiment. All of the considered factors are depicted in a cause-effect (or fishbone) diagram, as shown in Figure 1.

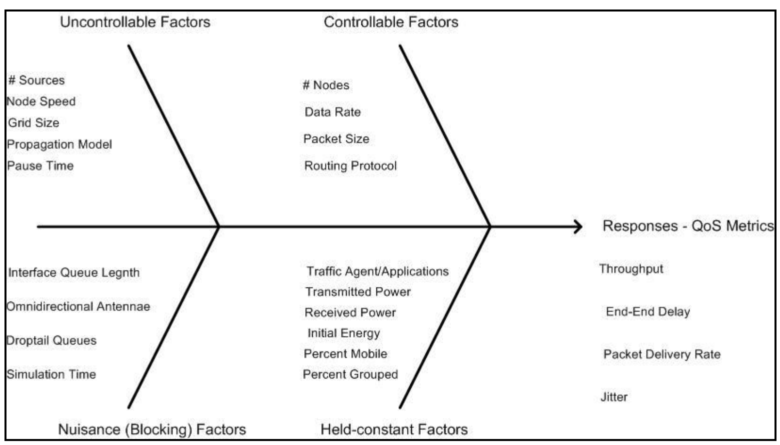

Figure 1. Cause-Effect Diagram (QoS Control Experiment)

After reviewing possible data analysis methods, three methods were considered with the most appropriate method chosen. First, a 2_{IV}^{9-4} fractional factorial (a 1/32 fraction of 9 factors in 32 runs), termed as Resolution IV, was considered feasible because only 32 non-replicated tests (simulations) would be required vice 512 (2^9) for a full factorial experiment. As necessary, a fold-over or alternate run could be applied, for verification purposes, to confirm if the dominant factors revealed in the first set of runs were indeed correct. A design matrix, shown in Table 1, was developed denoting the first five factors (A-E) with either a HIGH (+) or LOW (-) level indicated for each run (for all 32 runs) and the remainder of the factors (F-J, not including the defining relation ‗I‘) represented by the product of the signs of four of those five factors, with no set identical. For example, F = BCDE, would be either a HIGH or LOW level depending on the product of the signs (±) of all of those four factors. Responses for the four QoS metrics would need to be analyzed in a holistic fashion to glean the optimal case, if possible.

In the legend in Table 1, all of the design factors, under consideration and allowed to vary within the appropriate ranges, are enumerated. The first value in the range is designated LOW, while the second value is designated HIGH. For the purposes of this research, only two levels in the fractional factorial will be considered.

Table 1: MANET QoS Design Matrix

A - # Nodes (20,50) **B - % Nodes as Sources (25, 50)** **C - Node Speed (2, 20 m/s)** **D - Pause Time (0, 10 s)**
E - Grid Size (1, 2 km^2) **F - Data Rate (384, 2000 kbps)** **G - Packet Size (256, 1024 B)**
H - Routing Protocol (AODV, DSDV) **J - Propagation Model (TRG,w/Ricean fading)**

	Basic Design					**Design Generator**				QoS
Run	A	B	C	D	E	F=BCDE	G=ACDE	H=ABDE	J=ABCE	metric
1	-	-	-	-	-	+	+	+	+	
2	+	-	-	-	-	+	-	-	-	
3	-	+	-	-	-	-	+	-	-	
4	+	+	-	-	-	-	-	+	+	
5	-	-	+	-	-	-	-	+	-	
6	+	-	+	-	-	-	+	-	+	
7	-	+	+	-	-	+	-	-	+	
8	+	+	+	-	-	+	+	+	-	
9	-	-	-	+	-	-	-	-	+	
10	+	-	-	+	-	-	+	+	-	
11	-	+	-	+	-	+	-	+	-	
12	+	+	-	+	-	+	+	-	+	
13	-	-	+	+	-	+	+	-	-	
14	+	-	+	+	-	+	-	+	+	
15	-	+	+	+	-	-	+	+	+	
16	+	+	+	+	-	-	-	-	-	
17	-	-	-	-	+	-	-	-	-	
18	+	-	-	-	+	-	+	+	+	
19	-	+	-	-	+	+	-	+	+	
20	+	+	-	-	+	+	+	-	-	
21	-	-	+	-	+	+	+	-	+	
22	+	-	+	-	+	+	-	+	-	
23	-	+	+	-	+	-	+	+	-	
24	+	+	+	-	+	-	-	-	+	
25	-	-	-	+	+	+	+	+	-	
26	+	-	-	+	+	+	-	-	+	
27	-	+	-	+	+	-	+	-	+	
28	+	+	-	+	+	-	-	+	-	
29	-	-	+	+	+	-	-	+	+	
30	+	-	+	+	+	-	+	-	-	
31	-	+	+	+	+	+	-	-	-	
32	+	+	+	+	+	+	+	+	+	

Another considered method, a multiple response surface design accounts for each of the four QoS metrics and then determines a set of operating conditions that optimizes all of the responses (QoS metrics) and confines them into desired ranges. This method works well for only a relatively few number of factors, since inspecting overlaying contour plots, to determine proper operating conditions, in two-dimensions becomes unwieldy for more than three factors (Montgomery 2005). Clearly, nine factors would result in this situation. A split-plot design with fractional factorials was also considered, whose structure is divided into whole plots, including factors that are hard-to-change, and subplots with factors that are easy-to-change. Statistical analysis (including half-normal plots) would be applied for each the whole plot portion and the subplots, with the assumption that interactions beyond the second level were negligible (Montgomery 2005). Here, the hard-to-change factors are represented by ‗variables A-E', while the easy-to-change variables are represented by ‗variables F-J', not including the ‗defining relation I'.

The first and third methods would employ Analysis of Variation (ANOVA) for each QoS metric, while the second method could use the steepest ascent (for maximization) or descent (for minimization) method. Based on a number of considerations, some cited herein, the fractional factorial method will be employed with the actual simulation results documented in the first follow-on paper. The range of values, denoted in Table 1, for the design factors (A-J) were based on *ns-2* as well as the network specifications of prominent mobile devices, such as Hewlett-Packard's iPAQs and laptops, with IEEE 802.11 (integrated or PC-card) interfaces.

3.3 Systems Modeling (First Responders)

These QoS performance metrics (responses) will be analyzed statistically using design of experiment techniques to determine which design variables are more significant with respect to the QoS performance metrics. The simulations and associated analyses will be denoted in the follow-on paper entitled ―Modeling and Simulation Analyses of QoS in MANETs". These types of relationships will help formulate a MOF with the QoS metrics as functions and the influencing design variables as respective constraints. Then, depending on whether this MOF is NP-complete or NP-hard, this MOF will be solved (for optimum QoS control) using evolutionary computations techniques, such as genetic algorithm. The MOF formulation and solution will be denoted in the third and final paper, entitled ―Optimizing QoS in MANETs using Evolutionary Computation".

The results of these simulations will be recorded as QoS metrics tabulated and graphed using *tracegraph* as the software tool of choice together with *ns-2*. The vast majority of papers invoking simulations preferred *ns-2* to others, such as *Opnet* and *GloMoSim* by a margin of six-to-one. For those that chose *ns-2*, practically all selected 50 nodes as the basis for the simulations and invoked an entity-based Random Way Point (RWP) mobility model for node movement.

For the purposes of this research, a group-based mobility model Reference Position Group Movement (RPGM) introduced by (Hong et al. 1999) is preferable and is specifically suited for emergency relief first-responder efforts. The RPGM model was based, in some part on mobile cellular networks, and was developed to more realistically deal with group movement among MANETs. In the RPGM model, each group has a logical center whose motion defines the group's motion behavior (node speed, location, and direction). Each node is assigned a reference point, represented by a dot on a graph, which follows a group movement dictated by a group motion vector (**GM**). Nodes are usually uniformly distributed within some geographic region but are randomly placed near their respective reference points but can also be located at predefined positions. This scheme allows random motion among the nodes but also allowing for collective group movement. (Hong et al. 1999) In addition, the Overlap Mobility Model is an application within RPGM that describes different groups within the same overall geographic region, while permitting each group its own motion behavior characteristics. This application will be used for purposes of this research with the groups including the Police Department, the Fire (and Rescue) Department, a Medical unit, herein referred to as Emergency Medical Technician (EMT), and a Hazard Materials (HAZMAT) team. A representative 20-node configuration, comprised of these responders, is listed in Table 2. Although not shown here, the 50-node composition would be identical to the 20-node composition, but with more multiples of each group totaling 50 nodes.

Table 2: 20-node First Responder Configuration

Function	# Members per Group	# Groups	# Nodes
Police	2	2	4
Fire	6	1	6
EMT	3	2	6
HAZMAT	4	1	4
Totals			20

Each group will communicate and move within their own ranks and then intercommunicate with the other groups, as required, as they migrate towards the ‗ground-zero‘ destination. Figure 2 depicts a representative 20-node first-responders model on a 1 km^2 grid that will be a basis for a series of simulations. Here, each of the four groups is earmarked with its respective number of nodes and their corresponding reference points randomly placed, as shown as dots. Group motion vectors show the trajectories toward the ‗ground-zero‘ location.

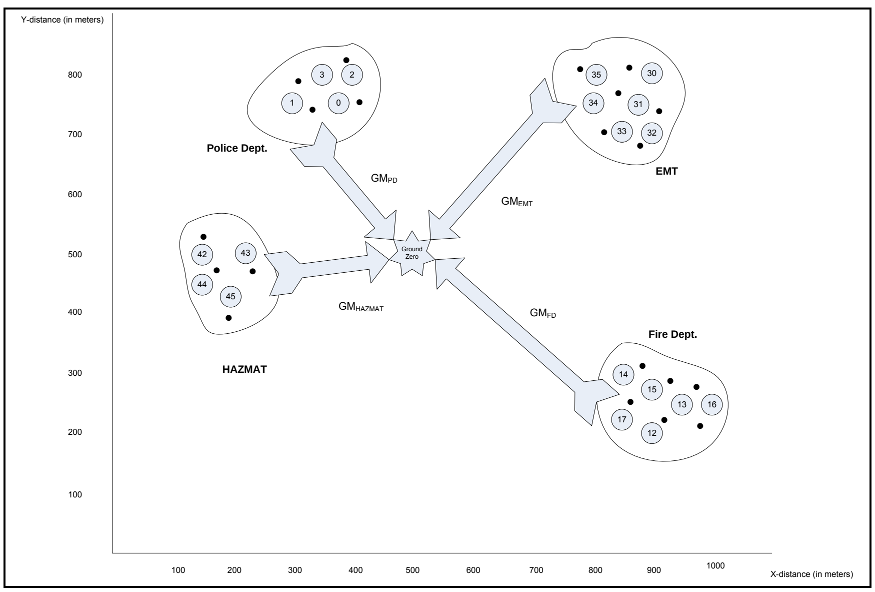

Figure 2. 20-node First-Responders Model

3.3 US Government Site Visit Discussions

Government facilities were visited to glean requirements representing ‗real-world‘ MANETs in the United States Department of Defense (DoD). These facilities included National Institute of Science and Technology (NIST) Advanced Networks Technology Division (ANTD) in Gaithersburg, MD, Naval Research Laboratory (NRL) Information Technology Division (ITD) in Washington D.C., and the Space and Naval Warfare Systems Center (SPAWAR) in Charleston, SC. All three sites were visited in the May 2008 timeframe. Presentations and follow-on discussions dealt with the pertinent points consistent with their designs and implementations. The discussions helped formulate the models to represent ―real-world" scenarios. The main points gleaned from these discussions pertained to the ―breadcrumb" technology testing at NIST for first-responders and the reliance of multicast communications in military applications. During the literature search, a number of papers dealt with multicast traffic in MANETS, including (Cheng et al. 2006), (Hu et al. 2005), Hui et al. 2005), (Narismha et al. 2008), (Umuhoza et al. 2007), and (Yang et al. 2006). These papers were synopsized, as were all reviewed papers, to demonstrate the applicability of this research compared to already published works, but were not chronicled herein.

4. Conclusions and Recommendations

QoS control in MANETs has become quite a hotbed for research in the recent past and will continue to be prominent in all three sectors (government, industry, and academia). There is a vested need to examine the ‗best' possible means to attain optimal QoS performance for MANETs, so as to improve the communications capability of first-responders, among others. Based on an extensive literature search of published works from various technical journals and conference proceedings, comprising over 70 papers, QoS control in MANETs have primarily been dealt with singular QoS metrics rather than multiple ones in a holistic one. This paper proposes a multivariate approach to solve the thorny problem of QoS control in MANETs by suggesting that design variables are constraints in an MOF with the QoS metrics as sub-functions and that this problem is NP-hard or NP-complete and solvable using evolutionary computation techniques.

5. Future Work

5.1 Modeling and Simulation

As mentioned earlier, a series of simulations, using *ns-2.27* or higher, based on different combinations of design variable values, will be run for the data model presented herein. The number of brute-force simulations for a full factorial experiment is 512, as calculated earlier. Clearly, this number of simulations is excessive in terms of time and resources consumed to determine which design factors influence QoS performance more than others. A reduction of that number, a fractional factorial totaling 32 initial simulations with another 32 simulations for confirmation testing to corroborate the results of the first simulation results, will suffice for the initial screening. If there are no discrepancies between the results of those two runs, then the results will be deemed valid and the screening process has been successfully completed. The raw network data (trace files) from *ns-2* will be inputted into *tracegraph* (version 2.0.2 or higher) for the analysis. Statistical analyses, using design of experiment methods, e.g., ANOVA with Sum-of-Squares, Half-Normal plots, etc., will examine which design variables are more influential than others with respect to the QoS metrics. A paper entitled ―Modeling and Simulation Analyses of QoS in MANETs" will be prepared chronicling the results and analyses of these simulations.

5.2 MOF Formulation and Solution

In classical engineering optimization problems, a Single Objective Function (SOF), i.e., $f(x)$, is defined, subject to various inequality $g(x)$ and equality $h(x)$ constraints and boundary conditions, such as x_1, $x_2 \geq 0$, and then solved using an appropriate, gradient-approach method, since the function and constraints are of polynomial form and are differentiable in the first and second orders. In this case, however, multiple functions are considered in a holistic fashion rather than as individual ones which was almost exclusively revealed in this extensive literature search. To solve such a multivariate problem, an MOF will need to be formulated and solved. MOFs differ from

SOFs in that multiple sub-functions will be required, i.e., $f_1(x)$, $f_2(x)$, $f_3(x)$, etc., one for each QoS metric, i.e., throughput, delay, packet delivery rate, and jitter. Here, it is desired to maximize received packet throughput and packet delivery rate, while minimizing E2E delay and received packet jitter, subject to the respective constraints.

Sub-functions may well often conflict to realize overall convergence, thus ‗true' optimality is not assured. Those MANET design factors, determined to significantly influence the QoS metrics, will become the requisite constraints. Furthermore, it is anticipated that since this problem will be NP-complete or NP-hard which functions need to be maximized (throughout and packet delivery rate), while others minimized (delay and jitter). Therefore, evolutionary computation techniques, such as genetic algorithms, will be preferred over the aforementioned conventional methods. After the optimum QoS metrics are chronicled, additional simulations will be run or some empirical method will be employed to validate that the MOF does indeed represent the ‗best' fitness function for these ―real-world" scenarios. The paper entitled ―Optimizing QoS in MANETs using Evolutionary Computation" will become the third and final paper.

References

Abdullah, J., Parish, D.2007. Impact of QoS Routing Metrics for MANETs in the Pervasive Computing Environment. Paper presented at the IFIP International Conference on Wireless and Optical Communications Networks, 2-4 July, in Singapore, Indonesia.

Badis, H., Al Agha, K. 2004. An Efficient QOLSR Extension Protocol for QoS in Ad hoc Networks. Paper presented at the IEEE Sixtieth Vehicular Technology Conference, 26-29 September, in Los Angeles, CA.

Badis, H., Gawedzki, I., Al Agha, K.2004. QoS Routing in Ad hoc Networks using QOLSR with no Need of Explicit Reservation. Paper presented at the IEEE Sixtieth Vehicular Technology Conference, 26-29 September, in Los Angeles, CA.

Brahma, M., Kim, K.W., Abouaissa, A., Lorenz, P. 2005. A New Approach for Supporting QoS in MAC layer over MANETs. Systems Communications, 14-17 August.

Canales, M., Gallego, J.R., Hernandez-Solana, A., Valdovinos, A. 2006. Cross-Layer Routing for QoS Provision in Multiservice Mobile Ad Hoc Networks. Paper presented at the IEEE Seventieth International Symposium on Personal, Indoor and Mobile Radio Communications, 11-14 September, in Helsinki, Finland.

Chakeres, I, Perkins, C. 2008. Dynamic MANET On-demand (DYMO) Routing, `http://tools.ietf.org/id/draft-ietf-manet-dymo-16.txt`.

Chakrabarti, S., Mishra, A. 2001, QoS Issues in Ad hoc Wireless Networks. *IEEE Communications Magazine*, Volume 39, Issue 2, February.

Chen, L., Heinzelman, W.B.2005. QoS-aware Routing based on Bandwidth Estimation for Mobile Ad hoc Networks. *IEEE Journal on Selected Areas in Communications*, Volume 23, Issue 3, April.

Cheng, H., Cao, J., Wang, X. 2006. A Heuristic Multicast Algorithm to Support QoS Group Communications in Heterogeneous Network. *IEEE Transactions on Vehicular Technology*, Volume 55, Issue 3, May.

Clausen, T., Jacquet, P. 2003. Optimized Link State Routing Protocol (OLSR). `http://www.ietf.org/rfc/rfc3626.txt`.

Crawley, E., Nair, R., Rajagopalan, B., Sandick, H. 1998. RFC 2386, A Framework for QoS-based Routing in the Internet. `http://www.ietf.org/rfc/rfc2386.txt`.

de Renesse, R., Friderikos, V., Aghvami, H. 2007. Cross-layer Cooperation for Accurate Admission Control Decisions in Mobile Ad hoc Networks. IET Communications, Volume 1, Issue 4, August.

Fung, C., Chen, Y-L, Wang, X.; Lee, J., Tarquini, R., Anderson, M., Linger, R. 2005. Survivability Analysis of Distributed Systems using Attack Tree Methodology. Paper presented at the IEEE Military Communications Conference, 17-20 October, in Atlantic City, NJ.

Haghighat, A.T., Khoshrodi, O.J. 2007. Stable QoS routing by AODV protocol. Paper presented at the Fifteenth International Conference on Software, Telecommunications and Computer Networks, 27-29 September, in Dubrovnik, Croatia.

Hanzo,II, L., Tafazolli, R. 2006. Quality of Service Routing and Admission Control for Mobile Ad-hoc Networks with a Contention-based MAC Layer. Paper presented at the IEEE International Conference on Mobile Adhoc and Sensor Systems, 9-12 October, in Vancouver, Canada.

Hejmo, M., Mark, B.L., Zouridaki, C., Thomas, R.K. 2005. A Denial-of-Service Resistant Quality-of-Service Signaling Protocol for Mobile Ad hoc Networks. Paper presented at the Second International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, 22-24 August, in Lake Buena Vista, FL.

Helweh-Hannan, A. 2006. Avoiding Misbehaving Nodes in Mobile Ad-Hoc Environments: Towards Improved QoS Routing. Paper presented at the Second International Conference on Distributed Frameworks for Multimedia Applications, 15-17 May, in Penang, Malaysia.

Hong, X., Gerla, M., Pei, G., Chiang, C-C 1999. A Group Mobility Model for Ad Hoc Wireless Networks. Paper presented at the Second ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems, 20 August, in Seattle, WA.

Hu, C-C, Wu, E. H-K, Chen, G-H 2005. Bandwidth-satisfied multicast trees in MANETs. Paper presented at the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, Volume 3, 22-24 August, in Montreal, Canada.

Hui Cheng; Jiannong Cao; Xingwei Wang; Mullai, S. 2005. A Heuristic Multicast Algorithm to Support QoS Group Communications in Heterogeneous Network, Paper presented at the Second International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, 22-24 August, in Lake Buena Vista, FL.

IEEE (Institute of Electrical and Electronic Engineers) 2007. Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY). `http://www.ieee802.org/11/`.

IETF (Internet Engineering Task Force) 2008: Mobile Ad-hoc Networks (manet). `http://www.ietf.org/html.charters/manet-charter.html`.

ITU – T (International Telecommunications Union – Telecommunications) 1994. Telephone Network and ISDN Quality of Service, Network Management and Traffic Engineering Terms and Definitions Related to Quality of Service and Network performance including Dependability. `http://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-E.800-1994`

08-S!PDF-E&type=items.

Johnson, D., Hu, Y., Maltz, D. 2007. The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4. http://www.ietf.org/rfc/rfc4728.txt.

Kone, V., Nandi, S. 2006. QoS Constrained Adaptive Routing Protocol for Mobile Adhoc Networks. Paper presented at the Ninth International Conference on Information Technology, 18-21 December, Bhubaneswar, India.

Kurkowski, S., Navidi, W., Camp, T. 2007. Discovering Variables that Affect MANET Protocol Performance. Paper presented at the IEEE Globecom, 26-30 November, in Washington D.C.

Labiod, H.; Quidelleur, A. 2002. QoS-ASR: An Adaptive Source Routing Protocol with QoS Support in Multihop Mobile Wireless Networks. Paper presented at the IEEE Fifty-sixth Vehicular Technology Conference , Volume 4, 24-28 September, in Lisbon, Portugal.

Lu, B., Pooch, U.W. 2005. Security in QoS Signaling Systems for Mobile Ad hoc Networks. Paper presented at the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, Volume 3, 22-24 August, in Montreal, Canada.

Mayhew, G.L. 2007. Quality of Service in Mission Orientated Ad-hoc Networks. Paper presented at the IEEE Aerospace Conference, 3-10 March, in Big Sky, MT.

Mbarushimana, C., Shahrabi A. 2008. Resource Efficient TCP: Reducing Contention-Induced Spurious Timeouts in QoS-Aware MANETs. Paper presented at the Twenty-second International Conference on Advanced Information Networking and Applications, 25-28 March, in Okinawa, Japan.

Medidi, S.R., Vik, K.-H. 2004. Quality of Service-aware Source-initiated Ad-hoc Routing. Paper presented at the First Annual IEEE Communications Society Conference on IEEE Sensor and Ad Hoc Communications and Networks, 4-7 October, in Santa Clara, CA.

Montgomery, D. 2005. *Design and Analysis of Experiments*, Sixth edition, Wiley.

Narsimha, G., Reddy, A.V., Kumar, B.S. 2008. QoS Multicast Routing Based on Bandwidth and Resource Availability in Mobile Adhoc Networks. Paper presented at the Seventh International Conference on Networking, 13-18 April, in Cancun, Mexico.

Nasir, Q., Albalt, M. 2008. History Based Adaptive Backoff (HBAB) IEEE 802.11 MAC Protocol. Paper presented at the Sixth Annual Communication Networks and Services Research Conference, 5-8 May, in Nova Scotia, Canada.

Perkins, C., Belding-Royer, E., Das, S. 2003. Ad-Hoc On-Demand Distance Vector (AODV). http://www.ietf.org/rfc/rfc3561.txt.

Perkins, D., Yang, J., Hughes, H., and Owen, C. 2004. Reducing the Impact of Mobility-Induced Route Failures in QoS MANETs. Paper presented at the IEEE Global Telecommunications Conference, Volume 6, 29 November - 5 December, in Dallas, TX.

Perkins, D., Hughes, H., Owens, C. 2002. Factors Affecting the Performance of Ad hoc Networks. Paper presented at the IEEE International Conference on Communications. IEEE Press, 28 April-2 May, in New York, NY.

Romdhani, L., Bonnet, C. 2005. A Cross-layer On-demand Routing Protocol for Delay-Sensitive Applications. Paper presented at the IEEE Sixteenth International Symposium on Personal, Indoor and Mobile Radio Communications, Volume 2, 11-14 September, in Berlin, Germany.

Sarma, N., Nandi, S. 2006. QoS in Mobile Ad hoc Networks. Paper presented at the IFIP International Conference on Wireless and Optical Communications Networks, 11-13 April, in Bangalore, India.

Shenoy, N., Pan, Y., Reddy, V.G. 2005. Bandwidth Reservation and QoS in Internet MANETs. Paper presented at the Fourteenth International Conference on Computer Communications and Networks, 17-19 October, San Diego, CA.

Stine, J.A., de Veciana, G. 2004. A Paradigm for Quality-of-Service in Wireless Ad hoc Networks using Synchronous Signaling and Node States. *IEEE Journal on Selected Areas in Communications*, Volume 22, Issue 7, October.

Subbarao, Madhavi W. 1999. Ad Hoc Networking Critical Features and Performance Metrics. Wireless Communications Technology Group. Gaithersburg, MD: National Institute of Science and Technology (NIST).

Transmission Control Protocol (TCP) DARPA Internet Program Protocol Specification; 1981. Request for Comment (RFC) 793. `http://www.rfc-editor.org/rfc/rfc793.txt`.

Umuhoza, D., Agbinya, J.I., Omlin, C.W. 2007. Estimation of Trust Metrics for MANET Using QoS Parameter and Source Routing Algorithms. Paper presented at the Second International Conference on Wireless Broadband and Ultra Wideband Communications, 27-30 August, in Sydney, Australia.

Vadde, K., Syrotiuk, V. 2004. Factor Interaction on Service Delivery in Mobile Ad hoc Networks. *IEEE Journal on Selected Areas in Communications*, Volume 22, Issue 7, October.

Yang, M.,Li, L., Fang, Y. 2006. Secure Efficient QoS Multicast Route Discovery for MANET. Paper presented at the First International Conference on Communications and Networking in China, 25-27 October, in Beijing, China.

Zhang,Y., Gulliver, T.A. 2005. Quality of Service for Ad hoc On-demand Distance Vector Routing. Paper presented at the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, Volume 3, 22-24 August, in Montreal, Canada.

Ziane, S., Mellouk, A. 2007. AMDR: A Reinforcement Adaptive Mean Delay Routing Algorithm for MANET. Paper presented at the IEEE Global Telecommunications Conference, 26-30 September, in Washington, D.C.

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