Dynamic Bandwidth Provisioning Using Markov Chain Based RSVP for Unmanned Ground Networks

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***Abstract*— An unmanned ground vehicle (UGV) network operates as an intermittently connected system, distributed over large geographic areas. The cooperative nature of a UGV network requires that bandwidth be allocated depending on necessity between individual UGV nodes. In this paper, we study the problem of dynamic bandwidth provisioning in a UGV network. Specifically, we integrate the use of a basic statistical model, known as the Markov chain with a widely known network reservation protocol known as the Resource Reservation Protocol (RSVP). The Markov chain is used to estimate future traffic demand along a path based on channel conditions. The Markov chain results are used as input to the RSVP which then allocates the required bandwidth along the path. Using a wireless network simulation platform called Qualnet, we show that the integrated Markov chain and RSVP algorithm provides higher bandwidth guarantees and better overall quality of service (QoS) when compared solely with using RSVP in wireless communication networks.**

I. Introduction

In recent years, the Department of Defense (DoD) has dramatically increased the use of mobile wireless communication devices for both tactical and non-tactical applications [1]. One area in which wireless communication has become an important tool is in the deployment of unmanned ground vehicles (UGV). A UGV network operates as an intermittently connected system, distributed over large geographic areas. They function as a cooperative mobile ad hoc network (MANET). Like all communication networks, the main bottleneck of a UGV based network is the availability of bandwidth. As the number of nodes in the network grows, the bandwidth required to continuously update all nodes may exceed the available bandwidth.

This paper focuses on the development of an algorithm for dynamic bandwidth allocation for mobile UGV nodes using basic statistical and network protocols, first presented in a Master's thesis at the Naval Postgraduate School [2].

A. Problem Statement and Motivation

An important aspect of wireless communication is efficiency. Efficient network resource management and quality of service (QoS) are parameters that need to be achieved especially when considering network delays. The cooperative nature of UGV networks requires that bandwidth allocation be shared fairly between individual UGV nodes, depending on necessity. Specifically, nodes that require more bandwidth for data transmission should not be starved and arbitrarily limited by bandwidth resources while, conversely, nodes requiring less bandwidth should not be over allocated. This form of bandwidth management is known as statistical multiplexing [3]. In other words, the shared transmission links adapt instantaneously to the traffic demands of the node connected to the link. This dynamic bandwidth allocation takes advantage of several assumptions of cooperative networks:

- All users are typically not connected to the network at one time
- Even when connected, all users are not transmitting data (or voice or video) at all times
- Most network traffic occurs in bursts meaning that there are gaps between the transmission of groups of packets

While bandwidth allocation schemes for wireless networks have been studied in the literature, UGVs would benefit from implementation of a dynamic bandwidth provisioning scheme. The successful implementation of an efficient bandwidth provisioning algorithm for UGV networks will contribute to help solve the limited bandwidth problem and prevent failures of UGV nodes in terms of communication.

In this paper, we study the problem of dynamic bandwidth provisioning in a UGV network. Specifically, we integrate the use of a basic statistical model known as the Markov chain with a widely known network bandwidth reservation protocol, known as the Resource Reservation Protocol (RSVP).

The Markov chain process is a stochastic process that has been used in wireless communications for the following tasks:

- Modeling wireless channels [4]
- Estimating future traffic demand when nodes are mobile [5]

RSVP is a transport layer protocol that enables Internet applications to obtain differing QoS for their data flows. It is designed to meet three basic needs: achieving higher bandwidth, dealing with real time traffic, and dealing with bursty data. The goals of RSVP can be summarized as follows [6]:

- Accommodate heterogeneous receivers
- Adapt to route changes

- Use network resources efficiently

The basic characteristics of the Markov chain and RSVP protocols are amenable for use in cooperative UGV networks. Specifically, the RSVP does not have a mechanism for traffic demand prediction and the Markov chain process cannot be used as a network tool for bandwidth allocation. Thus, by exploiting the characteristics of both and integrating them, we achieve a more robust and efficient dynamic bandwidth allocation algorithm.

B. Contributions and Organization

The contribution of this paper lies in the creation of a new algorithm that dynamically allocates bandwidth to nodes in a UGV network, taking into consideration the channel quality. First, the Markov chain process is implemented in a UGV network, where each UGV node has some velocity. The Markov chain model is demonstrated to predict channel conditions at each UGV node. The result of the Markov chain is used to formulate estimated bandwidth requirements. Second, the RSVP algorithm is implemented and integrated with the Markov chain process. The Markov chain results are used as input to the RSVP process such that the RSVP algorithm can either increase or decrease the bandwidth requirement at each node. More specifically, the Markov chain results are used with the RSVP to identify specific bandwidth allocation requirements along a path such that data transmission along that path is successful. We use Qualnet [7], a simulation platform for the wireless environment to verify the effectiveness of the algorithm developed. We show that this algorithm provides higher bandwidth guarantees and better overall QoS when compared solely with using RSVP as the bandwidth allocation protocol.

The remainder of this paper is organized as follows. In Section II, we discuss the related work. We provide a general discussion of the basics of a Markov chain and the RSVP in Section III. The integration of the Markov chain process and the RSVP is discussed in Section IV. In Section V, we show our simulations and provide an analysis of the results obtained. We conclude the paper in Section VI.

II. Related Work

There are two types of bandwidth allocation methods discussed in the literature: static bandwidth allocation and dynamic bandwidth allocation. Static bandwidth allocation is generally ineffective in terms of QoS. This is because a channel is dedicated some amount of predefined bandwidth, regardless of whether it uses it or not, and thus the bandwidth resources are never released for use by other services. On the other hand, dynamic bandwidth allocation works better in environments in which bandwidth is in high demand. Dynamic bandwidth allocation is defined in the literature as a technique by which traffic bandwidth in a shared telecommunications medium can be allocated on demand and fairly among different users of that bandwidth [4].

One of the chief benefits of dynamic bandwidth allocation is that applications which may require considerable resources at one point but can function with much less at a later time are automatically adjusted in terms of the amount of bandwidth set aside for that application. In the interim, any bandwidth that remains free can easily be allocated to other users.

In the literature, a common technique used to model the wireless channel is the discrete time Markov chain. A Markov process is a stochastic process in which the past history of the process is irrelevant if the current state is known. A discrete-time Markov chain is one in which the system evolves through discrete time steps. Thus, changes to the system can only happen at one of those discrete time values. For example, in a UGV network, the UGV nodes are moving according to an individual mobility pattern. The configuration of the network at a time t can be determined to be irrelevant to the past history of the network. The next move of the UGV node can be any direction. The next move only depends on the current position.

The wireless channel can be modeled using the Finite State Markov Channel (FMSC) [8] [9]. In general, for Markov chains, the set of possible values for each state is a countable set S. If S is finite, it is usually taken to be an integer number as $S = 1, 2, 3, , M$. When S is finite, it is called a FMSC. In the Markov chain process if the state space is finite, the transition probability distribution of states can be represented by a transition matrix. In [4], [8] and [9], the channel is modeled using a discrete time Markov chain. Similarly in [10] channel modeling is based on an N-state Markov chain for satellite communication (SATCOM) systems simulation.

In terms of bandwidth allocation, a Markov chain based model for dynamic bandwidth allocation in a Differentiated Services (DiffServ) network has been proposed [11]. In DiffServ networks, at a timeslot, the proposed Markov chain is used to predict the bandwidth requirement at the next time slot, and the resource (bandwidth) is then allocated accordingly. Such a pre-allocation scheme can effectively reduce the operation overhead in bandwidth allocation.

The Markov chain process can also be used to estimate the future demand in a cell of a cellular network while the nodes are moving. Location and request prediction have been analyzed using Markov chains in [12]. Furthermore in [13], which also studies cellular networks, the Markov chain process is used to provide dynamic QoS. Another similar approach is presented in [14]. The main idea of [14] is the utilization of the bandwidth pre-reservation phase in the admission control protocol through a Markovian approach in order to predict the amount of bandwidth needed by a mobile host during its movements among the cells it will probably visit.

The papers discussed above ([4] to [14]) study the Markov chain process without the implementation of dynamic bandwidth allocation. The literature that studies channel modeling using solely the Markov chain process does not take into consideration the benefit of implementing specific network protocols that will aid in dynamic bandwidth provisioning. In other words, the networking perspective that comes from using an RSVP type protocol has not been considered in the literature. Thus, the approaches studied are purely from a statistical point of view.

III. General Discussion of Markov Chains and RSVP

A. Markov Chain Overview

An important parameter of a Markov chain is its memoryless property [15]. This property indicates that given the present state, the next state is conditionally independent of the past, as shown in Eq. 1.

$$P[X(t_k) = j_k \mid X(t_{k-1}) = j_{k-1} ... X(t_1) = j_1] \\ = P[X(t_k) = j_k \mid X(t_{k-1}) = j_{k-1}] \quad (1)$$

for all finite sequences of times $t_1 < ... < t_n$ and Markov states $j_1, ..., j_n$.

There are three important elements to Markov chains: probability transition matrix, P, the initial state matrix, and steady state vector, π. The probability transition matrix establishes the switch between states in a Markov chain. Each element of the matrix represents the probability that the node switches to another state or remains in the current state. These switches are called transitions. P is a square matrix whose order is the same as the number of states. Each element of P is denoted as $P_{i,j}$ which denotes the probability of transitioning from state i to state j. All $P_{i,j}$ are non-negative values and the sum of each row in the matrix must be equal to 1.

The initial state matrix indicates the states of each node and the probabilities of starting at those states at time $t = 0$.

A steady-state vector for an M state Markov chain with transition matrix P is a row vector π that satisfies

$$\pi = \pi(P), where \sum_i \pi_i = 1, \pi_i \geq 0, and 1 \leq i \leq M \quad (2)$$

In terms of the Markov chain process, a steady-state vector of the Markov chain is an eigenvector for the transition matrix corresponding to the eigenvalue 1.

In a typical wireless communication system, the channel conditions vary with time. The transmitted signals are perturbed by additive thermal noise, frequency and time selective fading and interference from other transmitters. Relative mobility between transmitters and receivers causes the channel conditions to change accordingly. In communication systems, the Markov chain is used to characterize the temporal characteristics/changes in the wireless channel due to signal attenuation, path loss etc. [4], [8].

It must be noted that due to the complexity of monitoring state changes, in this paper we do not use higher order Markov chains for bandwidth allocation.

B. RSVP Overview

The RSVP is a transport layer protocol that is designed to reserve resources across a network. RSVP is based on signaling messages that traverse the network, allocating resources along the way. RSVP requests resources for simplex (unidirectional communication) traffic flows

There are two types of primary messages in RSVP. They are path messages (PATH) and reservation (RESV) messages. In multicast scenarios, the devices send out only one PATH message to multiple receiving devices, thus conserving network bandwidth [16]. A path message is sent to indicate to the receiver that the sender is requesting an RSVP capable path. Since the RSVP is end to end, the path from sender to receiver must be determined and agreed upon. In other words the resources required along every hop of that path must satisfy the requirements of the sender. Once the PATH message is received by the receiver, it sends back towards the sender a RESV message. The receiver will use the RESV message to request the specific reservation parameters along the path. This is known as QoS reservation.

It must be noted that RSVP is not a routing protocol but works well with current routing protocols, such as OSPF and Bellman-Ford. To obtain the routes, an RSVP process consults with the local routing databases. Routing protocols determine where packets get forwarded; RSVP is only concerned with the QoS of those packets that are forwarded in accordance with routing [16].

RSVP is a soft-state protocol, meaning that the reservation must be periodically refreshed or it expires. This supports dynamic automatic adaptation to network changes in order to efficiently accommodate large groups of nodes. The reservation information is cached in each hop tasked with managing resources. If the network's routing protocol alters the data path, RSVP attempts to reinstall the reservation state along the new route. When refresh messages are not received, reservations time out and are dropped, releasing bandwidth. The sender refreshes PATH messages, and the receiver refreshes RESV messages. At any time, the sender, receiver or other network device providing QoS can terminate the session by sending a PATH-TEAR or RESV-TEAR message [16].

Another important aspect of RSVP is bandwidth reduction [17]. The bandwidth allocated to an individual reservation may be reduced due to a variety of reasons. In some cases, when some of the reservation bandwidth is needed for other purposes, instead of tearing down the reservation, the endpoints can negotiate a new (lower) bandwidth. As given in an example in [17], two aggregate flows with differing priority levels may traverse the same node. If that node reaches bandwidth capacity, the node then has two choices: deny the request or preempt an existing lower priority reservation to make room for the new or expanded reservation. If the flow is preempted, the RSVP does not terminate all the individual flows. On the other hand, [17] describes a method where only the minimum bandwidth is taken away from the lower priority aggregated reservation and the entire reservation is not preempted. A similar approach is used in our algorithm.

It is possible that devices along an RSVP path may reject resource requests. If the reservation is rejected due to lack of resources, the requested application is immediately informed that the network cannot currently support that amount and type of bandwidth or the requested service level. The application determines whether to wait and repeat the request later or to send the data immediately using best-effort delivery.

RSVP has been upgraded and proposed in a new version called Resource Reservation Protocol-Traffic Engineering

(RSVP-TE) [18]. It is an extension of the RSVP. RSVP-TE still supports the reservation of resources across an IP network. The differences lie in the ability of RSVP-TE to allow the use of Multi-Protocol Label Switching (MPLS). MPLS involves setting up a specific path for a given sequence of packets, identified by a label put in each packet, thus saving the time needed for a node to look up the IP address of the next node for forwarding. MPLS is called multiprotocol because it works with various network protocols. For this reason, MPLS can carry more and different mixtures of traffic. Using MPLS with RSVP provides a more robust resource allocation mechanism. In this paper, the RSVP-TE protocol is used for our study. It is also the primary protocol used in the simulation platform, Qualnet. For further details on RSVP, please see RFC 2205 [16].

IV. Integration of the Markov Chain and RSVP for Dynamic Bandwidth Allocation

Building a transition matrix and the initial state probability vector is the first step of the Markov chain process. It is essential that the parameter or term which is chosen to exhibit the state transitions behave according to the Markov chain process. In other words it has to have all the necessary properties such as being random and memoryless.

In the literature of wireless communication and channel modeling, the attenuation, the SNR value, and transmission rates are chosen to build the transition matrix [6], [19]. In our model we prefer to choose average transmitted power and average pathloss. In our model, we define a state as the change in the average transmit power at a node. The state illustrates the level of transmit power so that the transition matrix consists of the probability of decreasing or increasing the power level. The average pathloss values are used as comparison with the average transmit power values. This will be further illustrated in Section V-B.

Once the state definition has been established, we next build the transition matrix and the initial state probability vector that will be used for the Markov chain process. The initial state vector is $p(t) = (p_1, ..., p_N)$ where N is the number of states, and p_i is the probability of starting in each state of the chain. We obtain the initial states from the simulation environment (i.e., we obtain the initial power and attenuation levels for each node from Qualnet).

Next, we define our bandwidth transition scheme. Our approach to establishing the bandwidth transition is to use the transmission rates and their associated states. This is a similar approach to the one taken in [10]. For a given bandwidth level, the bandwidth transmission model is completely characterized by the matrix P (transition probability associated with each state).We assume that the Markov chain is time-homogeneous so that the process can be described by a single, time-independent matrix $P_{i,j}$.

A. Integration Algorithm

RSVP is dynamic in terms of node status but it is not dynamic in terms of bandwidth allocation. The Markov chain process is used to make RSVP dynamic considering channel conditions. RSVP uses the output vector of the Markov chain process as feedback that it can use to decide which nodes need bandwidth, and thus, the bandwidth can be allocated dynamically.

The first step in the integration algorithm is to implement the Markov chain algorithm. Initially, at $t = 0$ we have the initial state of each node, obtained from the Qualnet average transmit power values. From the initial state vector ($p(t)$), we deduce the state transition probabilities for the initial state transition matrix, P, by comparing the change in the average transmit power values versus the average pathloss values at each node.

At every subsequent time step, the transition matrix may change depending on the nature of the system. To obtain the subsequent transition matrices, we rely upon the random walk procedure which is frequently used with Markov chains to model the change of the system from state to state [20]. The simple random walk is a Markov chain that mathematically formulates the path that consists of a succession of random steps that are discrete and of fixed length. In a random walk, a node moves within an appropriate state space using random displacements from its current position. This sequence of steps forms a chain. The random displacements are generated using a random number vector function. Essentially, the state of the channel is being modeled by the random value function. Since we do not know the nature of the wireless channel over time, we use the random walk/function method to determine the state of the channel.

Each row of P is then passed into a random vector function, which returns a random value based on a probability vector. The random value is in the range between 0 and 1. The chosen random value is compared to the value contained within the transition matrix at the current time interval. Based on this comparison, the following rules apply:

- If the random value is lower than the current transition matrix value, the node's state is decreased by one
- If the random value is higher than the current transition matrix value but lower than the next subsequent random value chosen, the state remains the same
- If the random value is higher than the current transition matrix value, the state increases by one

After initializing the random values and obtaining the transition probability matrix, the next step is to deduce and give feedback to RSVP about whether to increase or decrease the bandwidth or remain the same. We define the output vector as the vector containing the randomly generated Markov chain. The output vector must be stationary (i.e., the Markov chain converges to a specific chain length value). The maximum chain length we use in this study is 15. The steps for the Markov chain algorithm are given in Fig. 1.

In order to allocate bandwidth dynamically, this paper uses the RSVP-TE algorithm along with refresh messages which are sent periodically, so that reserved bandwidth can be decreased or increased.

Markov Chain Algorithm

Step1: Define/initalize the initial state transition matrix, P and the initial state vector, $p(t)$.
Step2: Define/initialize the output vector (output chain length).
Step3: Send the first row of P to a random function to obtain a random value between 0 and 1.
Step4: Compare the random value and the current value of the transition matrix. Step 4 is repeated iteratively until the output vector is achieved.
 Step4a: If the random value is lower than the current transition matrix value, the node's state is decreased by one.
 Step4b: If the random value is higher than the current transition matrix value but lower than the next subsequent random value chosen, the state remains the same.
 Step4c: If the random value is higher than the current transition matrix value, the state increases by one.
Step5: Find the output vector.
Step6: If the output vector is stationary (i.e., has reached a chain length of 15), terminate algorithm.
Step7: Output the randomly generated Markov chain.

Fig. 1. Steps involved in the Markov chain algorithm

V. Performance Evaluation

The simulation performance results discussed in this section were derived from Qualnet, a wireless communications simulation platform. We use the simulations to demonstrate and validate the integrated Markov chain and RSVP algorithm described in Section IV. As a benchmark, we use the traditional RSVP algorithm to compare against the integrated algorithm.

A. Description of Simulation Environment

We simulate four different networks that consist of 5, 10, 15 and 30 nodes. The scenario dimension is 1500m x 1500m. The altitude is 1500m above sea level. Simulation times were chosen to be 5 secs, 30 secs, 5 mins and 30 mins since there needs to be at least 5-10 secs for the Markov chain process to achieve stability. The mobility model of the UGV nodes is random way point. The maximum speed of each node is 10 m/s. The link receive and transmit frequency is 13.17 GHz. We use the IEEE 802.11b physical layer (PHY) protocol. The PHY 802.11b data rates used are 1, 2, 6, and 11 Mbps. Variable bit rate (VBR) traffic is used. A free space path loss and Rayleigh fading models are used for the wireless channel. The height of all antennas is 20 meters in order to provide line of sight (LOS) for all nodes. The chosen routing protocols are Bellman-Ford and OSPF. The buffer size is 16384 bytes. RSVP-TE is used. The subnets are designed using different numbers of nodes and different distances.

The performance metrics used for the analysis are as follows:

- average transmit power: average signal power is measured in dB from the beginning of the simulation up to the specified time in the Timestamp which is the length of the simulation period (5 secs, 30 sec, 5 mins, or 30 mins).
- average pathloss: average pathloss (in dB) is the reduction in power density (attenuation) of the signal. In the simulations, it is a measurement taken from the physical layer at the beginning of the simulation to the end of the simulation period (indicated by Timestamp).
- node utilization: node utilization is the average utilization of the nodes in terms of power measured from the physical layer from the beginning of the simulation to the end.
- bit error rate (BER): BER is characterized as the percentage of bits that have errors relative to the total number of bits received in a transmission

A total of 34 simulations were executed. Due to space constraints, we show a subset of the results. To view all the simulation results, please see [2] for further details.

B. Simulation Results and Analysis

We first look at a 5-node wireless network, shown in Fig. 2. We are using the OSPF routing algorithm. The average power and pathloss results of this network are shown in Table I. The average power is between -80dB and 6dB. We define the state level as 10dB. State 1 is defined as -80dB to -71dB, state 2 is -70dB to -61dB etc. Looking at Table I, it can be seen that the change of average pathloss versus average power at node 1, node 4 and node 5 is quite large (-76 to 89, 9 to 42 and 6 to 62, respectively). It must be noted that although the change in nodes 2 and 3 are also high, the paths in the network that contain these two nodes do not achieve as high a change as the nodes in the path 1-4-5. Thus, the path we choose for bandwidth allocation contains the nodes that undergo the most significant average pathloss and average power change. In this case the path is 1-4-5. Note that these paths have been defined using OSPF for the subnet shown in Fig. 2.

TABLE I
Average power and pathloss results for the 5 node network shown in Fig. 2

Node	Avg. Power (dB)	State	Avg. Pathloss (dB)
1	-76	1	89
2	-80	1	95
3	-75	1	91
4	9	10	42
5	6	10	62

We execute the Markov chain and RSVP processes on this path. The simulation time is 30 mins and the data rate is

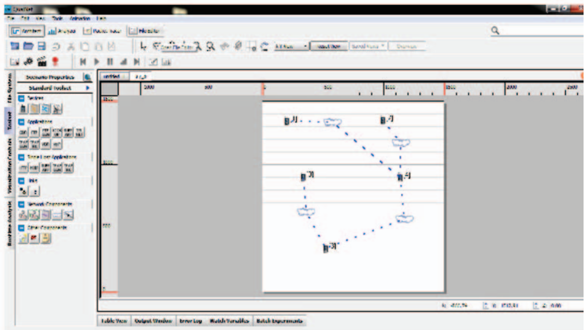

Fig. 2. The 5-node wireless network simulated in the Qualnet environme The dashed lines represent the wireless connectivity between nodes with the subnet

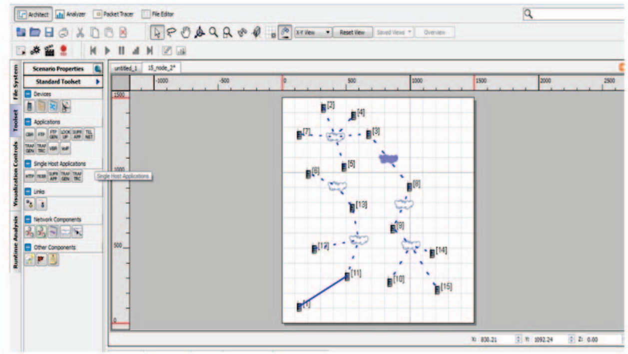

Fig. 3. The 15-node wireless network simulated in the Qualnet environment

11Mbps for those nodes on the path. The node utilization and BER results after the integrated algorithm (denoted RSVP-MC in the table) is executed are shown in Table II. The integrated algorithm results are compared with the results when only RSVP is used (denoted RSVP in the table). Note that the BER in the table is indicated as the number of bits in error/total number of bits sent.

We next look at a 15 node network, shown in Fig. 3. Due to space we show only the results after the integrated algorithm is executed (i.e., we do not show the average power and pathloss results for this network as was done in Table I for the 5 node network). However, the process by which the path is chosen for this network follows that of the 5 node network discussed earlier. The simulation time is 30 mins and the data rate is 11Mbps. The path that undergoes bandwidth allocation is 3-8-9-15. The results are shown in Table III. Similarly, we simulate a 30 node network (Fig. 4) and show the results after the integrated algorithm is executed in Table IV. The path chosen for this network is 2-8-21-18. The simulation parameters remain the same.

Comparing the results of all three networks, specifically looking at Tables II,III, and IV, we see that the node utilization and BER for all nodes along the path decreases (or stays the same) after the integrated algorithm is executed. Thus, it can be said that in terms of performance, overall the integrated algorithm works better than with RSVP alone. When BER and utilization decrease, it is an indication that the nodes on the path are able to continue transmitting with the appropriate resources (bandwidth) thus allowing the path to be successful in terms of packet delivery. This is an indication that the bandwidth allocation is being performed efficiently without a significant effect on network performance.

Recall that the process by which the paths chosen for bandwidth allocation is done based on comparison of the average power and pathloss results. This methodology works well for small networks (generally networks with 30 nodes or less). As networks get larger, our ability to look at the

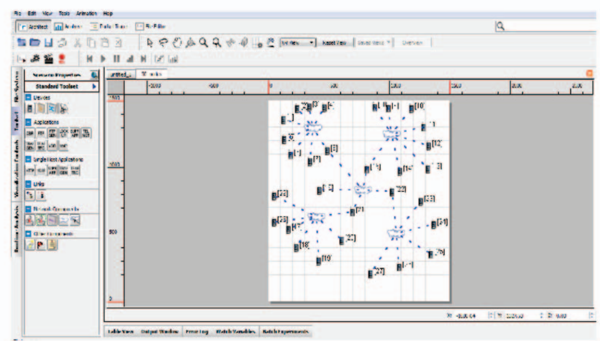

Fig. 4. The 30-node wireless network simulated in the Qualnet environment

results and choose the paths requiring bandwidth allocation is hindered. Thus, the drawback of this approach is lack of scalability.

It must also be noted that the node utilization and BER results only slightly changed when the routing algorithm was changed to Bellman Ford. The change was less significant in small size networks (i.e., 5 node network) rather than for the 30 node network. This can attributed to the fact that with a small node network, the likelihood of having diverse routes is less likely. Thus in small networks, OSPF and Bellman-Ford produced the same paths which did not change the overall results. In a larger network of size 30 nodes, the paths may change depending on which routing algorithm is used thus resulting in a slight change in the results. However, whether one uses OSPF or Bellman-Ford the integrated algorithm continues to perform better than the RSVP algorithm alone.

VI. Conclusion

In this paper, we study the problem of dynamic bandwidth provisioning in a UGV network. We integrate a Markov chain with the RSVP protocol to facilitate the bandwidth allocation

TABLE II
RESULTS FOR NODE UTILIZATION AND BER WHEN THE INTEGRATED MARKOV CHAIN AND RSVP ALGORITHM (MC-RSVP) IS USED VERSUS WHEN ONLY THE RSVP ALGORITHM IS USED (RSVP) FOR THE 5 NODE NETWORK

Node	Utilization (RSVP)	BER (RSVP)	Utilization (MC-RSVP)	BER (MC-RSVP)
1	0.000023	330/2454=0.13	0.000039	299/2556=0.11
4	0.0033	325/2563=0.12	0.00057	141/2546=0.05
5	0.00513	280/2264=0.12	0.00623	225/2332=0.09

TABLE III
RESULTS FOR NODE UTILIZATION AND BER WHEN THE INTEGRATED MARKOV CHAIN AND RSVP ALGORITHM (MC-RSVP) IS USED VERSUS WHEN ONLY THE RSVP ALGORITHM IS USED (RSVP) FOR THE 15 NODE NETWORK

Node	Utilization (RSVP)	BER (RSVP)	Utilization (MC-RSVP)	BER (MC-RSVP)
3	0.003353	2657/9824=0.27	0.001044	2230/8990=0.25
8	0.002828	2056/10026=0.20	0.002012	1385/9130=0.15
9	0.002442	1677/9949=0.17	0.001303	1641/9189=0.17
15	0.003141	2295/10297=0.22	0.003141	2126/9436=0.22

TABLE IV
RESULTS FOR NODE UTILIZATION AND BER WHEN THE INTEGRATED MARKOV CHAIN AND RSVP ALGORITHM (MC-RSVP) IS USED VERSUS WHEN ONLY THE RSVP ALGORITHM IS USED (RSVP) FOR THE 30 NODE NETWORK

Node	Utilization (RSVP)	BER (RSVP)	Utilization (MC-RSVP)	BER (MC-RSVP)
2	0.005366	8194/28445=0.29	0.002870	6150/27274=0.22
8	0.004020	4323/27684=0.15	0.002098	2916/26605=0.10
21	0.004214	5232/27818=0.18	0.002321	4711/26686=0.17
18	0.003141	5828/28377=0.20	0.002446	5505/27223=0.20

process. The Markov chain is used to identify the channel conditions and determine the paths that require a change in bandwidth allocation and the RSVP is used to provide the specific allocation. In our performance evaluation, we showed that the integrated algorithm has better node utilization and BER than when using solely RSVP. Thus, the integrated algorithm provides better bandwidth guarantees than using a reservation algorithm alone. In our future work, we will automate the process of identifying the paths for bandwidth allocation so that the algorithm can be made more scalable and thereby increase network performance.

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