Properties of Mobile Tactical Radio Networks on VHF Bands

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ABSTRACT

This work extends a network model that was developed for the study of mobile tactical scenarios employing VHF combat radios. The model uses VHF radio signal measurement data, integrating practical network deployment scenarios and node mobility models to evaluate network link probabilities, and to derive fundamental network properties including the average network node degree, network connectivity strength, network path hop count distribution and dynamics of network link updates. The results illustrate important network characteristics and provide insights for assessing applicability and optimization of network protocols for tactical radios operating in the VHF band.

1.0 INTRODUCTION

Mobile Tactical Networks (MTN) that use tactical radios operating in the VHF military bands [4-5] offer the potential for improved coverage and scalability through self-forming multi-hop capabilities. The MTN aims to deliver realtime integrated voice and data across command posts, vehicles and dismounted soldiers to provide enhanced C2 and situational awareness in the military operational theatre.

To support the multi-hop networking functions required by the MTN, many recent protocols proposed for mobile ad hoc networks (MANET) [6-9] may be considered candidate solutions. However, most of these proposals assume WiFi (e.g., IEEE 802.11) radios when conducting protocol analysis and simulations. The communication properties exhibited by VHF tactical radios are very different from those of generic WiFi radios, e.g., limited bandwidth and different signal path loss properties. To establish effective network protocol design guidelines and to evaluate networking solution options pragmatically, it is important to understand the fundamental properties of MTN in typical operational scenarios.

The purpose of this work is thus to investigate the network characteristics of MTNs in a practical deployment scenario. The approach taken combines an analytical network model [1], tactical VHF radio signal measurement data [2-3] and realistic mobility scenarios, taking into account different terrain types. In the model, numerical computations are applied to calculate the changing distance matrix of the network nodes through the duration of network simulation to capture the topology updates. The model computes the network link and path probability matrices, the network node degree, the link update ratio, the path length and cost distribution, etc. The results obtained illustrate the fundamental network properties of the MTN, which provide significant insights for assessing applicability and optimization of the mobile ad hoc network protocols and schemes in the MTN environment.

The rest of the paper is organized as follows: section 2 briefly describes the network model; the network deployment scenario is presented in section 3; section 4 illustrates the network properties obtained and section 5 concludes the paper.

2.0 NETWORK MODEL FOR MOBILE VHF NETS

The network model employed in this study is established for a mobile tactical network applying comprehensive radio signal measurement data [1-3]. As described in [1], the network model is based on an undirected geometric random graph where a tactical link is described using $p(r_{ij}, t)$, which is the probability of having a link between node i and j at distance metric r_{ij} at time t [1, 10]. The mobility scenario generator BonnMotion [12] is employed to produce MTN deployment scenarios for the model. The output file of BonnMotion traces the trajectory of each node by logging positions of the node through time. Then given a time interval sampled at instants n*T*, i.e., $t = \{T, 2T, \ldots, nT, \ldots\}$, the 2-dimensional position coordinates of all nodes in the network at each sampling instant t are collected in the $N \times 2$ position matrix $X_{N\times 2}(t) = \{(x_{i1}(t), x_{i2}(t)) \mid i = 1,2,\ldots N\}$, where N is the total number of radio nodes. A distance matrix is then formed for all nodes at each sampling instant as $d_{N\times N}(t) = \{d_{ij}(t) \mid i, j = 1,2, \quad \ldots, N\}$, where $d_{ij}(t) = \sqrt{\sum_{k=1,2}(x_{ik}(t) - x_{jk}(t))^2}$. Matrix $d(t)_{N\times N}$ is then applied to calculate $p(r_{ij}, t)$, using the radio signal measurement data taken in the terrain type of the deployment field [2, 3], as described in [1]. With T sufficiently small, the resulting $p(r_{ij}, t)$ characterizes the network link status through the entire modelling duration. Given $p(r_{ij}, t)$, the average node degree, the probability that a link changes its state at any given time t, and the expected number of links that change states at any given node i at time t can all be derived as presented in [1].

To gather the network connectivity information, path probability matrices of the network for both voice and data packets are computed at each sampling time t. Realtime voice traffic requires paths of high availability and low latency, without performing retransmissions even if errors occur in the reception. The path matrix for voice $VP[t]$, with (i,j)th element $vp_{ij}[t]$, is computed assuming that the transmission from source to destination prefers all the intermediate hops to be available simultaneously, and that the link probabilities are independent of each other. A modified Floyd shortest path algorithm is used selecting the maximum path probability [1] as:

```
$VP[t] = [p(r_{ij}, t)];$

for $k =$ 1 to $N$ do

 for all $i, j,$ do

   If $(vp_{ij}[t] < p_r)$, $vp_{ij}[t] = \max(vp_{ij}[t], vp_{ik}[t] \times vp_{kj}[t])$; where $p_r$ is the error threshold.
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Other auxiliary data structures are included in the path computation algorithm to capture the list of hops contained along each path; these are not shown here to keep the descriptions succinct.

Denote the required delivery ratio of voice packets as p_{dr}. L_p is the length of the packet and p_b is the BER. The error threshold is $p_r = \dfrac{p_{dr}}{(1 - p_b)^{mL_p}}$ for a path of m hops, assuming independent bit errors. Taking the NATO standard MELPe voice format of 7 bytes per frame and 4 frames packed into one voice packet to enhance the transmission efficiency as in many common implementations, an example voice packet size is assumed containing 50 bytes, i.e., L_p =400, including headers in compressed format. The voice paths are computed at each sampling time t using p_{dr} =95% and p_b =10^{-6}.

The path for data communications differs from that for voice. Data communications tolerate end to end latency but not errors. Retransmissions will be used, such as in the per-hop ARQ scheme to ensure reliable delivery. In this case, the "hop cost" is formulated as the expected number of transmissions taken for the packet to traverse a hop. This hop cost represents the spectral cost in terms of "number of sends", approximating the occupancy of timeslots in a TDMA network. As earlier, the link probability between nodes i and j at time t is $p(r_{ij},t)$, hence the probability that a packet is successfully received is $p = p(r_{ij},t)(1-p_b)^{L_p}$. The probability that node i receives the acknowledgement (ACK) from j after sending a packet is $p(1-(1-p)) = p^2$, assuming only one ACK is sent for each received packet. Then the expected number of times that node i sends the packet is $\frac{1}{p^2}$. At each time, the probability that a sent packet is received successfully at j is p. If received correctly, a single ACK is generated. The total expected number of ACKs sent by node j for this packet is then $\frac{1}{p^2} \times p \times 1 = \frac{1}{p}$. The total expected number of packet transmission attempts and acknowledgements sent across the hop between nodes i and j, which is the spectral cost of the hop, is thus:

$$w_{ij}(t) = \frac{1}{p} + \frac{1}{p^2} = \frac{1+p}{p^2}.$$

The path matrix for data, $DP[t]$ with its (i,j)th element $dp_{ij}[t]$, is thus computed as:

```
$DP[t] = [w_{ij}(t)];$
for $k =$ 1 to $N$ do
 for all $i, j$, do
   $dp_{ij}[t] = \min(dp_{ij}[t], dp_{ik}[t] + dp_{kj}[t]);$
```

The above two algorithms generate the path matrices for voice and data at each sampling instant during the modelling time of the network. The results will be illustrated in Section 4.

3.0 NETWORK SCENARIO

The network mobility traces are generated using the mobility scenario generator BonnMotion [12]. The semi-rural area is selected for network deployment, using the measurement data taken from this type of terrain [2-3]. The semi-rural environment measured has a significant amount of rural and forested areas, some overgrown farm fields and a few two or three story brick buildings [3].

The scenario has 38 deployed radio nodes in a field of 400 km^2 (20 km by 20 km), which is divided into four 10 km by 10 km non-overlapping quarters. Among all the nodes, 3 of them form a commander group positioned in the area of 5 km by 5 km at the center of the field. A group of 8 nodes is deployed in each of the four quarters. The commanders and the 4 groups are all running the reference point group mobility (RPGM) model [11]. The remaining three are individual nodes with assigned tasks such as reconnaissance or special operations. These three nodes move in the entire field of 20 km by 20 km according to a random waypoint model. Except the commander group, all the nodes travel in the speed range of 8.3 – 22.2 m/s with an average pause time of zero to 10 minutes. The commander group has an average pause time of 30 minutes and moves between the speed levels of 0 - 8 m/s. Within each group, the maximum distance from any node to the group center varies between 3 km and 5 km. A total of 10 networks are generated to average the computation results. The modelling time for each network is 9000 sec and the sampling interval is chosen to be 3 sec for semi-rural scenarios, which is sufficient to capture the updates caused by the defined mobility.

Figure 1 below illustrates some snap shots of one of such networks generated in the model, at different sampling times.

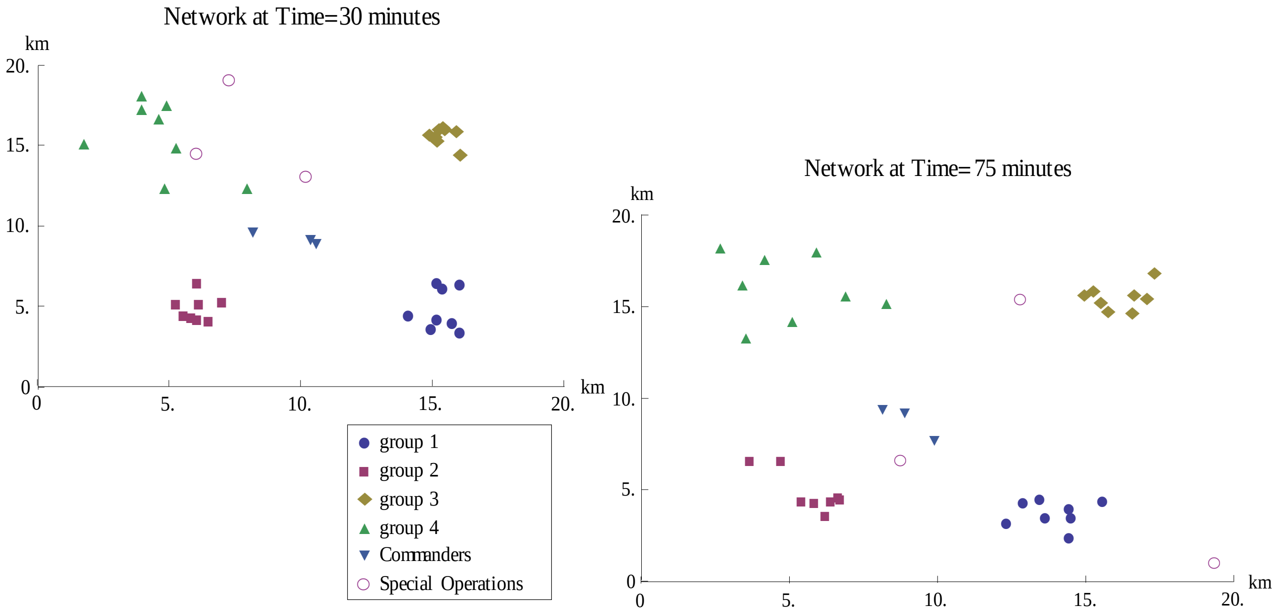


Figure 1 Tactical network deployment scenario example

4.0 NETWORK PROPERTIES

The radio signal frequency is at 57.0 MHz with channel bandwidth of 25 kHz. The data rates range from 20kbps to 96 kbps. The transmission power is 46 dBm for vehicle mounted unit. The reception noise floor in the field is -126 to -95 dBm. The required SNR for achieving the data rate, depending on the radio design, may range from 6 dBm to 23 dBm. From these parameters, the path loss margin is estimated to be around 140 dB. Given the reference distance $d_0 = 100$ m, the path loss parameters computed from the measurement data have the exponent η =3.18, the intercept $\alpha(d_0)$= 68.8 dBm, and the standard deviation of the shadowing δ = 4.11 dBm, for the selected terrain of semi-rural. Then applying the algorithms presented in the previous section and the formulas in [1], the link probability $p(r_{ij}, t)$ at each sampling instant *t* is obtained, which leads to the node degree distribution, as shown in Figure 2.

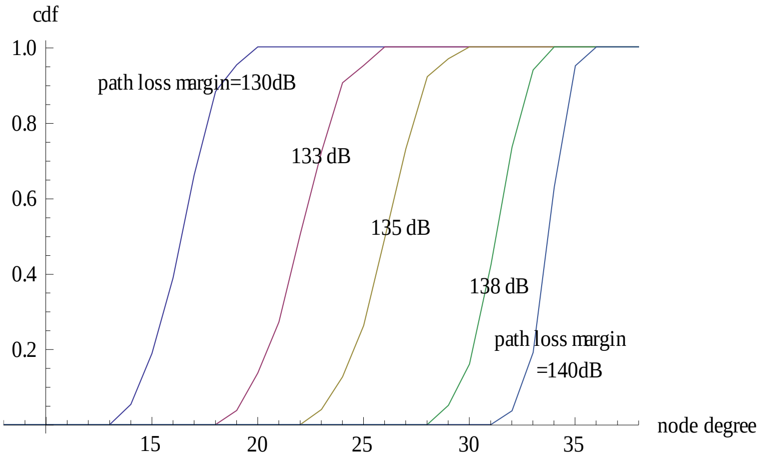


Figure 2 Distribution of network node degree

The average node degree varies from about 17 nodes to 33 nodes when the path loss margin changes from 130 dB to 140 dB, which is fairly high. To find out how the network connectivity is impacted under the different network conditions, the average network connectivity level $C_l(t)$ is defined as:

$$C_l(t) = \frac{2\sum_{i=1}^{N}\sum_{j=i+1}^{N}\gamma(i,j,t)}{N\times(N-1)} ,$$

where $\gamma(i,j,t)$ is the largest path probability between node *i* and *j* computed over all possible routes at time *t*. Note that $C_l(t)$ is the ratio of the expected number of paths over the total number of routes (node pairs) in the network. The matrix $\Gamma(t)=[\gamma(i,j,t)]$ is obtained by applying the voice path computing algorithm with p_r =1. The network $C_l(t)$ s for path loss margin of 130 dB and 140 dB are plotted in Figure 3 (a), showing the variation through the entire 9000 seconds of network modelling time. A network connectivity level of “1” indicates a fully connected network between all node pairs. It can be seen that when the average node degree decreases from 33 to 17, the network connectivity level moves from close to “1” all the time, to ranging between 85% and 99%.

Taking any of the three commander nodes in the network, its average path probability to all the other nodes in the network, referred as the average “overall path probability”, can be computed at each sampling time *t*. It is found that the average overall path probability of any of the commander nodes is closely related to the network connectivity level $C_l(t)$. In Figure 3 (b), the average overall path probability of one of the commander nodes is plotted together with the network connectivity level $C_l(t)$, for path loss of 140 dB, to illustrate this observation. The implication of this relationship is elaborated on later in the section.

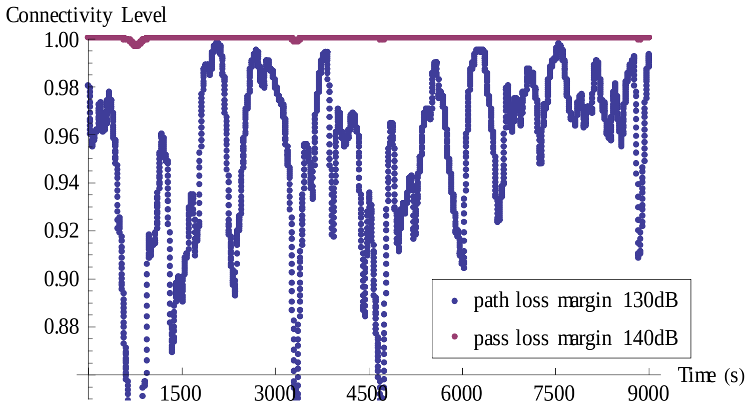


Figure 3 (a) Average network connectivity levels

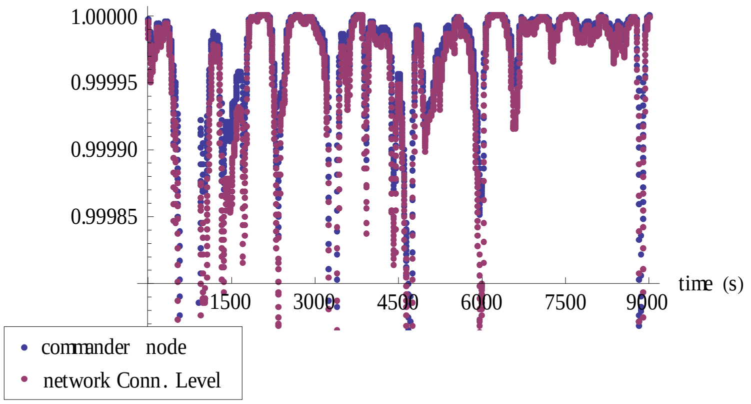


Figure 3 (b) Average overall path probabilities of commander nodes vs. network connectivity level

The voice path matrix VP[t] is computed with p_{dr} =95%, yielding the distribution of the voice path length in the network, which is depicted in Figure 4, for networks with average node degree ranging from 17 to 32 nodes, i.e., the path loss margin of 130 to 140 dB. When the path hop count is larger than three, the end-to-end throughput delivered on the very low speed tactical links may be practically too small and the latency too high. When the average node degree is below 25, i.e., the path loss margin <135dB, certain voice path will extend to more than 3 hops, causing QoS concerns. A practical MTN is often connected with many nodes within 1 hop and others reachable through a single relay. A few nodes at certain times may temporarily require two relay nodes to connect when they are separated due to path obstacles. Such strong connectivity maintains the high reliability and low latency required by tactical communications. At a path loss margin of 140 dB, the network is connected with nodes mostly 1 and 2 hops apart, and only a few paths traversing 3 hops. The average smallest best possible path probability found in matrices (t) was then 0.985, representing a strongly connected tactical network.

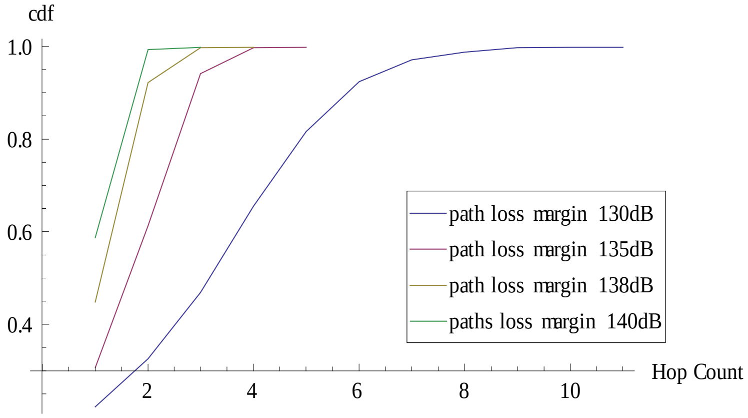
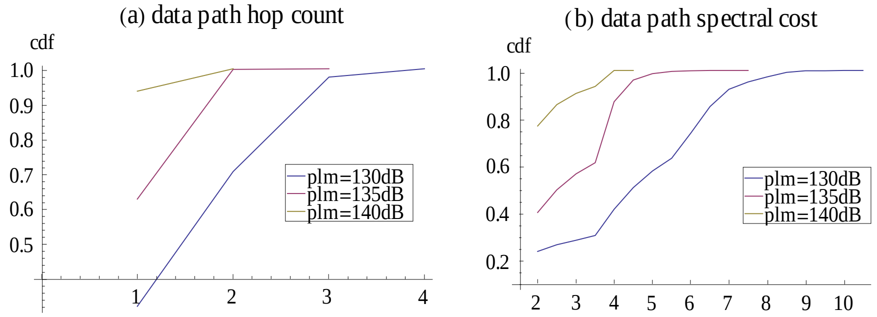


Figure 4 Distributions of voice path hop counts

The data path matrix DP[t] is computed by applying the algorithm presented in the previous section. The distribution of data path hop counts is illustrated in Figure 5(a) for different path loss margins (denoted as "plm" in the figure). It can be seen that data paths have relatively shorter hop counts than voice paths. However, because of the required reliability and the ARQ transmission scheme, the real sending cost on a data path is different from its hop count. On a single hop, two sends or even more will be needed to deliver a single data packet successfully. Each send consumes bandwidth and power. Thus the real cost of data paths is calculated as the number of transmissions required for a successful packet delivery, as the "path spectral cost", described in the algorithm presented in the previous section. The distribution of the data path spectral cost is illustrated in Figure 5 (b). The cost of data paths in the network is relatively higher than the voice path, because the send cost of voice traffic is the same as the hop count of its path.


(a) data path hop count

(b) data path spectral cost

Figure 5 Distributions of data path hop counts and costs

The probability that a link changes its state from sampling instant *t-1* to *t* can be calculated as [1]:

$$p\_linkChange(i, j, t) = (1 - p(r_{ij}, t-1))\, p(r_{ij}, t) + p(r_{ij}, t-1)(1 - p(r_{ij}, t))$$

The link between node *i* and *j* incurs a state change from time instant *t-1* to *t*, if there is a link between node *i* and *j* at time *t* while none existed at time *t-1*; or there is no link between node *i* and *j* at time *t* while there was one at time *t-1*. The distribution of the percentage of links that change their states across each sampling interval is depicted in Figure 6. In comparison, when the node degree is around 17, i.e., path loss margin is 130 dB, on average more than 23% of the links in the network experience state changes in the 3 sec sampling interval. This amounts to about 150 links changing their state at a given time in the network.

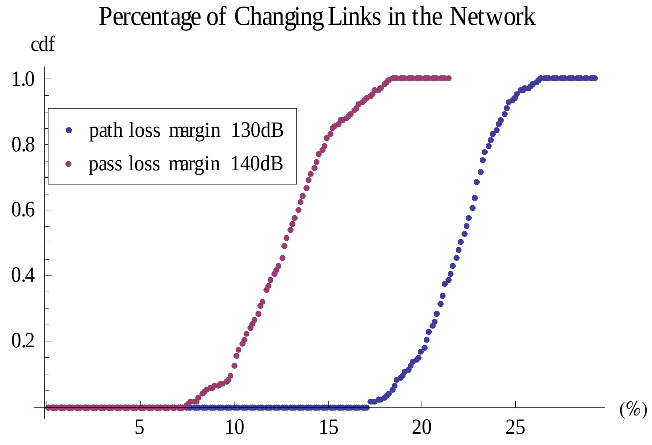


Figure 6 Percentage of changing links per sampling interval

The above results illustrate the basic structural and dynamic network properties of the selected typical VHF tactical deployment scenario. It can be seen that the network has a relatively dense neighbourhood with nodes having high average node degrees. When average network node degrees decrease, the path hop counts will increase. To maintain the useful voice paths in the network without too many traversing hops, the node degree may need to stay quite high, e.g., about 17 to 20 nodes on average. However, the increase in data path spectral cost is even faster than the increase of the hop counts. Hence to maintain a low cost for data communication paths, the average node degree may need to be even higher. For low node degrees, there may be an average of 6 sends for a data packet along the path. With a high node degree and very limited link bandwidth, e.g., 20 kbps to 96 kbps of shared link rates for the next generation NATO narrowband waveforms operating in the typical 25 kHz VHF channel, a protocol updating the two hop neighbourhood information, e.g., the popular HELLO protocol [6-10] may result in a fairly heavy traffic overhead in the shared neighbourhood, when node degrees are so high [13]. In general, the comprehensive exchange of link status information can be quite costly in such densely formed networks. Even when the node degree decreases, e.g., if the path loss margin is reduced to 130 or 135 dB, the number of links that need to report an update would increase, which produces more data in the update messages [1, 13].

It should also be noted that this network configuration concentrates the highest node degrees on the commander nodes. As shown in Figure 7, which depicts the average node degrees of each of the 38 nodes in the network, the commander nodes, numbered as node 33, 34 and 35, have much higher average node degree compared to the other nodes. In fact, the commander nodes become the major relay nodes for network paths. On one hand, this fortifies the connections between the commander nodes and the rest of the network, which is desirable; but on the other hand, it leads to increased congestion and contention in the neighborhood of the commander nodes, and increases their vulnerability. This also explains the result illustrated in the Figure 3(b). As major relay nodes, the average overall path probabilities observed by the commander nodes reflect the overall connectivity strength among all nodes at that time. This property may lead to a network route and topology control strategy for this type of network deployment scenario that exhibits a central area. The nodes placed in the central area will not only become the hub/relay points, but also have visibilities on network connectivity situations. Such nodes can even be dedicated hub/central nodes if it is desirable to shield the commander nodes from the vulnerability and heavy traffic load entailed in being in the role of network hubs. Then the commander nodes may maintain a one hop strong connectivity to these central relay nodes to achieve their strong network reachability as well as network situational awareness.

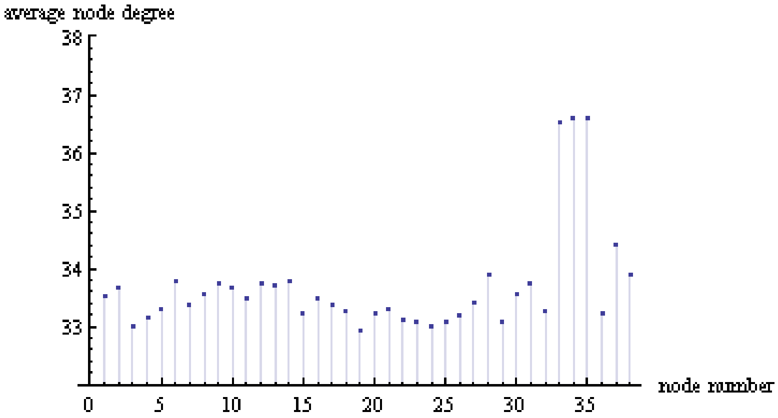


Figure 7 Average node degrees for all nodes in the network

5.0 CONCLUDING REMARKS

In this paper, real VHF radio signal measurement data are applied to study the network properties of mobile VHF radio networks in a typical deployment scenario. This is accomplished using a geometric random graph integrating tactical mobility scenarios with radio measurement data to establish a network model. The model is further extended to capture the important properties of the network such as the link probability, the path probability, the path hop counts and the network connectivity strength. These models have identified the fundamental structural and dynamic characteristics of the network formed. The results indicate the possible heavy overhead cost of popular networking protocols when updating two-hop neighbour information in the dense network neighbourhood. It has also demonstrated the critical role of the central/hub nodes in such deployment scenarios when network hop counts are small. The different path hop count distributions for voice and data traffic call for a suitable path selection mechanism to support their different QoS requirements. It is evident from this study that the network properties of mobile tactical radio networks need to be considered when designing and optimizing networking solutions.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

[1] L. Li and T. Kunz, “Efficient Mobile Networking for Tactical Radios”, Proceedings of IEEE MILCOM 2009, Boston, MA, USA, Oct 2009

[2] J. Pugh, R. Bultitude, and P. Vigneron, “Path Loss Measurements With Low Antennas for Segmented

Wideband Communications at VHF", Proceedings of IEEE MILCOM'06, Washington DC, Oct 2006

[3] J. Pugh, R. Bultitude, and P. Vigneron, "Propagation Measurements and Modelling for Multiband Communications on Tactical VHF Channels", Proceedings of IEEE MILCOM'07, Orlando, Florida, Oct. 2007

[4] H. Wang, et al., "Implementing Mobile Ad hoc Networking (MANET) over Legacy Tactical Radio Links", Proceedings of IEEE MILCOM 2007, Orlando, Florida, Oct 2007

[5] A. Blair et al., "Tactical Mobile Mesh Network System Design", IEEE MILCOM 2007, Orlando, Florida, Oct 2007

[6] L. Villasenor-Gonzalez et al., "H-OLSR: A Hierarchical Proactive Routing Mechanism for Mobile Ad hoc Networks", IEEE Communications Magazine, Vol. 43, No.7, Jul 2005

[7] J. Luo et al., "A Survey of Multicast Routing Protocols for Mobile Ad-hoc Networks," IEEE Communications Surveys & Tutorials, Vol 11, Issue 1, 2009

[8] G. Pei, M. Gerela and X. Hong, "LANMAR: Landmark Routing for Large Scale Wireless Ad Hoc Networks with Group Mobility", in Proceedings of IEEE/ACM MObiHoc 2000, Boston, MA, Aug. 2000

[9] R. Rajaraman, "Topology control and routing in ad hoc networks: a survey", ACM SIGACT News. Issue 33, 2002

[10] Ramin Hekmat, "Ad-hoc Networks: Fundamental Properties and Network Topologies", Springer, 2006, ISBN-10 1-4020-5165-4

[11] X. Hong, M. Gerla, G. Pei and C.-C. Chiang, "A Group Mobility Model for Ad Hoc Wireless Networks", in Proceedings of ACM / IEEE MSWiM'99, Sealttle, WA, Aug. 1999

[12] "BonnMotion - a mobility scenario generation and analysis tool", http://iv.cs.uni-bonn.de/wg/cs/applications/bonnmotion/, Univ. of Bonn, 2002

[13] L. Li and T. Kunz, "Efficiency of Multiparty Networking Protocols over Mobile Tactical Radios on VHF Bands", too appear in Proceedings of IEEE MILCOM 2010, Nov. 2010, San Jose, CA.