A MOBILE BACKBONE NETWORK ROUTING PROTOCOL WITH FLOW CONTROL

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ABSTRACT

We have recently introduced Mobile Backbone Network based architecture to support applications transported across ad hoc wireless networks. Under our MBN topological synthesis algorithm, Backbone Capable Nodes (BCNs) are elected as Backbone Nodes (BNs) to form a mobile backbone network (Bnet). Once constituted, the mobile backbone network provides a preferred infrastructure for supporting the transport of multimedia streams and other message flows across the ad hoc network, and is exploited to make the routing, access control and congestion control problems tractable.

In this paper, a so-called Mobile Backbone Network Routing with Flow Control (MBNR-FC) is introduced. We define an on-demand routing protocol under which route discovery messages are distributed solely across the Mobile Backbone, leading to a highly scalable and robust mobile ad hoc network operation. We use the embedded signaling mechanism that is used for the route discovery process to regulate the admission of flows by guiding admitted flows through less congested areas. The employed flows control mechanism is also used to protect the quality-of-service performance of supported message flows. We show our new flow controlled based routing method to significantly improve network throughput, packet delay, packet delay jitter, and packet loss ratio performance.

1. INTRODUCTION

We have been investigating the operation of mobile wireless networks through the embedded establishment of a Mobile Backbone Network (MBN). In [1]-[4], we have presented objectives and methods for the design of MBN topological layouts. The MBN is composed of two classes of network nodes: Regular Nodes (RNs) and Backbone Capable Nodes (BCNs). RNs employ a single module radio that possesses limited communications and data processing capabilities. BCNs may have higher storage and processing resources and may employ multiple radio modules with the ability to operate at multiple power levels. A group of BCNs are elected to function as Backbone Nodes (BNs). BNs effectively serve as mobile base-stations for BCNs and RNs. Each BN is associated with several BCNs and RNs, together forming an Access network (Anet). The BNs with their interconnecting communication links constitute a Backbone network (Bnet). An example of the Mobile Backbone Network is illustrated in Fig. 1.

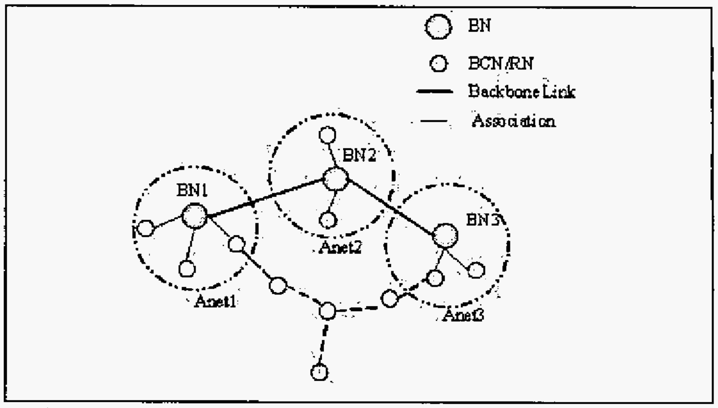

Figure 1: An example of the Mobile Backbone Network

The mobile backbone structure provides a reliable framework for routing messages and packet flows. Using an on-demand routing protocol for ad hoc networks, such as AODV [5] or DSR [6], an active source node that wishes to initiate a flows across the network first proceeds through a route discovery process. For this purpose, it floods route request (RREQ) packets across the entire network. This flooding operation can potentially require the participation of many (if not all) network nodes, reducing the scalability of the underlying method. If the network size is large, or when the network operates under high traffic loading conditions, the control overhead induced by the flooding based route discovery procedure can impose significant demand of link capacity resources, leaving insufficient residual capacity to support data packet transport. In addition, the generation of a high control packet rate induces severe MAC contentions, ultimately leading to distinct throughput degradations.

In this paper, we introduce a Mobile Backbone Network on-demand routing mechanism that employs Flow Control (MBNR-FC). We note that by just using our Mobile Backbone Network Routing (identified as MBNR) procedure without the inclusion of our flow control mechanism, we achieve a significant reduction of routing control overhead, since the flooding scope is restricted through the use of the backbone based selective forwarding process. In addition, routes discovered by the MBNR mechanism tend to be more stable than routes discovered by generic typical on-demand routing protocols [5], [6], since our topological synthesis algorithm assigns higher weights to less mobile BCNs, making it more probable for them to be elected as BNs, and thus yielding a more robust backbone structure. This phenomenon is further accentuated when Unmanned Vehicles (UVs) are deployed as BNs, particularly when they are guided into preferred locations and are kept them as stationary relays nodes for a desired period of time. To investigate the performance features and behavior of our new flow-control based protocol, we have implemented our new protocols and conducted extensive simulation results (using QualNet v3.6 simulation program). We present many key performance results in this paper. We show that under high offered traffic loads, our method yields a much better delay-throughput performance than that exhibited by common on-demand routing algorithms. We demonstrate the ability of our MBN oriented flow control operation to provide and guarantee packet delay and delay jitter performance levels that allow the ad hoc wireless network to reliably support admitted real-time streams.

As noted above, we make use of the signaling mechanism employed for route discovery to guide traffic admitted into the network to traverse network parts that are less congested. In [7], a congestion control mechanism is described that acts to prevent congested network nodes from participating in the flooding of route discovery packets. Our study shows that it is highly effective to not only regulate the admission of flows at congested BNs, but also that one should prevent neighbors of a congested BN from themselves relaying request packets. This latter element, which we embedded into our operation, serves to avoid further congestion-induced performance deterioration.

The remainder of this paper is structured as follows. In Sections 2 and 3, the MBNR and the MBNR-FC procedures are introduced, respectively. In Section 4, we present performance results for these routing algorithms. Conclusions are drawn in Section 5.

2. MOBILE BACKBONE NETWORK ROUTING

2.1. Characteristics of the Mobile Backbone Network

Consider a Mobile Backbone Network composed of BNs, BCNs, and RNs. By using our distributed topological synthesis algorithm [2], the MBN is formed so that it has following characteristics. The primary route discovery process attempts to discover routes from a source BN to a destination BN by using a selective flooding method that employs only the backbone network's nodes (i.e., the BNs) to distribute route discovery packets. In this manner, if feasible, a path that consists exclusively of BNs is discovered and employed. BCNs are elected to serve as BNs to satisfy two key conditions: a) to provide access coverage to its nodal clients; b) to provide sufficiently high local connectivity (so that its neighboring nodes have an alternate path to use in case of a local failure or movement of another BN. Hence, if feasible, each BCN has at least one BN neighbor. In doing so, when multiple candidates are available, the BCNs with highest weights are preferred for conversion to BN status. By setting the nodal weight to be a function of its (as measure over a recent time window interval) mobility level (as well as a function of other parameters such as those that relate to capacity and connectivity) a more robust backbone network structure is dynamic synthesized. Hence, BNs tend to be less mobile than BCNs.

We also allow for location registration, so that each non-backbone node (BCN/RN) registers itself with its BN (i.e.; the BN with which it has elected to associate, conditioned on the acceptance by the latter BN), and is included in the latter's registration table as its client. The location registration tables are updated dynamically. In particular, we note that the client node and its associated BN manager both record the hop length of the shortest path between the client and the underlying BN. The length of such a path is discovered through the use of BN beacon packets that are hierarchically distributed across the Anet starting from the BN, subsequently relayed by all nodes that are 1 hop away from the BN, then relayed by nodes that are 2-hops away, etc.

2.2. The Route Discovery Process

Under our MBNR protocol, when a source node starts a route discovery process, it floods a *route request* message within n_s+1 hops. The parameter n_s represents the hop count length of the shortest path connecting the source node with its associated BN. As noted above, our topological synthesis algorithm ensures that the delivery of a *route request* message to the Mobile Backbone can be accomplished by traversing at most n_s+1 hops across the Anet. To accommodate nodal movements that occur even before the new registrations take place, we select a targeted flooding range that is one hop longer than that necessary in accordance to current registration.

If a *route request* message reaches the destination node before it reaches the Mobile Backbone, a *route reply* message is immediately issued by the destination for delivery to the source node. Subsequently, the latter employs the discovered non-backbone route. If a *route request* message reaches the Mobile Backbone, and no local route has been discovered, the *route request* message is flooded solely within the backbone network (Bnet).

As the *route request* message is flooded within the Bnet, the destination BN with whom the destination node is associated recognizes the destination node as its client. This BN then removes the *route request* message from the network. It then floods it in its Anet distributing it to nodes that are within n_d+1 hops from itself. The hop count n_d represents the hop length of the path leading from the BN to the destination node, as recorded during the topological synthesis phase. Thus, a *route request* message is guarantied to reach the destination node by traversing at most n_d+1 hops. Upon receiving the *route request* message, a *route reply* message is initiated by the destination node and forwarded to the source node. To accommodate nodal movements that occur even before the new registrations take place, we select a targeted flooding range that is one hop longer than that necessary in accordance to current registration

2.3. Performance Analysis of MBNR

We show that the MBNR method significantly reduces the system's routing control overhead by limiting the flooding scope of route discovery messages.

For a network whose nodes are all of BCN type, under te condition that a node can communicate with its BN if the latter is within a range equal to r, we have shown in [8] that our topological synthesis algorithm elects a number of BNs in an $L \times L$ area that is of the order of $\left(L/\sqrt{3}r\right)^2$. Hence, the total number of nodes that participate in the flooding of route discovery messages, under the MBNR protocol, is then estimated to be of the order of $\left(L/\sqrt{3}r\right)^2$.

Assuming the nodal density over the area of operations is equal to ρ, the total number of nodes in the MBN is ρL^2. By using a customary on-demand routing protocol, the latter also represent the number of nodes that participate in the flooding of route discovery messages. Hence, the flooding scope reduction ratio realized by MBNR is approximately equal to $1-1/\left(3\rho r^2\right)$. Thus, as the nodal density increases, the control overhead is significantly reduced.

When the offered traffic load increases, the packet loss ratio will increase as a consequence of higher loading rates of the communications links, which leads to more congested operations at the nodal network layer queues. Furthermore, nodes employ omni-directional antennas so that radio channels must be shared among multiple nodes. The sharing of these multiple access radio channels is regulated by medium access control (MAC) protocols, using access control algorithms. For example, a CSMA/CA MAC protocol is used by IEEE 802.11 based implementations. The latter involves a random access mechanism under which nodes that contend to access the medium may experience collisions, resulting in packet retransmissions. As the network loading increases, such contention based collision rapidly accelerates, leading to significant degradations in the effective MAC throughput performance. The resulting data packet losses in turn induces the source node to repeat the route discovery process (or induces multiple local route repair attempts), aggravating further the link and network state of congestion. We show in Section 4 that, when the network is subjected to high offered load rates, by employing our MBNR protocol, the delay-throughput and delay jitter performance behavior functions are significantly improved.

As noted above, and as confirmed by our simulations, the Bnet tends to offer more robust routes to communicating entities. Hence, we expect routes that are discovered by the MBNR along the Bnet to be more stable than those that are discovered by a normal on-demand routing algorithm that requires the destination node to configure the route based on the selection of the *route request* message that reaches it first. A significant enhancement in the stability of the backbone can be achieved by deploying less mobile or stationary Unmanned Ground Vehicles (UGVs) or Unmanned Airborne Vehicles (UAVs). In accordance with our topological synthesis algorithm, client nodes will autonomously associate with less mobile UGVs/UAVs (or BNs). In [8], we have demonstrated the coverage and connectivity improvement provided by the MBN when UGVs are used. In this paper, we demonstrate in Section 4 that the deployment of stationary UGVs and their automatic inclusion in our MBNR operation provides a noticeable enhancement in the throughput and message delay jitter performance.

3. MOBILE BACKBONE NETWORK ROUTING WITH FLOW CONTROL

Congestion control mechanisms employed by routing mechanisms used for ad hoc networks, such as the one described in [7], strive to assist the route discovery process to establish flows across less congested routes, by preventing congested nodes from forwarding *route request* messages. However, the sole use of such a mechanism in the context of our MBN based routing operation imposes a number of key disadvantages, that we avoid by implementing a new flow control method: a) Preventing only congested nodes from participating in the route discovery process will not offer sufficient benefits. Since multiple access radio channels are employed, it is essential that the neighboring nodes of congested nodes are also filtered out of the flooding scope. Clearly, MAC level radio channel access contentions among congested nodes and their neighboring nodes could lead to significant performance degradations; b) It is important to employ a congestion control mechanism that does not admit a newly generated flow if no acceptable routes can be provided, and furthermore terminates as early as possible the route discovery process for new flows if the system is congested so that it is likely that acceptable routes will not be discovered. In this manner, we are able to protect currently supported admitted flows from performance degradations induced by the excessive control overhead that can be produced by newly generated route request control messages.

To ensure the performance of admitted flows across the network, we incorporate into the MBN routing system a flow control mechanism. The resulting mechanism is identified as Mobile Backbone Network Routing with Flow Control (MBNR-FC). The MBNR-FC has an embedded signaling mechanism that is used as part of the route discovery process to protect congested network zones and in turn admit flows into and navigate packets across less congested areas.

Under MBNR-FC, each BN monitors its own congestion status by recording its backlogged (network layer) packet queue size. (To regulate access by traffic/service classes and by message/flow priority levels, we keep record of the queue size levels of separate queues used to store packets by their corresponding categories.) If the queue size level surpasses a prescribed threshold, the BN stops relaying *route request* messages. Each BN includes its congestion status in its periodically sent Hello messages, thus informing its neighbors about its congestion state. Furthermore, since the neighboring nodes of a congested BN share the communications resources of a multiple access radio channel with the congested BN, excess packet transmissions by these nodes can further reduce the channel capacity available to the congested BN, aggravating the congestion status of the latter. Hence, our flow control procedure prevents neighbors of a congested BN from relaying request packets, thus acting to reduce MAC layer induced performance deteriorations.

Under our MBNR-FC scheme, we differentiate admitted flows from newly generated flows. A newly generated flow starts a new route discovery process, disregarding previously obtained routes. A newly generated is terminated after a specified maximum number of unsuccessful attempts. In this manner, the flow control process protects the performance behavior of admitted flows. As we show in Section 4, our MBNR-FC method significantly improves the throughput versus offered load performance behavior of the network system, when compared with the AODV routing protocol and with our MBN routing protocol that does not employ the underlying Flow Control scheme. We also show that the MBNR-FC algorithm yields a significant reduction in the packet delay jitter performance of admitted flows, under relatively high traffic loading conditions.

4. SIMULATIONS AND PERFORMANCE STUDIES

In this section, we present results of our performance evaluations studies for the flow control based MBNR-FC routing protocol presented in this paper. We carry our extensive Monte-Carlo based simulation analyses using the QualNet v3.6 platform. We have programmed into the tool our MBN based topology synthesis mechanism, our MBNR routing algorithm and our Flow Control procedure. Our evaluations compare the performance behavior of AODV, MBNR, and MBNR-FC mechanisms. We integrate into our analyses the use of nodes that use radio platforms that employ an IEEE 801.11b MAC layer protocol, and omni-directional antennas.

4.1. Scenario 1: Performance Enhancement by Reducing Control Overhead

Under this evaluation, the system's topology and traffic scenarios are described as follows.

Nodes Placement: 100 BCNs are initially deployed, located uniformly over a terrain of 1350m×1350m. The communication range is approximately within 300m. Thus each node has about 20 neighboring nodes.

Topological Synthesis: By using our topological synthesis algorithm, ultimately all BCNs are 1-hop away from the Bnet. We observe that approximately 26 BNs are elected to form a backbone at any given time. The number of BNs is higher than that estimated in [8], since the interference between neighboring nodes reduces somewhat the effectiveness of the BN coverage by association process.

Traffic: 10 traffic flows are generated between 10 source - destination pairs. Packets arrive in accordance with a Poisson process. The packet size is fixed as 512 bytes. Various offered load rate levels are used to drive the network. The queue size threshold is set equal to 8 packets for the MBNR-FC flow control algorithm.

Mobility: The source and destination nodes are assumed to be stationary to allow us to focus on performance behavior for situations under which the hop count lengths of source-destination paths are relatively stable. The average path length is equal approximately to 7 hops. The rest of the nodes are moving in accordance with a Random Waypoint mobility model at an average speed of 3 m/s.

Transport, MAC and Physical Layer: UDP is used as the transport layer protocol. MAC802_11b is used as the MAC protocol. The physical layer data rate is 2Mbps.

In Fig. 2, we present overall throughput vs. offered load performance curves for the underlying three routing schemes. We note that when the offered traffic load rate is light, the underlying three schemes (AODV, MBNR, and MBNR-FC) exhibit similar throughput performance behavior. When the offered traffic load is sufficiently high to drive the network into its throughput saturation region, the MBNR scheme yields distinctly higher throughput levels. The latter scheme prevents the throughput level from deteriorating under high offered loading rates by properly regulating the admission of flows, as well as by preventing the route discovery control overhead from growing to a level that will cause it to exhaust residual capacity resources. We note that the spatial reuse factor (s) achieved by our flow distribution is equal to about 2.0. The average path length L is 7. The MAC utilization factor ρ is 0.7. The throughput capacity attained is about 400Kbps, which is approximately equal to 2 Mbps $\times\rho\times(s/L)$.

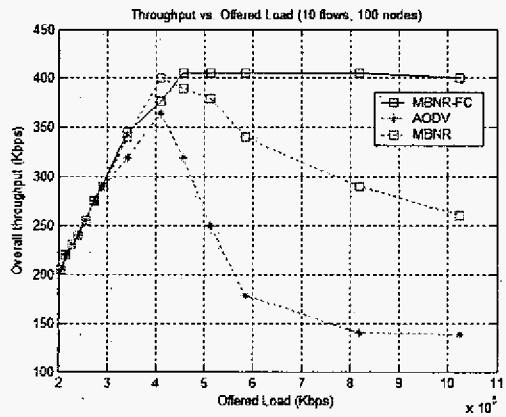

Figure 2: Overall Throughput vs. Offered Load

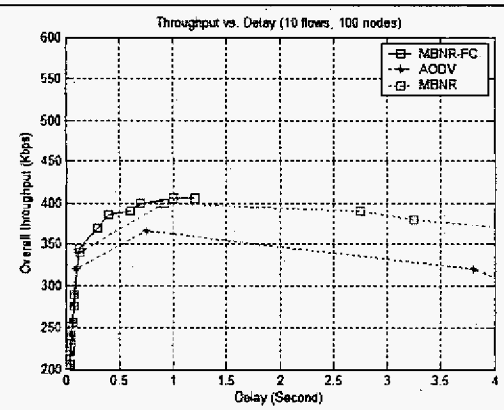

Figure 3: Overall Throughput vs. Delay

In Fig. 3, we show that the MBNR scheme yields better delay-throughput performance under high traffic loading rates. The MBNR-FC scheme keeps the end-to-end delay level to a low value by blocking new traffic flows when the network reaches a desired level of congestion, while maintaining at the same time a high network throughput level.

In Fig. 4, we show that under both the MBNR-FC and MBNR schemes much lower delay jitter values are realized when compared with the AODV scheme, under high traffic loading conditions. It demonstrates that the process used in regulating admissions of flows is of crucial importance in ensuring the provision of good delay jitter performance for real-time traffic flows.

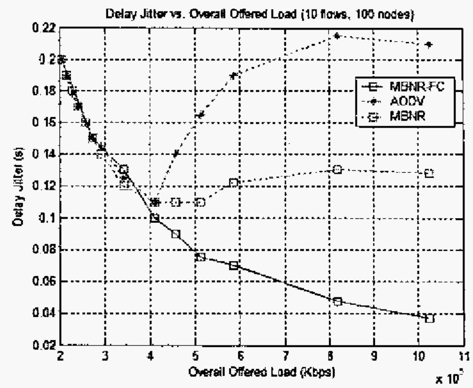

Figure 4: Delay Jitter vs. Offered Load

Our evaluation analyses show that it is of higher value to be able to block new flows when the network has already entered into its operation in the overloading (and throughput saturation or degradation) region. By rejecting newly generated flows, not only each admitted individual flow experiences better performance, but also the overall throughput performance is stabilized so that it is maintained at a value that is equal to the throughput capacity level, rather than experiencing rapid degradation.

4.2. Scenario 2: Benefits from Stationary UGVs Deployment

Under this scenario, we demonstrate the performance enhancement that the MBNR and MBNR-FC schemes can realize with the deployment of stationary UGVs. This improvement is a result of the use of the UGVs to form a more stable backbone network.

The geographical setup in this Scenario is the same as stated for Scenario 1. All 100 nodes are assumed to be BCNs. We load the system at a medium offered load level, to focus on the performance of the system as a function of the mobility features of the nodes. The network is driven by 10 flows that yield an overall offered load rate of 341Kbps.

The source and destination nodes are assumed to be stationary. The employed source-destination path consists of approximately 7 hops.

Two mobility patterns are simulated to illustrate the benefits attained by deploying stationary UGVs. In the first case, all BCNs except for the source and destination nodes move in a Random Waypoint manner at the same average speed. In the second case, in addition to the above mentioned 10 pairs of source-destination nodes, 20 BCNs are forced to be stationary and regarded as UGVs. The rest of BCNs move in a Random Waypoint manner at the same average speed.

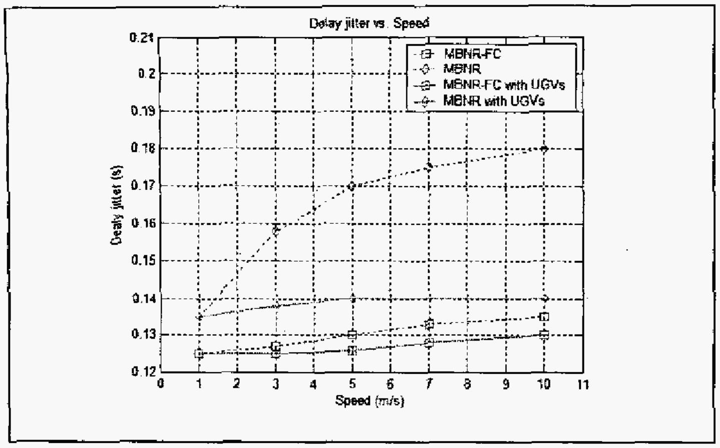

Figure 5: Delay Jitter vs. Average Speed

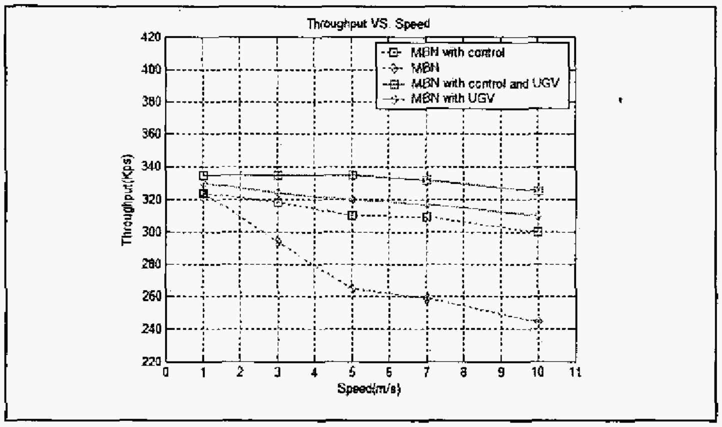

Figure 6: Throughput vs. Average Speed

In Fig. 5, we show that the MBNR scheme significantly reduces the packet end-to-end delay jitter, when UGVs are deployed. This is explained by noting that the MBNR scheme is now able to discover routes through the more stable Mobile Backbone network that is automatically synthesized by our MBNP [2] topology formation algorithm.

In Fig. 6, we show that by deploying stationary UGVs, the routes are more stable, which in turn reduces the packet loss ratio and consequently results in higher throughput performance.

4.3. Scenario 3: Performance Studies under Different Flow-Control Queue-Size Thresholds

Under this scenario, we study the impact of different queue size thresholds used for the flow control mechanism of the MBNR-FC scheme. By setting the threshold to a low level, the scheme acts in a more restrict manner in admitting new flows. However, if tow strict, the network capacity resources may not be sufficiently utilized. In turn, as the threshold level is set to higher value, more flows are admitted; by admitting an excessive number of flows, the delay performance experienced by admitted flows may be degraded.

Under this Scenario, 100 BCNs are deployed uniformly over an operational area of dimensions 1350m×1350m. 20 traffic flows are generated involving 20 distinct source-destination pairs. Packets arrive in accordance with a Poisson process. The packet size is fixed at 512 bytes.

The source and destination nodes are kept stationary. The source-destination path length consists approximately of 7 hops. The rest of the nodes are moving in accordance with a Random Waypoint mobility model at an average speed of 3m/s.

The queue size threshold assumes values from the following set: $q_t = \{1, 2, 4, 6, 8, 10, 16, 24, 100\}$ packets. Different offered loading rate levels are generated.

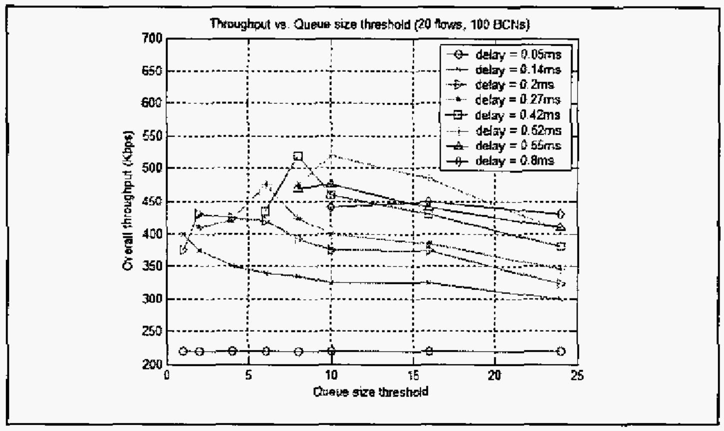

Figure 7: Throughput vs. Queue Size with Delay Constraints

In Fig. 7, we present the maximum throughput level attained by the MBNR-FC scheme, under various queue-size threshold levels. Each performance curve is produced under a prescribed message delay constraint.

Using these performance curves, one can synthesize the flow control mechanism by concluding the proper queue-size threshold level that should be selected, under a prescribed end-to-end message delay objective, to yield the highest level of network throughput level. We observe that when the desired delay value is low, it is more effective to choose a lower queue size threshold level.

In Figs. 8 – 9, we increase the offered loading rate to demonstrate the performance behavior of the flow blocking ratio (induced by the flow control based admission control algorithm) and of the message delay jitter experienced by admitted flows, when working under the MBNR-FC scheme at various threshold levels. The simulation results can be effectively used to choose the proper value of the threshold under various values of QoS requirements. For a threshold level that is set to 8, the traffic performance behavior has been shown in Fig. 2 – 4.

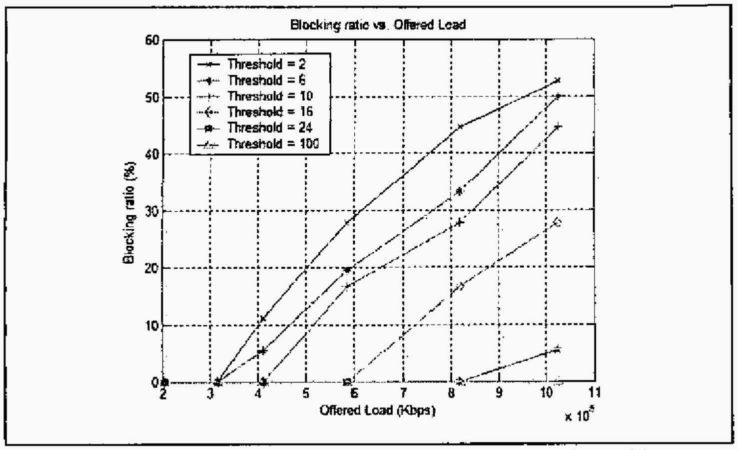

Figure 8: Blocking Ratio vs. Offered Load under Different Thresholds

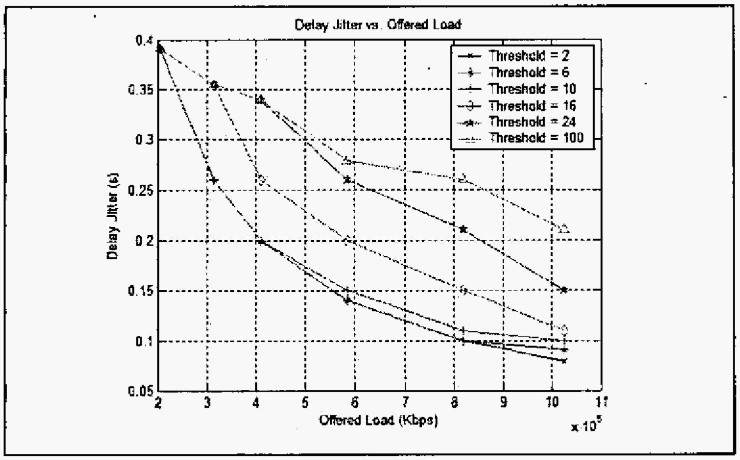

Figure 9: Delay Jitter vs. Offered Load under Different Thresholds

5. CONCLUSIONS

We design and implement a Mobile Backbone Network Routing with Flow Control (MBNR-FC) scheme for Mobile Backbone Networks. The latter dynamically form a backbone network that serve for the transport of messages and flows across a mobile ad hoc wireless network. Our scheme uses the backbone to selectively flood route request messages, leading to an on demand routing protocol identified as MBNPR. We show the MBNR-FC scheme to significantly reduce the control overhead produced by an on-demand routing operation, leading to a highly scalable ad hoc networking implementation. We then incorporate a flow control mechanism into the MBNPR operation, by using the MBN based control subsystem operation of the ad hoc network to admit route discovery packets and flows into the backbone network only if the involved nodes are not overly congested. The flow control mechanism ensures acceptable QoS performance for admitted flows. We demonstrate that MBNR and MBNR-FC schemes significantly improve the throughput, delay and delay jitter performance of the network system, especially under high offered traffic loading conditions. Under the MBNR-FC scheme, the throughput of each individual flow as well as the overall network throughput is assured. For this purpose, we demonstrate that the selection of a stable and robust backbone network, as autonomously achieved by our topology synthesis protocol, is highly advantageous for the support of multimedia applications. The inclusion of stable platform as backbone nodes, including properly located unmanned vehicles (UGVs and UAVs) is shown to further aid in enhancing the robustness of the mobile backbone and subsequently in producing significant improvements in network system performance. Our evaluation studies exhibit the performance behavior characteristics of our schemes. They also well demonstrate the effect of various key system parameters (including the threshold level used by the flow control admittance algorithm) on overall system throughput and end-to-end delay performance.

ACKNOWLEDGEMENT

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