Improving the Performance of Land Tactical Digital Networks Using Measures of Network Capacity

Andrew Coyle and Hung Nguyen
Centre for Defence Communications Information and Networking
The University of Adelaide
Adelaide Australia
andrew.coyle@adelaide.edu.au

Peter Boyd and Gregory Judd
Land Division
Defence Science and Technology Group
Adelaide Australia

***Abstract*—Land tactical radio networks are used in military operations to create communication channels for tactical units at the force's edge. These radios must work in a dynamic, contested environment where bandwidth is usually at a premium due to the limited radio capabilities and the many demands placed on the system. It is important therefore to manage the networks as efficiently as possible. Measuring the state and performance of the network is required to achieve this, which is a non-trivial exercise due to the complexity and variability of network designs. Any measurement schema must take into consideration the implementation, state and use of the radio network. Previous work in this area has concentrated on commercially available networks rather than the bespoke networks that are often employed in the military. As part of the SMARTNet research programme, this paper looks at techniques that are currently available for measuring a tactical network's performance, investigates what other work needs to be done, and suggests a way forward. A simple network has been analysed mathematically and then emulated using the Enhanced Mobile Ad-hoc Network Emulator (EMANE) to highlight the issues discussed in this paper.**

Keywords—MANET, Measurement, TDMA

I. Introduction

The advent of digital messaging over land tactical edge radio networks has led to greatly increased amounts of information being exchanged at a much increased rate. As a result, human communicators can no longer effectively prioritise and control the information disseminated across these networks without automated help. Current tactical automated information systems however, do not manage this information anywhere near as intelligently as a human would if they could. As part of a collaborative SMARTNet research programme, Defence Science and Technology Group (DSTG) and its international, academic and commercial collaborators are investigating how the 'intelligence' of these automated tactical information management systems can be improved.

A key challenge is the vastly increased complexity of land tactical networks. This is especially the case when using Mobile Ad-hoc Network (MANET) technologies designed to support military and emergency services when the usual civilian communications wireless networks are not available. When nodes in a MANET rapidly change location in complex terrain the effect is much reduced bandwidth and rapidly changing levels of connectivity. This in turn, makes it extremely difficult to understand current network capacity in order to avoid flooding an already overloaded network. Without this up-to-date capacity information however, an automated information management system cannot effectively prioritise and throttle traffic flows.

It is important therefore, to measure the state of a network before determining whether data should be transmitted, and what priority these data should be given. At the simplest level if there is no path to a unit, then there is little point in loading a network with traffic. Metrics such as the link and path connectivity, delay, loss and load should be measured throughout the network. These metrics can then be used to control the flow of data into and across the network. In many military MANETs some of this information may already have been collected by the radio, but this information is often unavailable to other users or applications. The question therefore is what aspects of a network can, or should, an 'intelligent' information management system measure and how can this be achieved?

Most previous measurement research either concentrates on networks that use the IEEE 802.11 MAC protocol or completely ignore lower layer and other context information. We show in this paper how a bandwidth measurement approach could be tailored for Time-division Multiple Access (TDMA) MANETs that uses network context information to improve measurement accuracy while reducing overheads. The concepts in this approach should also be applicable to other network types and configurations. We show, using a simple network emulation, that our approach achieves accurate bandwidth estimation results with minimal measurement overhead.

The remainder of the paper is laid out as follows. Section 2 looks at issues of measuring a MANET's performance. In Section 3 research previously undertaken in this field is investigated. In Section 4 an exemplar application needing network measurement is presented. Section 5 demonstrates, with a simple example, how an understanding of a network's protocols and parameters enables better measurement techniques to be created. Section 6 shows some results using the EMANE emulated framework. Section 7 is the conclusion.

II. BACKGROUND

A MANET has several defining characteristics including: limited capacity wireless links, no central control, and the topology is dynamic. These lead to uncertain, variable, and often limited, network bandwidth conditions creating the necessity for controlling the amount of traffic entering the network. There are several implementation decisions that can significantly affect the performance and stability of these networks; including: Medium Access Control (MAC), the routing protocol, prioritisation mechanisms, protocol support, signal modulation technique, network size restrictions and more. All of these factors influence the behaviour and performance of the MANET. The choice of MAC is one of the most important factors in the behaviour of a MANET and this paper will focus on the impact of the MAC to explore challenges with measurement and management techniques.

The two main classes of MAC that MANETs use are the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and Time Division Multiple Access (TDMA) MAC, see for example [1]. The behaviour of these two MAC protocols is quite different. The CSMA/CA protocol senses the wireless channel, and uses the Request to Send/Clear to Send (RTS/CTS) mechanism to gain access to a channel. The CSMA/CA protocol is used for Wi-Fi MANETs since it works well in unlicensed spectrum. Only nodes on the same network use the RTS/CTS protocol, other competing nodes on the same frequency only listen to this, they do not participate. However, CSMA/CA can be unfair, lack an efficient priority mechanism, and can result in a congested network when over utilised.

For this and other reasons several military MANETs use variations of the TDMA protocol. The TDMA protocol assigns time slots to individual users, allowing transmission only during their slots and avoiding contention with other users. Slot allocation may be fixed, dynamically assigned based on request, or assigned using a hash number assignment. In contrast to CSMA/CA networks there has not been a lot research looking at measuring TDMA networks. Whilst some of the previous work can be utilised, better approaches will work by considering the particular nature of the TDMA networks. This paper explores these issues.

III. RELATED WORK

Bandwidth estimation of a network link and path is the most researched topic in MANET measurements since the outcomes are directly used in adaptable routing and flow control algorithms. We concentrate in this work on *available bandwidth,* which is the maximum unused bandwidth at a link. The available bandwidth of a path at any given time is the minimum available bandwidth of all the links in the path. Bandwidth measurement techniques for MANETs can be grouped into three groups: (1) model based approaches, (2) active probing approaches and (3) passive measurement approaches.

In a model based approach, mathematical models are developed to predict link and path available bandwidth. There have been a few analytical models for the 802.11 Distributed Coordination Function (DCF) ad hoc networks, each with their own set of assumptions. An early example of this approach is the work of Bianchi et al [3] that used a two- dimensional Markovian model to develop a closed-form expression for saturation throughput of 802.11 based networks. The model assumes that the channel is in ideal conditions, i.e., there is no hidden terminal and capture effect. There have been several extensions to Bianchi's model for realistic network conditions [4], [5] and [6]. It should be noted that these models have focused on 802.11 networks and are not applicable to other MANET implementations.

Active probing techniques estimate the available bandwidth by injecting probes into the network. Active probing offers deployment flexibility and controllable measurements. However, the probes introduce additional load to the network, degrading network performance and affecting the accuracy of the bandwidth estimation. The probes can be purely application layer based without the need for information from the lower layers. These tools include pathChirp [7], pathload [8], WBest [9] and Ad Hoc Probe [10]. Other techniques combine active probes with detailed knowledge and information at the MAC layer to provide better estimate of link available bandwidth for IEEE 802.11 MANETs. These works vary greatly in the details of the 802.11 MAC layer that they model, see [11] to [14].

It was found in [15] that Ad Hoc Probe [10], a packet pair tool, was incompatible with TDMA-based links. If both packets in a pair could fit into a single time slot, there was no correlation between the packet dispersion and the path capacity. If, however the packet-pair could not fit into a single time slot, there was correlation, but the estimates were biased to severely over- or underestimate the path capacity for packet sizes that did not correspond exactly to the size of a time slot. In general, the amount of data that fits into a time slot will be link dependent, making the Ad Hoc Probe estimator unfit for use in networks where the path capacity is limited by TDMA based links.

In passive techniques, the wireless medium is passively monitored over a certain period of time. The available bandwidth is estimated using the measured channel-usage without any impact on the existing flows. The most common method is to monitor the channel usage based on CSMA scheme of IEEE 802.11 via sensing the radio medium. The vast majority of works in this direction [16] to [19] use information at the 802.11 MAC layer to develop more accurate bandwidth estimation that takes into account all the specific details of the MAC layers. HELLO type packets, used by many routing or MAC protocols to discover the local network topology, could also be used as measurement packets. These techniques are considered as non-intrusive since HELLO packet exchanges are an intrinsic part of network management. Again, many techniques in this class are oblivious to the MAC protocol. These include [20] and [21] that use a crude approximation of the available bandwidth as a product of the total bandwidth with the fraction of time the link was used.

Most existing bandwidth estimation methods are developed specifically for IEEE 802.11 networks. They use information about the MAC layer and develop detailed models of the bandwidth given these inputs. Some techniques use information from the application and transport layer, for example using TCP stream information, to assist in the

measurement process [6]. Approaches that are MAC layer agnostic often only provide a very crude approximation of the bandwidth or require many probes to achieve statistically significant estimations. There is not a great deal of results for networks using MAC protocols that are not based on 802.11.

Some Passive Techniques are MAC agnostic, although these tend to be crude and unreliable. At some level information about a network's performance can be inferred from any measurement. For example, the delay of a single packet traversing the network tells us something about the network. If this delay were to increase, then we could possibly infer that the network is busier, however, the increase could also be due to changes in network topology or a number of other factors.

IV. Admission Control Middleware

It has been observed that on tactical networks there is often insufficient bandwidth to service all data requirement. This problem may be temporal or constant but either way an admission control system should be put in place to manage network data flows to improve network utilisation. This would most likely be implemented in a middleware application with the goal to:

- Avoid overloading the network bearer,
- Filter and prioritise information for network dissemination, and
- Inform users of network conditions and filtering decisions that have been made.

While some end user applications already address aspects of this problem we suggest that this needs to be considered across all network applications to correctly understand the performance implications. Current solutions have typically been tuned for a specific set of networks and performance conditions. The variable nature of tactical networks, particularly MANETs, requires a dynamic solution to fully address admission control based on an appropriate assessment of the network over time. As mentioned above, DSTG's SMARTNet project is looking to address this problem through the development of a middleware concept demonstrator that will utilise and extend the ideas presented in this paper.

To achieve this, the first requirement is to understand the network's needs for filtering or prioritisation. If the network has sufficient capacity for all traffic flows there will be no need to modify them. However, when traffic increases or network capacity decreases the system must be able to detect or predict this change in order to adapt. The key challenges to this are:

- Representing network, user and environmental context,
- Developing computer based decision mechanisms that adapt to potentially conflicting contexts,
- Appropriately using contextual information to disseminate and display information as required.

A critical part of this research is to determine how to measure the dynamic performance and capacity of networks to build a network context.

V. Measuring a TDMA Network

How then do we measure network performance to implement Admission Control Middleware? This paper will focus on a specific TDMA network implementation to address this more generic question, with the aim to identify concepts that can be more generically applied. We will consider three scenarios, these are:

1. MAC protocol unknown.
2. MAC protocol known but no topology data.
3. MAC protocol known and topology data.

Firstly consider a tactical radio network with an unknown MAC protocol. Consider a packet being transmitted to all the nodes on the network. The packet is time stamped at its origin allowing destination nodes to determine how long it has taken for the packet to be delivered by the network. Can we deduce from this time how busy the transmitting node is? In general, the answer is no since we have no other information about the network. Without knowing the network's MAC protocol or its parameters the analysis is simply

$$P_{int} = F_1(\text{Congestion})$$

where P_{int} is the distribution of times between packets. To infer the network congestion the inverse of F_1 is calculated so that

$$\text{Congestion} = G_1(P_{int}),$$

where G_1 is some statistical function or technique that is in some sense the inverse of F_1.

The size of the origin node's queue has a direct correlation with the packet delay. This information by itself is useful, but without other information about the network MAC and the topology it is hard to correctly interpret the measurements. A lightly loaded large network would appear similar to a congested small network. Delays in TDMA networks may be due to slot allocation protocols and not congestion, therefore further information is needed to get better accuracy.

Now suppose we now know the network's MAC is using the TDMA variant, the Node Activation Multiple Access (NAMA) protocol [2]. For NAMA, every node determines its set of two hop neighbours and their unique NAMA addresses. Then at each time slot every node is assigned a priority number using a hash function based on the slot number and the node's unique address. This calculation occurs at all the node's neighbours. If a node's priority is higher than all its neighbours, then it can transmit with the assurance that all other nodes in its two-hop neighbourhood will not. In this way, the network capacity is shared out fairly amongst all sets of 2-hop neighbours. If a MAC neighbourhood is large then there can be long delays between sending consecutive data packets, since slots are shared with equal probability amongst the neighbourhood. How does NAMA affect a packet's journey through the network?

When a packet enters a NAMA node's queue and there are already k packets in the queue, the distribution of time until the packet is transmitted is the convolution of k+1 geometric distributions, $P(X=j) = (1-p)^{j-1} p$. where p is the probability a node is allocated a slot, the inverse of the size of the MAC neighbourhood. This is the negative binomial distribution

$$P(X=j)=\left(\frac{j-1}{k}\right)p^{k+1}(1-p)^{j-k-1} \quad . \qquad (1)$$

Which has mean

$$\mu=\frac{pk}{(1-p)} \qquad (2)$$

For different values of k and p we can get different packet delay distributions. For example, suppose we have 10 nodes so that p=0.1, then we can calculate the distributions for different queue sizes, some are shown in Fig 1. Results are also shown for 4 nodes so that p=0.25 in Fig 2. Now we want to calculate

$P_{int} = F_2(p, \text{Protocols}, \text{Congestion})$.

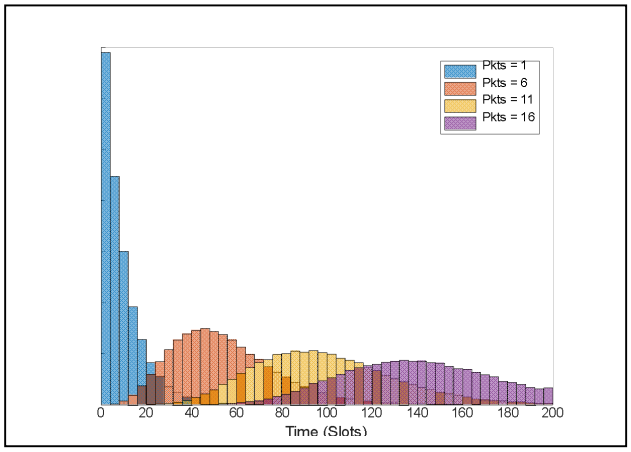


Fig. 1. The histograms for different number of served packets p = 0.1

However, we do not yet know the MAC neighbourhood size, and hence we do not know p. The measurement problem is to measure both k and p, a measure of the node queue's size and network size respectively. This is done by inverting this function so that we get the Bayesian statistical equation

$(\text{Congestion}, p) = G_2(P_{int} \mid \text{Protocols})$.

A simple way of doing this calculation is as follows. We start by recording the time taken in time slots for packets to arrive at the measuring node. This will give us a vector of measurements from a single originating node, $(j_1, j_2, \ldots, j_N)$. Then we can use Maximum Likelihood Estimation (MLE) to approximate the expected number of packets in a queue and p the probability that the node gets allocated a slot time. The distribution of the numbers of time slots that the packet takes to arrive is given by equation (1). The MLE technique chooses the value of k and p which maximises the probability of getting $(j_1, j_2, \ldots, j_N)$. This is equivalent to choosing from the set of all possible distributions (which include those in Fig 1 and Fig 2) the one that fits the data best. The accuracy of the MLE depends on the number of packets that we can measure and it will be shown to be inaccurate for this problem. Essentially this is because the distribution of the curves for different network sizes and queue sizes are too similar. Whilst with a very large number of packets the MLE works well, realistically there are not enough packet measurements to statistically infer the difference between separate distributions.

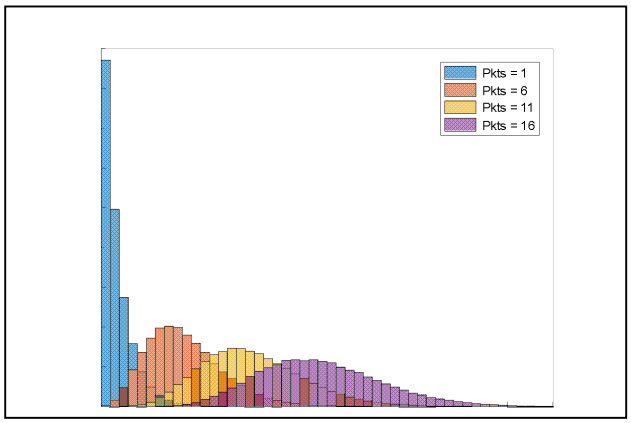


Fig. 2. The histograms for different number of served packets p = 0.25

Finally let us now assume that we also know topological information about the network. This would include for example the size of the network's two hop neighbourhoods used by NAMA to allocate slots. So now

$P_{int} = F_3(\text{Protocols}, \text{Parameters}, \text{Congestion})$

The analysis problem is then to invert this function so that we get the Bayesian statistical equation

$\text{Congestion} = G_3(P_{int} \mid \text{Protocols}, \text{Parameters})$.

A more accurate and efficient congestion calculation is now possible with not only the protocol information, but also the relevant protocol parameters available.

In the MLE analysis it was assumed that we did not know the number of neighbouring nodes, and hence the probability that the node would be served. This had to be approximated along with the queue sizes. We now directly know the value of p, so rather than using the MLE technique a simple but accurate moment matching technique can be used. Using equation (2) we can simply get the sample mean of our N measurements

$$\mu=\sum_{i=1}^{N} j_i$$

And then the following

$$\hat{k} = \frac{(1-p)}{p}\mu$$

is an approximation for k.

This is a very simple analysis that relies on knowing the number of nodes in the network. It will be shown to give efficient and accurate results.

VI. EMULATING A NETWORK

To further illustrate the effect that the network size and topology has on measurements we have conducted an experiment that looks at the packet transmit time in an emulated NAMA network. A five node fully connected network has been created in the Extendable Mobile Ad-hoc Network Emulator (EMANE). This software has been created by the Naval Research Laboratory (NRL) to model real world network deployments [22] and is currently used by the United States Army Research Laboratory (ARL) to model their tactical networks.

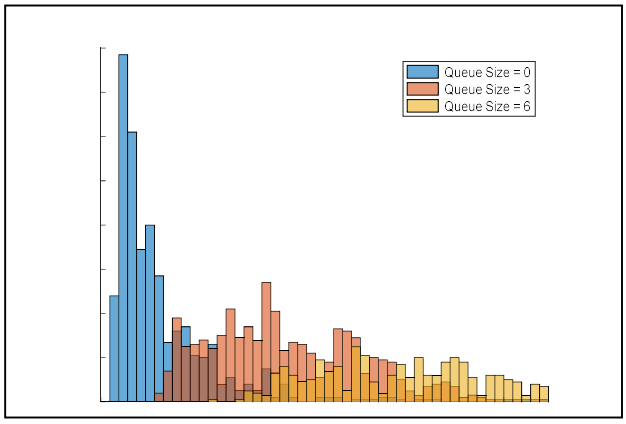


Fig. 3. Histogram of packet times in the network for different network delays.

It is acknowledged at this point that a small, fully connected network has very different characteristics and complexity than a fully deployed, large scale tactical network. However, the following example demonstrates that an increase in knowledge about the network improves the measurement technique and results. These techniques can be generalised to larger, more complex networks, although more work would need to be undertaken to establish their accuracy. This will be explored through the SMARTNet experimental campaign in collaboration with the US ARL, who is capable of emulating large scale EMANE networks (over 300 nodes).

For our experiment packets have been sent from node to node and the delay times measured. The network traffic has been increased and the packets once again measured. The TDMA protocol has 1000 slots per second, slot size is 0.001 seconds, with each slot randomly allocated to one of the five network nodes. The slot size has been set to 1000 bits. Packets are sent between the emulated nodes using the Unix ping command, and then the packets and their delays are captured using the Unix tcpdump command.

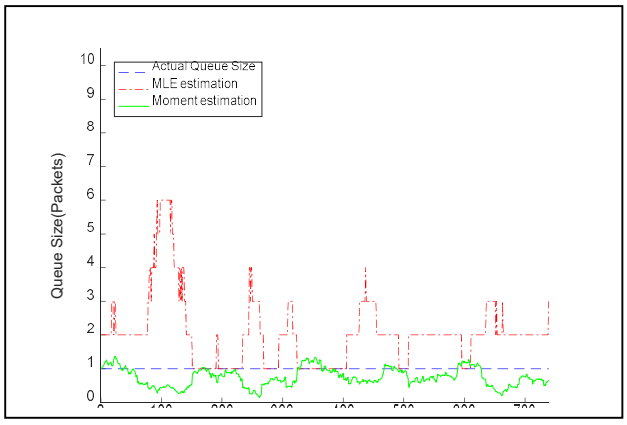


Fig. 4. The MLE and moment matching results for a queue size of 1.

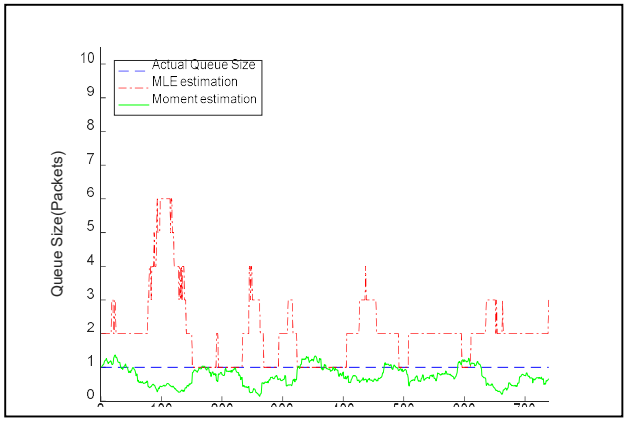


Fig. 5. The MLE and moment matching results for a queu size is 6.

Histograms of the packet trip times between two nodes in the network, for different queueing delays, are shown in Fig 3. Comparing these with the results in Fig 1 and Fig 2, we can see the same packet distributions as predicted by the mathematical model. This is maybe surprising given the added complexity of the emulated environment. It also bodes well that techniques created in the cleaner modelling environment can be used in the emulated environment. Simple statistics from the emulations can be recorded and by themselves these metrics are useful, but more information can be deduced by using the simple mathematical analysis demonstrated in this paper. Both the MLE and the moment matching technique created for the NAMA distribution have been used to get the approximate queue size for the emulations. Some results are shown in Fig 4 and Fig 5 for the case when the origin node's queue size is 1 and 6 slots respectively.

The emulated environment is both noisy and complex with routing packets being sent around the network, transmission errors, and dropped packets. Despite this the moment matching results are reasonably accurate, showing that the mathematical understanding of the underlying NAMA MAC protocol helps us get accurate measurements of the network's state. In comparison, the MLE results are not because trying to

approximate both queue size and number of neighbourhood nodes is more complex, and multiple solutions are metrically close to one another. This highlights the importance of getting the neighbourhood data, so that a simpler, more accurate and more efficient technique can be applied to the measurement problem. How these results translate into a much busier, noisier complex environment is yet to be determined.

In this simple network knowing both the MAC used and some topology information has enabled an efficient accurate technique for measuring the traffic in the network to be created. While most networks will be more complex than the example shown in this paper, the fundamental issues discussed here will still be relevant. That is, the more network data that are available the more accurate the measurement of the network. The SMARTNet research programme will extend this technique to more complex scenarios and start to answer key questions such as: how we can get this information in a reliable fashion; and how to identify the most effective measures required to intelligently apply admission control and prioritisation to get the best performance from a MANET?

VII. CONCLUSIONS

In this paper, some issues with measuring the performance of tactical radio networks have been presented. Techniques for measuring network performance of TDMA networks were investigated and the benefits of an improved understanding of network implementation were demonstrated. A simple example of this has been presented, and investigated using the EMANE emulation platform. The positive results from this work will be extended as part of the SMARTNet research programme, where larger, more complex networks will be investigated using ARL's significant EMANE capability. No doubt the techniques discussed in this paper will need to be extended as more complex scenarios are investigated. It has been shown how knowledge of the network's implementation details assist in the measurement of these networks. This could also be useful in informing vendors of the metrics they need to expose to allow network applications and managers to improve communication performance across the network.

REFERENCES

[1] N. Makhlouf and P. Vajsar Mac Protocols in Mobile Ad Hoc Networks, International Journal of Advances in Telecommunications, Electrotechnics, Signals and Systems, 2012, vol. 2012, no. 1, p. 1-4, 2012.

[2] L.Bao, "Distributed dynamic channel access scheduling for ad hoc networks", Journal of Parallel and Distributed Computing, vol. 63, Issue 1, pp 3-14, 2003.

[3] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE J.Sel. A. Commun., vol. 18, no. 3, pp. 535–547, Sep. 2006.

[4] K. Wang, F. Yang, Q. Zhang, and Y. Xu, "Modelling path capacity in multi-hop IEEE 802.11 networks for QoS services," IEEE Transactions on Wireless Communications, vol. 6, no. 2, pp. 738–749, Feb 2007.

[5] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated throughput analysis of IEEE 802.11 in presence of non-ideal transmission channel and capture effects," IEEE Transactions on Wireless Communications, vol. 7, no. 4, pp. 1276–1286, April 2008.

[6] Z. Yuan, H. Venkataraman and G. M. Muntean, "MBE: Model-Based Available Bandwidth Estimation for IEEE 802.11 Data Communications," in IEEE Transactions on Vehicular Technology, vol. 61, no. 5, pp. 2158-2171, Jun 2012.

[7] V. J. Ribeiro, R. H. Riedi, R. G. Baraniuk, J. Navratil, and L. Cottrell, "pathchirp: Efficient available bandwidth estimation for network paths," in Passive and Active measurement workshop, 2003.

[8] M. Jain and C. Dovrolis, "End-to-end available bandwidth: measurement methodology, dynamics, and relation with TCP throughput," IEEE/ACM Transactions on Networking, vol. 11, no. 4, pp. 537–549, Aug 2003.

[9] Mingzhe Li, Mark Claypool, and Robert Kinicki, "WBest: a Bandwidth Estimation Tool for IEEE 802.11 Wireless Networks", In Proceedings of 33rd IEEE Conference on Local Computer Networks (LCN), Montreal, Quebec, Canada, October 14-16, 2008

[10] Chen, Ling-Jyh and Sun, Tony and Yang, Guang and Sanadidi, M. Y. and Gerla, Mario, "AdHoc Probe: end-to-end capacity probing in wireless ad hoc networks", Wireless Networks, vol. 15, no. 1, pp. 111-126, 2009

[11] Z. Yuan, H. Venkataraman, and G.-M. Muntean, "iBE: A novel bandwidth estimation algorithm for multimedia services over IEEE 802.11 wireless networks," in IFIP/IEEE International Conference on Management of Multimedia Networks and Services. Springer, 2009, pp. 69–80.

[12] C. T. Calafate, M. P. Malumbres, J. Oliver, J. C. Cano, and P. Manzoni, "QoS support in MANETs: a modular architecture based on the IEEE 802.11e technology," IEEE Transactions on Circuits and Systems for Video Technology, vol. 19, 2009.

[13] M. A. Ergin, M. Gruteser, L. Luo, D. Raychaudhuri, and H. Liu, "Available bandwidth estimation and admission control for QoS routing in wireless mesh networks," Computer Communications, vol. 31, no. 7, pp. 1301–1317, 2008.

[14] W. E. Castellanos, J. C. Guerri, and P. Arce, "A QoS-aware routing protocol with adaptive feedback scheme for video streaming for mobile networks," Computer Communications, vol. 77, pp. 10 – 25, 2016.

[15] E. Flydahl, "Path capacity estimation for measurement based admission control in military IP networks," Master's thesis, UNIVERSITY OF OSLO, June 2012.

[16] C. Sarr, C. Chaudet, G. Chelius, and I. G. Lassous, "Bandwidth estimation for IEEE 802.11-based ad hoc networks," IEEE Transactions on Mobile Computing, vol. 7, no. 10, pp. 1228–1241, Oct 2008.

[17] H. Zhao, E. Garcia-Palacios, J. Wei, and Y. Xi, "Accurate available bandwidth estimation in IEEE 802.11-based ad hoc networks," Computer Communications, vol. 32, no. 6, pp. 1050 – 1057, 2009.

[18] L. Chen and W. B. Heinzelman, "QoS-aware routing based on bandwidth estimation for mobile ad hoc networks," IEEE Journal on Selected Areas in Communications, vol. 23, no. 3, pp. 561–572, March 2005.

[19] R. Belbachir, Z. M. Maaza, and A. Kies, "The mobility issue in admission controls and available bandwidth measures in MANETs," Wireless personal communications, vol. 70, no. 2, pp. 743–757, 2013.

[20] C. Chaudet and I. G. Lassous, "Bruit-bandwidth reservation under interferences influence," in European Wireless, 2002.

[21] Y. Yang and R. Kravets, "Contention-aware admission control for ad hoc networks," IEEE Trans. Mob. Computing, vol. 4, 2005.

[22] Extendable mobile ad-hoc network (EMANE) https://www.nrl.navy.mil/id/ncs/products.emane