# Simulation of a Medium Frequency Mesh Network for Communications in Underground Mines

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***Abstract*—Signals at the lower end of the medium frequency range (300 kHz to 3 MHz) propagate with relatively low attenuation along existing metallic infrastructure in an underground mine, such as cables, pipes and rails. Exploiting this capability, low-bandwidth medium frequency mesh networks are being developed to extend digital voice and data communications throughout a mine. This paper presents a network modeling and simulation tool that can be used to plan and evaluate medium frequency mesh networks in mines. Examples are given of mine communication scenarios that can be modeled and the quantitative analysis that can be performed using communication performance metrics such as end-to-end delay and packet delivery rate.**

## I. Introduction

Recent mine tragedies worldwide combined with the growing prevalence of communications technologies in other industries have highlighted the need for improved communications and tracking capabilities in underground mines, especially in a post-accident scenario. However, the mine environment poses a number of unique challenges that must be addressed in order for modern communications technologies to be applied successfully. In response to these challenges, a concerted effort has been launched to develop and improve communications and tracking capabilities and to expedite their commercialization and implementation.

In [1], Novak *et. al.* reviewed three types of communications technologies that have the potential to provide post-accident communications: enhanced leaky feeder, wireless mesh, and medium frequency systems. A cable that is designed to emit and receive wireless signals along its length, *leaky feeder* has been used for routine voice communications in mines since the 1980s. Enhanced leaky feeder operating in the ultra high frequency (UHF) band exhibits better propagation down mine entries and crosscuts compared to VHF and provides additional bandwidth to support ancillary services.

*Wireless mesh* systems consist of a number of wireless nodes deployed throughout the mine that can form a communications path between any two nodes, using other intermediate nodes when necessary. Because communications are not centralized but rather distributed over the nodes, a wireless mesh more easily supports redundancy and self-healing capabilities in the event of a localized failure. Furthermore, a wireless mesh can also function as a tracking system by using signal measurements at multiple nodes to locate and track a miner carrying a portable device. Wireless mesh systems typically operate at UHF and microwave frequencies in order to provide both adequate bandwidth for routine communications and reasonable propagation distances along mine tunnels.

*Medium frequency* (MF) systems typically operate at the lower end of the MF band, which extends from 300 kHz to 3 MHz. While propagation through air at these lower frequencies is very limited, MF systems are designed to exploit their unique characteristic of parasitic coupling to nearby metallic structures. An MF transceiver with a magnetic dipole (loop) antenna can propagate a signal relatively long distances (2–3 km) along existing mine infrastructure such as cables, pipes, and rails. MF systems offer limited bandwidth but are well suited for post-accident communications because of the survivability of metallic conductors that already exist in the mine.

The testing and evaluation of these technologies in underground mines can be costly and time-consuming. A computer simulation capability enables preliminary evaluation of a technology and various options for its implementation. It can also be used to predict and plan a network deployment for a specific mine. This paper describes a computer simulation system which models the use of multiuser voice and data applications over a medium frequency mesh network in an underground mine. An MF mesh network combines the long-distance and survivability of MF links with the redundancy and digital retransmission capabilities of a mesh. The simulation system described below models the communication channel in mines and the communication protocols ranging from the radio (physical) layer up to the application layer. While the current version models an MF mesh network in particular, future versions can extend the model to include more general wireless mesh networks as well as other technologies.

The simulation system uses the MATLAB and OPNET simulation engines along with models for channel propagation, channel noise, and the communication layers to generate network performance metrics. Fig. 1 shows a block diagram of the simulation environment. Models of the MF radio's physical layer and the communication channel noise are used with MATLAB to generate packet error rate (PER) tables that are

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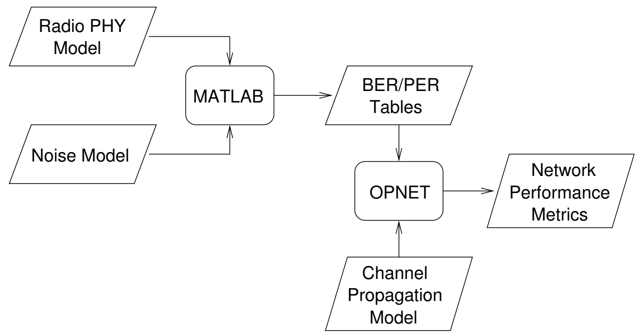



Fig. 1. Overview of simulation system

indexed by the received signal-to-noise ratio (SNR). These tables, in turn, are used by OPNET along with the channel, application, network, and medium access models to generate the network performance metrics. Section II describes the model of the MF mesh node and its applications, Section III describes the channel model and its implementation in simulation, and Section IV presents sample simulation results.[1]

## II. MF Mesh Node Model

### A. Applications

Two classes of applications are modeled, push-to-talk (PTT) voice communications and data messaging. PTT voice operates in half-duplex, meaning that voice is transmitted in one direction at a time. When the PTT button is pushed, the analog audio waveform is digitally sampled and encoded at a rate of 2,400 bits per second (b/s). Encoded bits are grouped into message units (packets) of 48 bytes per packet.

The data application transmits fixed-size messages (e.g., text, location, sensor values). Matching the size of a voice packet, data messages are also 48 bytes in length. In both cases, a 4-byte application header is added to each packet which distinguishes the applications and contains other control information such as sequence numbers.

Both applications can be employed in one-to-one (unicast) or one-to-many (multicast) communication modes. For example, a PTT voice transmission in group multicast mode transmits the voice of the speaker to all members of the group.

### B. Network Layer

The network layer of the communications stack is responsible for delivering packets from one node in the network to one or more other nodes, potentially going through intermediate nodes as needed. While numerous network layer protocols have been developed for mesh networks, the simulation implements a simple flooding protocol, which can be satisfactory under modest scalability requirements. In simple flooding, the source broadcasts a packet to all its neighbors. Each node that receives a packet rebroadcasts it once. Eventually, a packet will reach every node in the network.[2]

Besides its simplicity of implementation, an advantage of simple flooding is that it inherently fulfills the need for group multicast communications. Disadvantages include the overhead of sometimes unnecessary transmissions as well as the lack of support for retransmission over lossy links.

### C. Medium Access Control

The medium access control (MAC) layer is responsible for mediating access to the shared MF channel. Since all nodes share a common channel, it is possible for multiple nodes within range of one another to transmit simultaneously, resulting in corrupted packets. The simulation assumes use of a well-known protocol for decreasing the likelihood of packet collisions known as carrier sense multiple access with collision avoidance (CSMA/CA), which is used in many of today's wireless local area networks. With this protocol, a node wishing to broadcast a packet will first listen for an existing transmission by another node. If a transmission is detected, it will wait for it to complete, and then wait an additional randomly selected period of time known as a backoff. By independently choosing their own random backoff times, two or more nodes contending for the channel at the same time will be less likely to collide.

The MAC layer adds a header to each packet containing node address and other information. The length of the MAC header is 9 bytes.

### D. Physical Layer

The physical layer (PHY) is responsible for modulating the medium frequency carrier with the digital information contained in the packet on the transmission side, and demodulating and decoding the signal on the receiving side. The modulation scheme assumed in the model is minimum shift keying (MSK). A 2-byte cyclic redundancy check (CRC) is added to each packet for error detection. An 8-byte preamble is added for synchronization. Thus, the total length of a packet, comprising the 52-byte application payload, the 9-byte MAC header, and 10 bytes of PHY overhead, is 71 bytes. The data rate supported by the MF channel is assumed to be 26 kb/s. At this data rate, a 71-byte packet is transmitted in just under 22 ms.

Fig. 2 plots the simulated results of the packet error rate obtained using the MSK modulation feature of the MATLAB Communications Toolbox. Results were obtained for two types of background channel noise, additive white Gaussian noise (AWGN) and electromagnetic interference (EMI), which is described further in Section III below. These packet error rate results are used as input to OPNET so that it can emulate packet losses due to noise and interference.

## III. Channel Model

The channel model consists of a model of the noise and electromagnetic interference at the receiver and a propagation

[1]Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

[2]In practice, some packets will be lost due to collision or corruption by noise and interference, as demonstrated in the simulation results below.

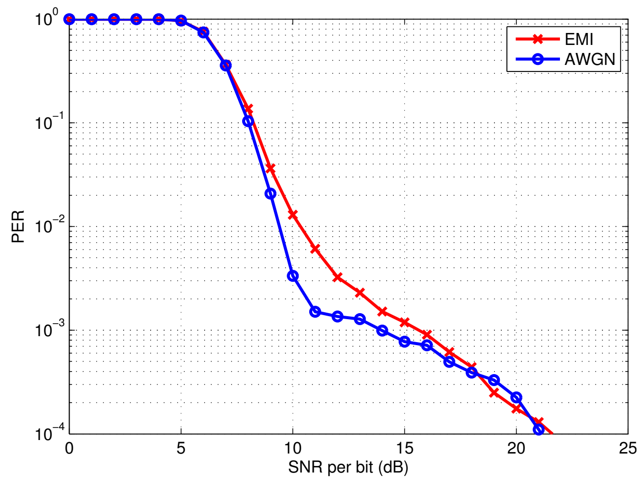



Fig. 2. Packet error rate vs. SNR of 71-byte packets using MSK

model for the signal attenuation between transmitter and receiver.

### A. Noise and Interference

Thermal noise at the receiver is typically modeled as an additive white Gaussian process. However, the electromagnetic interference generated by mine machinery is characterized by a more impulsive (heavier tail) distribution [4]. Simulated packet error rates as a function of the received SNR were obtained for both the Gaussian and non-Gaussian cases (Fig. 2). The non-Gaussian case is based on experimental measurements of the magnetic field strength probability distribution at 1 MHz obtained during active mine operation [4, Fig. 7-e, p. 33]. The non-Gaussian case would be used to model the system during normal operations. The Gaussian noise case would be used to model a post-accident scenario in which mine machinery is not operating.

In addition to the background noise and interference due to receiver electronics or operating machinery, multiple access interference (MAI) occurs when two or more mesh nodes transmit simultaneously. The simulation system totals the received power from all interfering transmissions, accounting for the channel propagation loss of each signal, and adds to it the background noise to determine the total interference and noise at the receiver. Taking the ratio of the received signal power of interest to this total interference and noise power yields the received signal-to-interference-and-noise ratio (SINR). This SINR is then used as an index to obtain the relevant PER. The simulation system then deems the transmitted packet to be lost with probability $1 - \mathrm{PER}$ and to be received successfully with probability $\mathrm{PER}$.

### B. Propagation Loss

Two sources of signal attenuation are currently modeled: (i) the inductive coupling loss between a transceiver antenna and a metallic conductor, and (ii) the attenuation with distance along the conductor.

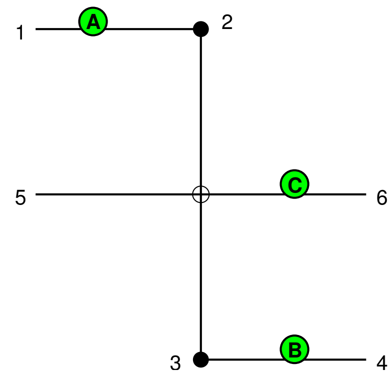



Fig. 3. Example of a conductor graph

The inductive coupling loss has been observed experimentally to be 30–40 dB over $d_0 = 0.305$ m (1 ft) [2]. For larger antenna-conductor separation distances, we assume an additional loss of $40\log_{10}(d/d_0)$ dB with distance $d$. The inductive coupling loss can be expressed, then, as

$$L_{\mathrm{ic},j} = \begin{cases} L_{\mathrm{ic},j,\min} & ; \quad d \le d_0 \\ L_{\mathrm{ic},j,\min} + 40\log_{10}(d/d_0) & ; \quad d > d_0 \end{cases}$$

where $L_{\mathrm{ic},j,\min}$ is the minimum inductive coupling loss to conductor $j$.

The attenuation rate along a conductor at the lower end of the MF band varies from approximately 3 dB per 305 m (1000 ft) for the bifilar mode of conduction to 24 dB per 305 m for monofilar mode [3], depending on the type of conductor (e.g., twisted pair, single conductor). Putting this together with the inductive coupling loss, the total channel propagation loss across $N$ sections of conductor is modeled as

$$L_{\mathrm{total}} = L_{\mathrm{ic},1}(d_{\mathrm{tx}}) + \sum_{i=1}^{N} \alpha_i \frac{l_i}{305} + L_{\mathrm{ic},N}(d_{\mathrm{rx}})$$

where $d_{\mathrm{tx}}$ and $d_{\mathrm{rx}}$ are the over-the-air distances from the transmitter and receiver, respectively, to the nearest conductor, $\alpha_i$ is the attenuation rate on conductor section $i$, and $l_i$ is the length (m) of conductor section $i$ along which the signal travels.

### C. Conductor Model

Conductors in a mine are modeled in the simulation system as a graph with edges and vertices. The vertices are location coordinates in the mine. Each edge in the graph models a section of conductor and has two numbers associated with it, its attenuation rate in decibels per 305 m (1000 ft) and its minimum inductive coupling loss. Fig. 3 illustrates a simple example of a conductor graph. The graph is specified in two data files, a list of vertex coordinates and a list of edges. The vertex file for the example in Fig. 3 contains six sets of coordinates, one for each vertex. The edge file for this example has four lines, one for each section of conductor.

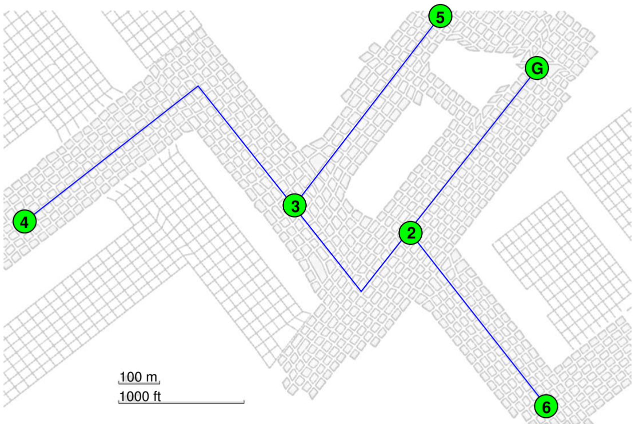



Fig. 4. Mine mesh network topology

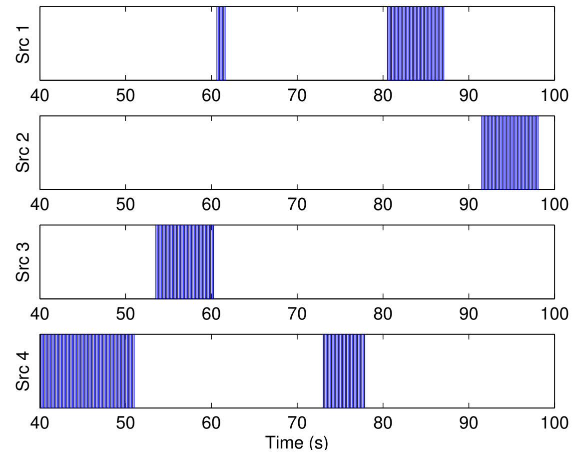



Fig. 5. PTT group traffic example with four sources

| *Vertex File* | | |
|---|---|---|
| 1: | 0 | 0 |
| 2: | 200 | 0 |
| 3: | 200 | 400 |
| 4: | 400 | 400 |
| 5: | 0 | 200 |
| 6: | 400 | 200 |

| *Edge File* | | | |
|---|---|---|---|
| 1 | 2 | 24.0 | 40.0 |
| 2 | 3 | 20.0 | 40.0 |
| 3 | 4 | 24.0 | 40.0 |
| 5 | 6 | 20.0 | 40.0 |

Line two of the edge file, for instance, specifies that there is a section of conductor between vertex 2 and vertex 3 with an attenuation rate of 20 dB per 305 m and a minimum inductive coupling loss of 40 dB.

In the example of Fig. 3, three nodes are depicted near the conductors. Node A can communicate with node B, provided the cumulative loss is sufficiently low. However, because conductor section 2-3 is not connected to section 5-6, nodes A and C are unable to communicate. If, however, a new vertex were introduced at the intersection of edges 2-3 and 5-6, to model coupling between the two conductors, then a path would exist between nodes A and C.

## IV. Sample Results

This section presents the results of a sample mine communication scenario that was simulated by the system described above.

### A. Topology

The topology of the scenario is illustrated in Fig. 4. Blue lines indicate metal conductors and discs represent network nodes. Node 'G' represents a gateway node with access to the surface. The other nodes, labeled 2–6, represent other MF transceivers either carried by individual miners, positioned near a group of miners, or serving as relays.

All conductors in this example were assigned an attenuation rate of 24 dB per 305 m and a minimum inductive coupling loss of 40 dB.

### B. Traffic Model

The application traffic of this scenario consists of PTT voice considered in two separate cases. In the first case, nodes G, 4, 5, and 6 form a multicast group, and voice traffic originated from each member of the group is destined to all the other members of the group, with only one member transmitting at a time. In the second case, two unicast PTT sessions operate concurrently, one session between nodes G and 4, and another session between nodes 5 and 6.

The PTT traffic is generated using statistics based on an analysis of public safety traffic on a trunked land mobile radio system [5]. This study found that the PTT hold time could be approximated as having a lognormal distribution, with an underlying normal random variable having a mean of 3.9 s and a standard deviation of 3.3 s, and that the inter-hold time had an exponential distribution with a mean of 8 s. Fig. 5 illustrates a 60 s slice of the generated PTT traffic for the case of the multicast group with four sources.

### C. Performance Evaluation

This scenario was simulated for a post-accident scenario, meaning that packet error rates for Gaussian noise were used (see Section III-A). The noise floor was set to $-121$ dBm, and the transmission power was set to 37 dBm.

Among the network performance metrics generated by the simulation is a measure of the transmission reliability of the end-to-end communications path known as the *packet delivery ratio*, or the ratio of the number of packets successfully received by the destination to the number of packets transmitted by the source. Another important metric is the *end-to-end delay*, or the duration of time between the transmission by the source and reception by the destination. Delay is particularly important for real-time interactive applications such as two-way voice.

Fig. 6 plots the network delay of node G's packets as a function of time for the case of group multicast communication. We observe delays of three different levels, at approximately 44 ms, 66 ms, and 88 ms, corresponding to 2, 3, and 4 packet transmission times. (Recall that each packet takes 22 ms to transmit.) The minimum delay is 44 ms because the shortest path in the given topology is G-2-6 requiring at least two transmissions, the original transmission by node G and a

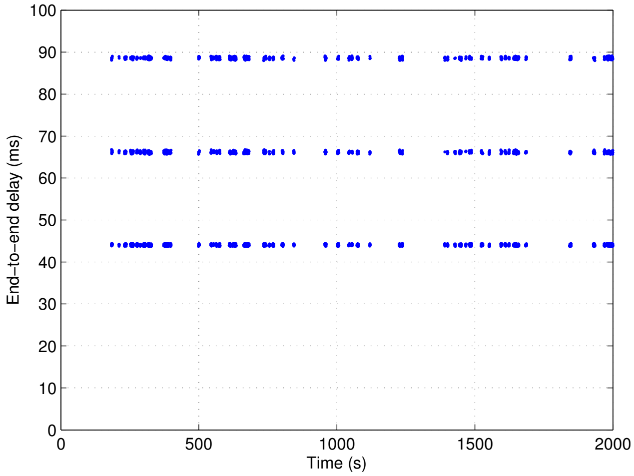
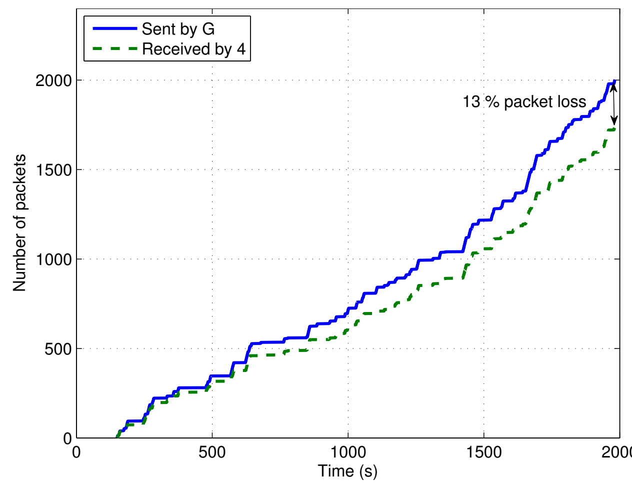
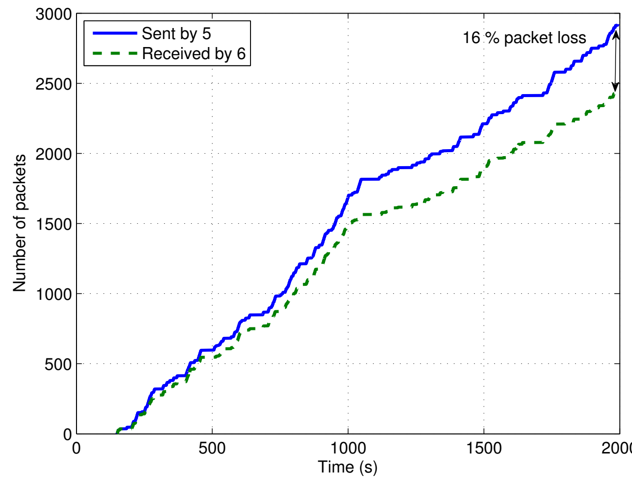



Fig. 6. End-to-end delay, group multicast




(a) node G to node 4




(b) node 5 to node 6

Fig. 7. Number of packets sent/received vs. time, unicast

relayed transmission by node 2. The paths to nodes 4 and 5 require at least three transmissions (G-2-3-4 and G-2-3-5). The maximum delay of 88 ms (or 4 packet transmission times) is due to the contention between nodes 3 and 6. Based on the random backoff time selections of nodes 3 and 6, sometimes node 3 must defer to node 6 before it can relay its packet to nodes 4 and 5. In any case, these delays are quite reasonable for interactive PTT communication.

The percentage of packets lost in the multicast scenario above is less than one percent. Link SNRs in this scenario in the absence of MAI are sufficiently high that the only losses occur for the low likelihood of cases that two nodes choose the same random backoff time resulting in a packet collision (i.e., high MAI).

Fig. 7 shows the cumulative number of packets sent and received over time for the concurrent unicast PTT traffic from node G to node 4 (Fig. 7(a)) and from node node 5 to node 6 (Fig. 7(b)). In this case, we observe overall packet loss rates of 13 % and 16 %, respectively, owing to the collisions between the two sessions. Unlike the previous case in which the nodes were part of a single group and only one member could speak at a time, in this case there are two independent sessions sharing a limited channel and resulting in some packet collisions. Depending on the voice decoder, such packet loss rates may result in degraded voice quality.

### *D. Scenario with Mobility*

The scenario described above was for a fixed topology. The following illustrates a simple example of a scenario with mobility. Fig. 8 shows the topology consisting of nodes G, 2, and 3 at fixed locations along the conductor. Node 4 is a mobile node that moves from one end of the conductor to the other starting at node G, at a pedestrian speed of 1 m/s. During the simulation, nodes G and 4 are engaged in a two-way PTT session.

Fig. 9 is a screen shot of the simulation of this mobile scenario. A time controller window (lower left corner) permits the user to launch, pause, and rewind the simulation while

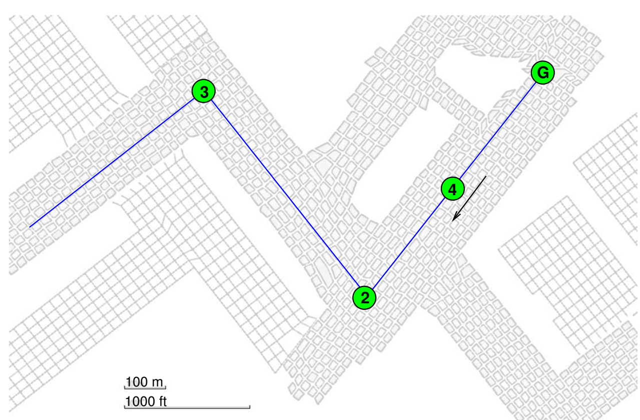



Fig. 8. Topology of mobile scenario

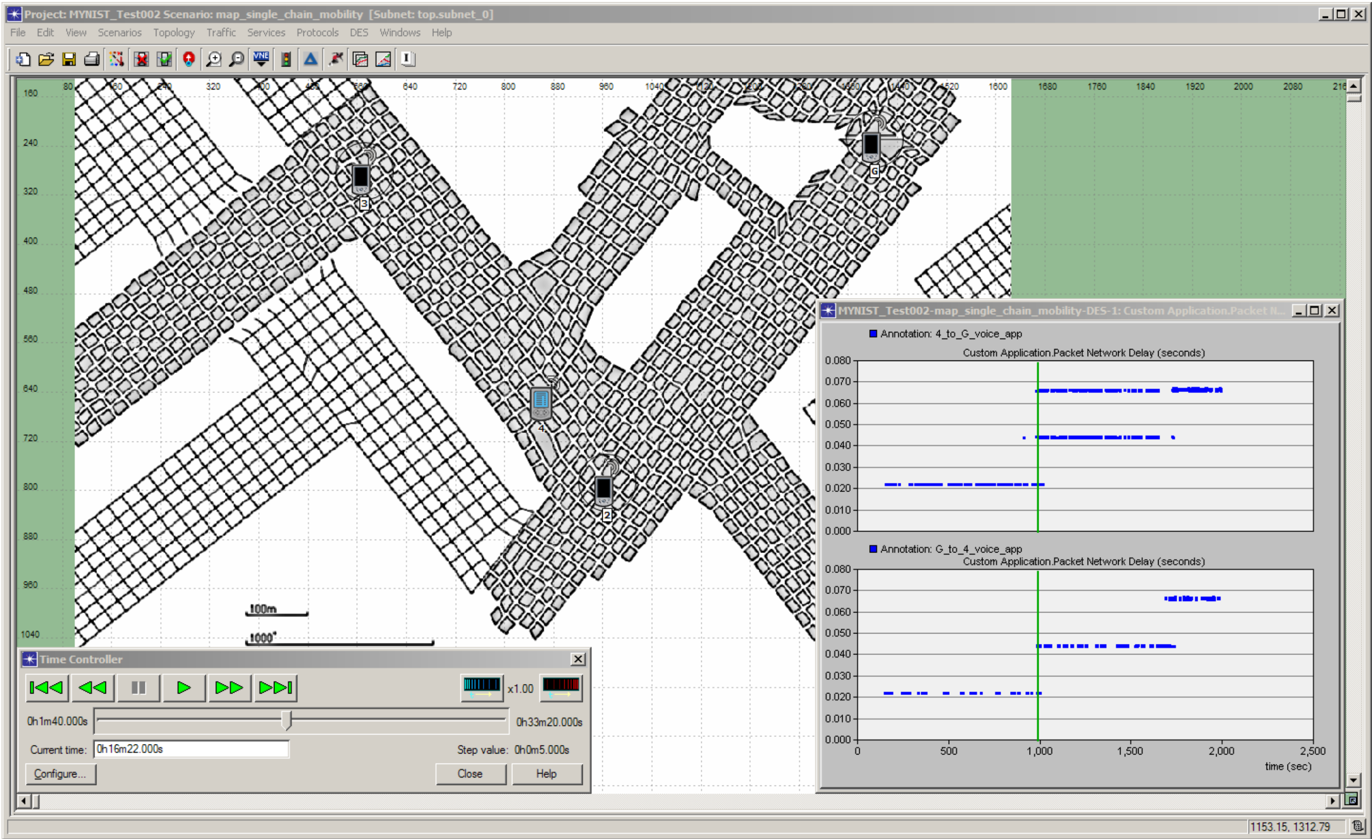



Fig. 9. Screen shot of simulator running mobile scenario

observing the changing topology in the main window. In addition, performance results, such as the end-to-end delay shown in the lower right corner, can be viewed in relation to the simulation clock. For example, the snapshot in Fig. 9 shows node 4 located between nodes 2 and 3. As seen in the delay plots, at this point in the simulation the delay from G to 4 (bottom half of delay results) is transitioning from 22 ms to 44 ms (i.e., from one packet transmission time to two packet transmission times), as node 4 leaves the communication range of G and receives the packets relayed by node 2. The delay in the other direction, 4 to G (top half of delay results), is as high as 66 ms (three packet transmission times) because of the contention and randomly selected backoff of nodes 2 and 3 upon receiving a packet from node 4: sometimes node 2 transmits before node 3, resulting in a total delay of 44 ms, and sometimes node 3 transmits before node 2, resulting in a total delay of 66 ms.

## V. Conclusion

This paper described a simulation system to model the performance of a medium frequency mesh network, the basis of a proposed post-accident communication system in an underground mine. The simulation system can be used to evaluate implementation options of the network and as an initial step in planning and designing a deployment in a mine. In terms of implementation options that can be evaluated, additional modulation schemes beyond MSK could be modeled as well as forward error correction codes such as Reed Solomon codes and convolutional codes. Analyzing these varitations would simply entail entering PER tables for the modulation-coding schemes of interest. In addition, more sophisticated network routing protocols than simple flooding could be analyzed, such as ad hoc on-demand distance vector (AODV) routing, which may be more efficient in large deployments. Among the enhancements that can be made to the simulation system, the conductor model can be improved to account for coupling losses between nearby conductors as well as losses due to breaks and gaps in a conductor.

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