QUANTIFYING NETWORK PERFORMANCE OF MOBILE AD-HOC NETWORKS

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ABSTRACT

The rapid deployment requirements, limited infrastructure, and mobile nature of tactical edge networks have led the Department of Defense (DoD) to investigate and implement Mobile Ad-hoc Networks (MANETs) to support its mission needs. MANETs rely on spectrum as the transmission medium, and their performance depends heavily on the electromagnetic environment (EME) where they operate. Traditional methods of assessing MANET performance have been focused on link capacity and network throughput, without adequately accounting for the effects of the EME. The Joint Spectrum Center of the Defense Spectrum Organization (DSO/JSC) has developed the Spectrum Simulation Testbed to adequately account for spectrum impacts on MANET performance. As part of the DSO/JSC Spectrum Simulation Testbed development, a number of capability gaps were identified, specifically in areas of quantifying the relationship between spectrum requirements and MANET performance. The purpose of this paper is to report the results of a survey to identify the current capabilities to address MANET performance within the context of accounting for available spectrum and to describe two capabilities that were developed to help bridge the analysis gap in the area relating spectrum requirements to system performance predictions.

INTRODUCTION

The rapid deployment requirements, limited infrastructure, and mobile nature of tactical edge networks have led the Department of Defense (DoD) to investigate and implement Mobile Ad-hoc Networks (MANETs) to support its mission needs. MANETs are characterized by groups of mobile nodes communicating with each other via wireless channels, often without a centralized control mechanism. MANETs rely on spectrum as the transmission medium, and their performance depends heavily on the electromagnetic environment (EME) where they operate.

To adequately account for spectrum impacts on MANET performance, the DSO/JSC has developed the Spectrum Simulation Testbed that enables quick integration of spectrum analysis, modeling, and simulation tools to quantify spectrum requirements for purposes such as MANET performance analysis, mission planning, system design, and technology development. By implementing a flexible evaluation architecture, the Testbed is capable of modeling the networking and spectrum aspects of wireless network devices (WNDs), including the functionality of radio frequency (RF) communications devices, adaptive RF devices, emerging spectrum management (SM) concepts, MANETs, smart antennas, and realistic EMEs. It also provides an M&S platform to study the operational impact of realistic EME on emerging spectrum technology (EST) systems and waveforms, to develop and assess advanced SM methodologies for EST systems, and to support policy analysis and development.

Traditional methods of assessing MANET performance have been focused on link capacity and network throughput, without adequately accounting for the effects of the EME. Furthermore, using throughput as a figure of merit often fails to capture the multi-hopping nature of MANETs. As part of the DSO/JSC Spectrum Simulation Testbed development, a number of capability gaps were identified, specifically in areas of quantifying the relationship between spectrum requirements and MANET performance. Often, the emerging waveform and system developers quantify spectrum bandwidth requirements based on theoretical considerations. However, they do not consider the practicality of obtaining the required spectrum allocation, either nationally or internationally. Little attention, if any, is given to quantifying network performance as function of spectrum availability.

The purpose of this paper is two-fold: (1) to report the results of a survey to identify the current capabilities available to address MANET performance within the context of accounting for spectrum-related issues and (2) to describe two capabilities that were developed to help

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bridge the gap in the area relating spectrum requirements to system performance predictions.

SURVEY

Our interests lie in two primary areas: (1) quantifying spectrum requirements for emerging waveforms and (2) quantifying the operational impact of not meeting spectrum requirements, focusing on communications network performance. Several capabilities are required to address the above areas:

- The ability to quantify communications network performance metrics, such as delay, throughput, completion rate, etc. for mobile, wireless networks employing one or more of the emerging networking waveforms (e.g., WNW, SRW, TTNT, FAST)
- The ability to relate these performance metrics to the amount of spectrum available versus requirement
- The ability to account for the effects of electromagnetic interference on the performance metrics

A survey of existing DoD and commercial spectrum tools was performed within the context of providing the capabilities above. While the tool set is comprehensive in terms of analytical strength, visualization techniques, and functional maturity, no single tool was identified that could be used to bridge the capability gap between the quantifying spectrum requirements and relating these requirements to communications network performance.

Many of the tools reviewed for this paper are focused on physical and link layer performance versus network performance. These tools include Builder [1], Integrated Intersite Model (IIM) [2], Satellite Took Kit (STK) [3], MATLAB [4], Wireless Insite [5], and Visualyse [6]. Of this set, Builder, IIM and Wireless Insite were developed to address the effects of electromagnetic interference on link performance. Furthermore, these tools generally take a narrow focus on individual component performance versus the impact on the communications network as a whole.

A few of the tools reviewed can be viewed as "support" tools that can be applicable to a variety of capabilities being sought but, in and of themselves, do not have the functional capability to address any of the 3 areas mentioned above. These tools include TIREM [7] (useful to perform complex path attenuation calculations) and GIS tools [8] (useful to enhance visualization and mapping applications).

Several of the tools are well suited to support the generation of network performance metrics. These tools include OPNET Modeler [9], Qualnet [10], and the Joint Communications Simulation System (JCSS) – formerly NETWARS [11]. Each of these tools provides significant capabilities to support detailed analysis of complex networks and a vast array of performance metrics related to communications networks. However, none of these tools includes the capability to relate network performance to the amount of spectrum available, and only NETWARS has the ability to generate performance metrics on an Information Exchange Requirement (IER) and thread basis, which is often essential for DoD applications. It should be noted that some of these tools have been used to support spectrum-related studies in the past; however, the tools did not inherently include the analytical basis to relate these performance metrics to spectrum-related issues, thereby requiring the analysts to develop custom models and techniques to use in carrying out these types of analyses.

In summary, the tool set reviewed is quite rich in terms of analytical strength, visualization techniques, and functional maturity. However, no single tool was identified that could be used to bridge the capability gap between the amount of spectrum required and its relationship to network performance.

The above statements are not meant to disparage the existing tool sets – the relationship between network performance and available spectrum is quite complex and requires the development of a new set of algorithms to relate the two. Therefore, it is time to identify and address this apparent shortcoming or gap, to ensure that adequate performance can be achieved for the emerging networking systems and waveforms.

APPROACH

The survey above indicates that no single tool or set of tools is currently available that can be used to effectively bridge the capability gap between the quantification of spectrum requirements and its impact on communications network performance. Related to network-level considerations, one common thread identified was the use of OPNET Modeler to perform communications network calculations and to generate related performance metrics. Several weaknesses of using OPNET Modeler as a stand-alone capability were identified that include:

- Inability to generate IER/Thread-based performance metrics

- Weak in the area of scenario generation and visualization of physical layer and link layer functionality
- Limited ability to relate spectrum-related issues to communications network performance (development of custom models and techniques are required for these types of analyses)

Our approach is to significantly leverage existing capabilities and tools, in order to address the gap between the quantification of spectrum requirements and its impact on communications network performance.

The tools being developed to address this gap are built on existing MITRE capabilities, including the Bandwidth Tool (BW Tool), the Communications Resource Planning Tool (CRPT) ([12], [13]) and the JTRS M&S environment (MSE) [14]. The following technical approach is adopted:

- Utilize the algorithms present in the BW Tool and incorporate them into the CRPT
- Extend the capabilities of the CRPT into the Spectrum Planning Tool (SPT)
- Extend the capabilities of the JTRS MSE into the Spectrum & Waveform Efficiency Evaluation Tool (SWEET).

SPT

In tactical environments where radio communications are critical to operational missions, the ability to predict connectivity is of primary importance. Success in maintaining radio links in these scenarios depends to a great degree on degradations of the link including obstructions that might obscure the line of sight between transmitters and receivers. Jammers can also severely degrade communications performance. The effects of these factors must be taken into consideration during the planning and performance prediction of tactical wireless links. The Spectrum Planning Tool (SPT) can be used to plan communications links in the presence of degradations such as path obstructions or the effects of jammers.

There are two attenuation models available in the SPT: the Terrain Integrated Rough Earth Model (TIREM) and the OPNET Path Attenuation Routine (OPAR) [13]. TIREM is used to account for the path attenuation due to terrain. OPAR accounts for the excess path attenuation caused by obstructions such as buildings and foliage. Analyzing obstruction losses can be difficult because of the geometry involved and the need for path loss models. OPAR considers both free space loss and a plane earth model for paths that are obstruction-free. Excess path loss due to obstructions including buildings and foliage are analytically quantified and combined with the free space and/or plane earth generated losses, as appropriate.

In addition to the signal attenuation caused by free space and additional path loss, jamming can also reduce communications performance. A criterion is needed for determining when a receiver can successfully demodulate a desired signal in the presence of noise and interference from a jammer. SPT assumes that the source of the noise is from the receiver itself, and the jammer produces a Gaussian noise-like signal of bandwidth (BW). We also assume that the receiver must achieve an overall signal to noise (Eb/No) of a given value in order to demodulate the signal successfully.

The SPT allows the user to easily adjust the locations and parameters of radios deployed in a scenario to immediately see the effect on the network in an environment of terrain, buildings, foliage and jammers. The SPT can be configured to show the theoretical maximum link capacity (Shannon's Law) as well as the expected average traffic on all links and through all nodes using a simple traffic model. An SPT screen shot is shown in Figure 1.

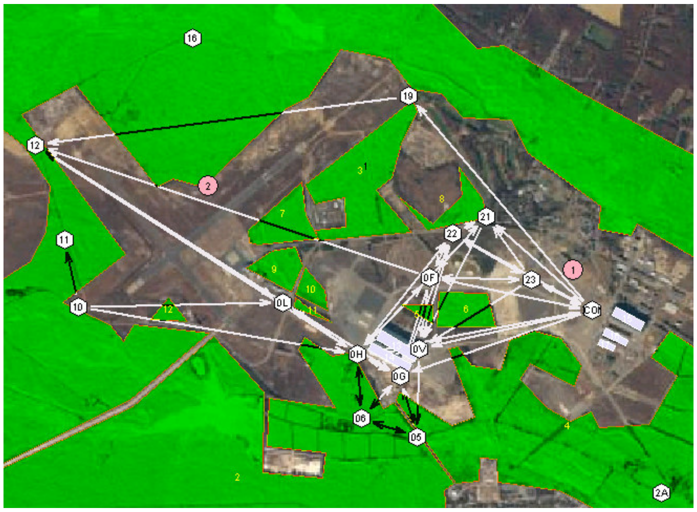


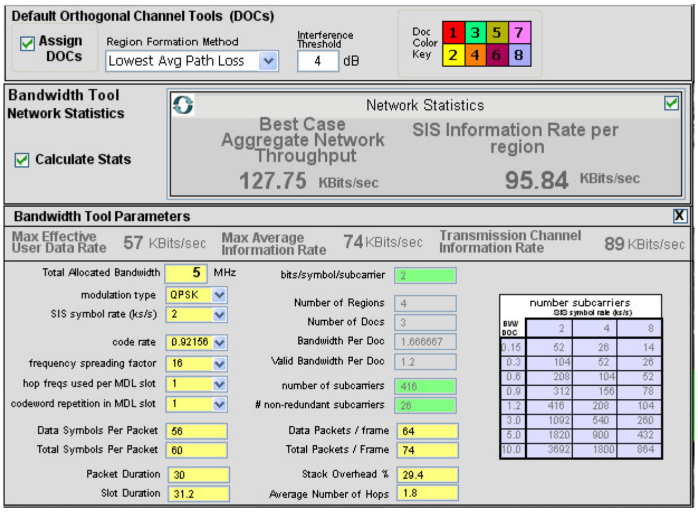
Figure 1: SPT Screen Shot Showing Link Connectivity in the Presence of Foliage

SPT includes a number of tools to facilitate the evaluation of a given radio scenario including:

- Map Tool (ruler, latitude/longitude, elevation)
- Transmission Tool (used to identify successful transmission paths based on node locations and using OPAR or TIREM to quantify path attenuation)
- Range & Coverage Tool (portrays range and coverage area of each radio)

- Matrix Tool (generates a matrix of radio connectivity)
- Subnet Tool (includes two algorithms to assign nodes to regions/frequency assignments)
- Bandwidth Tool (quantifies achievable aggregate network throughput as a function of BW and other parameters)

Using the Subnet Tool, SPT is capable of clustering the radios based on one of its two region formation algorithms. The radios are then assigned frequencies with the goal of maximizing frequency reuse, satisfying the following condition -- given a region with a specified frequency, the lowest received power from any radio in that region must exceed the received power from any radio at that frequency outside the region by at least a user-specified dB level. Once frequencies are assigned, network statistics are calculated based on user-assigned parameters and parameters derived from the user's scenario. The Bandwidth Tool implemented in the SPT is used to calculate network statistics. These statistics include: the Best Case Aggregate Network Throughput, the Signal in Space (SIS) Information Rate Per Region, the Maximum Effective User Data Rate, the Maximum Average Information Rate, and the Transmission Channel Information Rate. SPT spectrum-related input parameters and results of the aggregate network throughput are shown in Figure 2.



Default Orthogonal Channel Tools (DOCs)

☑ Assign DOCs

Region Formation Method: Lowest Avg Path Loss

Interference Threshold: 4 dB

Doc Color Key: 1 3 5 7 / 2 4 6 8

Bandwidth Tool Network Statistics

☑ Calculate Stats

Network Statistics ☑

Best Case Aggregate Network Throughput: 127.75 KBits/sec

SIS Information Rate per region: 95.84 KBits/sec

Bandwidth Tool Parameters

Max Effective User Data Rate: 57 KBits/sec

Max Average Information Rate: 74 KBits/sec

Transmission Channel Information Rate: 89 KBits/sec

Total Allocated Bandwidth: 5 MHz

modulation type: QPSK

SIS symbol rate (ks/s): 2

code rate: 0.92156

frequency spreading factor: 16

hop freqs used per MDL slot: 1

codeword repetition in MDL slot: 1

Data Symbols Per Packet: 56

Total Symbols Per Packet: 60

Packet Duration: 30

Slot Duration: 31.2

bits/symbol/subcarrier: 2

Number of Regions: 4

Number of Docs: 3

Bandwidth Per Doc: 1.666667

Valid Bandwidth Per Doc: 1.2

number of subcarriers: 416

non-redundant subcarriers: 26

Data Packets / frame: 64

Total Packets / Frame: 74

Stack Overhead %: 29.4

Average Number of Hops: 1.8

number subcarriers

BW/DOC	2	4	8
0.15	52	26	14
0.3	104	52	26
0.6	208	104	52
0.9	312	156	78
1.2	416	208	104
3.0	1092	540	260
5.0	1820	900	432
10.0	3692	1800	864

Figure 2: SPT Screenshot Showing the Spectrum-related Input Parameters and Aggregate Network Throughput Results

SWEET

SWEET was developed by augmenting an existing capability referred to as the M&S environment (MSE) [14]. The MSE was developed in support of the DARPA Future Combat System Communications (FCS-C) technology program and the Joint Tactical Radio System (JTRS) program. It supports the performance evaluation of emerging communications technologies using operational scenarios having traffic profiles comprised of information exchange requirements (IERs) and threads. The MSE also accounts for terrain-induced path attenuation and includes a model to represent the deleterious effects of foliage attenuation on the communications channel.

The MSE is depicted in Figure 3. It is comprised of two COTS products, COMTEST and OPNET Modeler [9], augmented by a number of specially developed software (S/W) components depicted in gray in Figure 3.

COMTEST is used to develop the operational scenarios. It provides a graphical user interface (GUI) to facilitate the placement of nodes, define their mobility, and build the IER and thread-based traffic profile using a detailed set of linked property tables. OPNET Modeler is used as the simulation kernel. The contractor-developed OPNET models for their respective technologies are integrated into the MSE. Once the OPNET simulation is completed, performance data is generated that is IER and thread-based and includes a variety of performance parameters, such as completion rates and latencies.

As shown in Figure 3, there are three sets of S/W components that were developed as part of the MSE: (1) the Parser, (2) the Pathloss Routine, and (3) the OPNET-Internal S/W components. The Parser and the OPNET-Internal S/W components serve as the "glue" that support the COMTEST/OPNET interface while the Pathloss routine provides the means by which terrain- and foliage-based attenuation can be quantified. The MSE supports the use of TIREM or the plane earth model to quantify path attenuation. Additional detail for each of the S/W components identified above can be found in [14].

Two sets of enhancements were performed in the development of SWEET. The first set was made directly to the MSE to augment its functionality. The second set was made to the MANET OPNET model, in order to compute and compile statistics in support of the Gupta-Kumar calculations [15]. Each of these is described below.

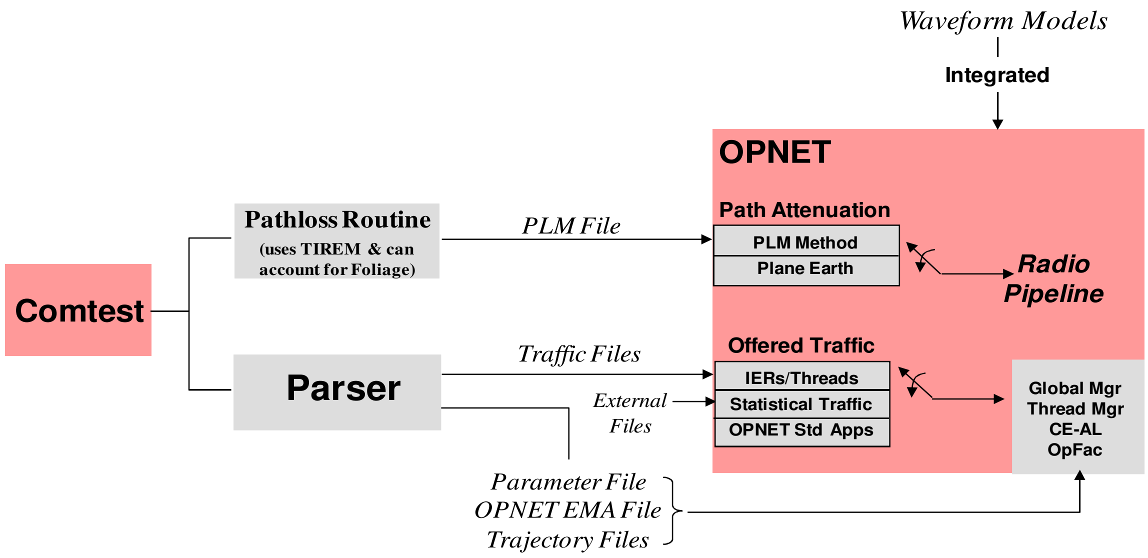


Figure 3: MSE with SWEET Enhancements for Offered Traffic

MSE Enhancements: SWEET assesses emerging waveforms to support MANETs. As part of the enhancements made for SWEET, we integrated support for three different approaches for generating application traffic into the MSE: threads/IERs, statistical, and some OPNET-based application model solutions (i.e., Standard Applications Model and Custom Model Application). Support for thread and IER-based traffic was an original component of the MSE [14]. The statistical traffic capability was added and uses a set of files to statistically characterize different flows between defined sources and destinations (both unicast and multicast). The OPNET Standard Applications capability models detailed traffic characteristics of specific applications, while the OPNET Custom Model Application provides a generic, customizable application capability. All three traffic approaches were incorporated into each platform node model as separate modules, allowing for each to generate and receive application traffic for that node. Each type of traffic also includes one or more global components to support its configuration.

Using a set of global attributes, one or more traffic types can be turned on or off for a given simulation run, depending on the study being conducted. Model attributes are also included to resolve conflicts between application types.

Model Enhancements: A M&S approach is proposed below that is capable of quantifying the relationship between spectrum availability and MANET network performance. Gupta and Kumar [15] were the first to analytically address throughput and capacity on a network level for MANET applications. The waveform model was enhanced to compute and plot the following information:

- Gupta-Kumar capacity
- Gupta-Kumar throughput
- End-to-end number of hops for traffic

Gupta-Kumar capacity varies proportionally with channel capacity and square root of number of nodes and operational area of the network. The Gupta-Kumar capacity was calculated using the following formula:

$$Capacity_{GK} = \frac{1}{6} b \sqrt{\frac{2}{\sqrt{3}} A \times n} \ ,$$

where b denotes the bandwidth in bits per second, A denotes the area in square meters, and n denotes the number of nodes.

The waveform under study uses automatic bandwidth calculation and uses optimal bit rate with respect to the signal-to-noise ratio (SNR). The actual bit rate associated with each received packet was used for the channel capacity.

In SWEET, the operational area of the network was determined by calculating the area of a rectangle that includes all the nodes. Assuming that the location of each node is identified by its x and y coordinates (e.g., x_i, y_i, for node i), the area A of the rectangle was calculated using the following formula:

$A = [max(x_i) - min(x_i)] * [max(y_i) - min(y_i)]$, for $1 \leq i \leq n$,

where n denotes the number of nodes.

The Gupta-Kumar throughput for each time interval t was calculated according to the following formula:

$$Throughput_{GK} = \frac{\sum p * d}{t} \text{ (bit-meter/second),}$$

where p denotes the packet size in bits, and d denotes distance from source to destination in meters.

Finally, the end-to-end number of hops traveled by each packet was computed and plotted.

The waveform OPNET model was enhanced to model and plot the values of these metrics. We added a global model and modified a receiver pipeline stage, a module belonging to the link layer, and two application modules to perform these functions. The function of the global model was to periodically compute the Gupta-Kumar capacity and plot the result. The thread/IER-based and statistical-based application modules (traffic generators) were modified to calculate Gupta-Kumar throughput and plot it. Gupta-Kumar throughput is calculated by computing the distance traveled by each packet and multiplying it by its size; the result is then written to a statistics probe. The receiver pipeline stage examines each packet and obtains its transmission burst rate. This burst rate is passed to the global application module to be used for Gupta-Kumar capacity calculations. Finally, the link layer module was modified to identify packets that have reached their destination node. Each of these packets is then examined to ensure it contains an application packet. If this is the case, the end-to-end number of hops traveled by the packet is calculated and plotted.

EXAMPLE APPLICATION OF SWEET

As a proof of concept, we applied these new capabilities to evaluate a 20 node scenario, where each node includes a single channel radio, running a proprietary protocol stack below IP. Above IP, support for UDP is assumed, which our traffic generation models utilize. For this case study, only statistical traffic was defined and turned on. Technical characteristics for this notional scenario are listed below:

- Channel allocations : 1.2 MHz, 3 MHz, and 5 MHz
- Packet sizes : 500B, 1000B, and 1400B
- Traffic inter-arrival times: Traffic was increased every 500 seconds, from 500 seconds to 3000 seconds, with traffic flows defined ranging from 8,000 b/s to 8 Mb/s.
- Each test case was executed 3 times, with different seeds

For our evaluation study, we were unsuccessful in getting any user data delivered for the 1.2 MHz case, but obtained results for the 3 MHz and 5 MHz cases. For these two cases, we saw that larger packet sizes improved the Gupta-Kumar Throughput values (in bit-meters/seconds), as illustrated in Figure 4. In this figure, Gupta-Kumar Capacity is also plotted as a basis for comparison.

CONCLUSIONS AND FUTURE WORK

A survey of existing DoD and commercial tools was performed to identify capabilities currently available to help quantify network performance, while considering spectrum-related issues. While the tool set identified was comprehensive in terms of analytical strength, visualization techniques, and functional maturity, no single tool was identified that could be used to relate spectrum requirements to system performance predictions. Two tools being developed will help bridge this gap– SPT (link analysis) and SWEET (waveform evaluation). These tools can be considered proof-of-concept prototypes of the family of tools needed in this area. Further work is required to continue to develop these types of capabilities in order to ensure that adequate performance is achievable in MANETs when taking spectrum limitations and constraints into account.

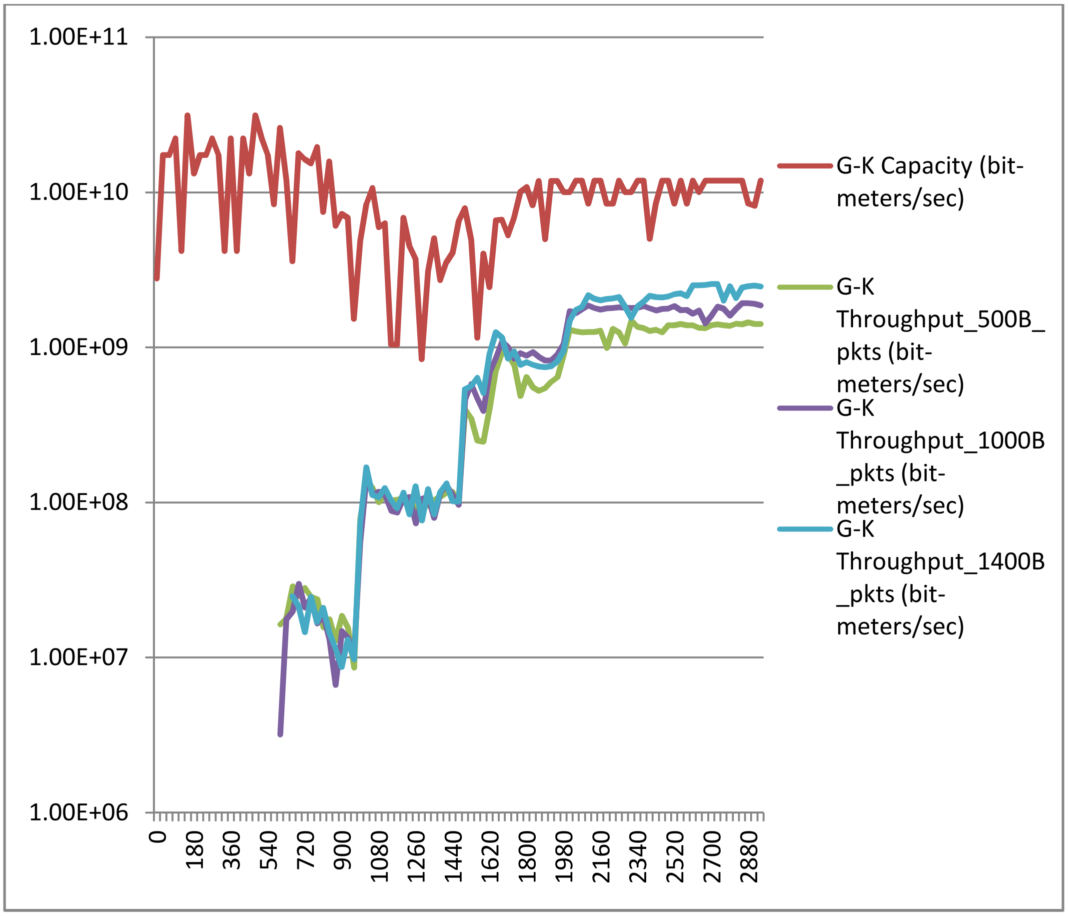


Figure 4: 5MHz Channel, Varying Packet Size, Bit-meter/sec versus Time (second)

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