

Network Working Group
Request for Comments: 5136
Category: Informational

P. Chimento
JHU Applied Physics Lab
J. Ishac
NASA Glenn Research Center
February 2008

Defining Network Capacity

Status of This Memo

This memo provides information for the Internet community. It does not specify an Internet standard of any kind. Distribution of this memo is unlimited.

Abstract

Measuring capacity is a task that sounds simple, but in reality can be quite complex. In addition, the lack of a unified nomenclature on this subject makes it increasingly difficult to properly build, test, and use techniques and tools built around these constructs. This document provides definitions for the terms 'Capacity' and 'Available Capacity' related to IP traffic traveling between a source and destination in an IP network. By doing so, we hope to provide a common framework for the discussion and analysis of a diverse set of current and future estimation techniques.

Table of Contents

1. Introduction	3
2. Definitions	4
2.1. Links and Paths	4
2.2. Definition: Nominal Physical Link Capacity	4
2.3. Capacity at the IP Layer	5
2.3.1. Definition: IP-layer Bits	5
2.3.1.1. Standard or Correctly Formed Packets	5
2.3.1.2. Type P Packets	6
2.3.2. Definition: IP-type-P Link Capacity	7
2.3.3. Definition: IP-type-P Path Capacity	7
2.3.4. Definition: IP-type-P Link Usage	7
2.3.5. Definition: IP-type-P Link Utilization	8
2.3.6. Definition: IP-type-P Available Link Capacity	8
2.3.7. Definition: IP-type-P Available Path Capacity	8
3. Discussion	9
3.1. Time and Sampling	9
3.2. Hardware Duplicates	9
3.3. Other Potential Factors	9
3.4. Common Terminology in Literature	10
3.5. Comparison to Bulk Transfer Capacity (BTC)	10
4. Security Considerations	11
5. Conclusion	11
6. Acknowledgments	11
7. References	12
7.1. Normative References	12
7.2. Informative References	12

1. Introduction

Measuring the capacity of a link or network path is a task that sounds simple, but in reality can be quite complex. Any physical medium requires that information be encoded and, depending on the medium, there are various schemes to convert information into a sequence of signals that are transmitted physically from one location to another.

While on some media, the maximum frequency of these signals can be thought of as "capacity", on other media, the signal transmission frequency and the information capacity of the medium (channel) may be quite different. For example, a satellite channel may have a carrier frequency of a few gigahertz, but an information-carrying capacity of only a few hundred kilobits per second. Often similar or identical terms are used to refer to these different applications of capacity, adding to the ambiguity and confusion, and the lack of a unified nomenclature makes it difficult to properly build, test, and use various techniques and tools.

We are interested in information-carrying capacity, but even this is not straightforward. Each of the layers, depending on the medium, adds overhead to the task of carrying information. The wired Ethernet uses Manchester coding or 4/5 coding, which cuts down considerably on the "theoretical" capacity. Similarly, RF (radio frequency) communications will often add redundancy to the coding scheme to implement forward error correction because the physical medium (air) is lossy. This can further decrease the information capacity.

In addition to coding schemes, usually the physical layer and the link layer add framing bits for multiplexing and control purposes. For example, on SONET there is physical-layer framing and typically also some layer-2 framing such as High-Level Data Link Control (HDLC), PPP, or ATM.

Aside from questions of coding efficiency, there are issues of how access to the channel is controlled, which also may affect the capacity. For example, a multiple-access medium with collision detection, avoidance, and recovery mechanisms has a varying capacity from the point of view of the users. This varying capacity depends upon the total number of users contending for the medium, how busy the users are, and bounds resulting from the mechanisms themselves. RF channels may also vary in capacity, depending on range, environmental conditions, mobility, shadowing, etc.

The important points to derive from this discussion are these: First, capacity is only meaningful when defined relative to a given protocol layer in the network. It is meaningless to speak of "link" capacity without qualifying exactly what is meant. Second, capacity is not necessarily fixed, and consequently, a single measure of capacity at any layer may in fact provide a skewed picture (either optimistic or pessimistic) of what is actually available.

2. Definitions

In this section, we specify definitions for capacity. We begin by first defining "link" and "path" clearly, and then we define a baseline capacity that is simply tied to the physical properties of the link.

2.1. Links and Paths

To define capacity, we need to broaden the notions of link and path found in the IP Performance Metrics (IPPM) framework document [RFC2330] to include network devices that can impact IP capacity without being IP aware. For example, consider an Ethernet switch that can operate ports at different speeds.

We define nodes as hosts, routers, Ethernet switches, or any other device where the input and output links can have different characteristics. A link is a connection between two of these network devices or nodes. We then define a path P of length n as a series of links (L_1, L_2, \dots, L_n) connecting a sequence of nodes $(N_1, N_2, \dots, N_{n+1})$. A source S and destination D reside at N_1 and N_{n+1} , respectively. Furthermore, we define a link L as a special case where the path length is one.

2.2. Definition: Nominal Physical Link Capacity

Nominal Physical Link Capacity, $NomCap(L)$, is the theoretical maximum amount of data that the link L can support. For example, an OC-3 link would be capable of 155.520 Mbit/s. We stress that this is a measurement at the physical layer and not the network IP layer, which we will define separately. While $NomCap(L)$ is typically constant over time, there are links whose characteristics may allow otherwise, such as the dynamic activation of additional transponders for a satellite link.

The nominal physical link capacity is provided as a means to help distinguish between the commonly used link-layer capacities and the remaining definitions for IP-layer capacity. As a result, the value of $NomCap(L)$ does not influence the other definitions presented in this document. Instead, it provides an upper bound on those values.

2.3. Capacity at the IP Layer

There are many factors that can reduce the IP information carrying capacity of the link, some of which have already been discussed in the introduction. However, the goal of this document is not to become an exhaustive list of such factors. Rather, we outline some of the major examples in the following section, thus providing food for thought to those implementing the algorithms or tools that attempt to measure capacity accurately.

The remaining definitions are all given in terms of "IP-layer bits" in order to distinguish these definitions from the nominal physical capacity of the link.

2.3.1. Definition: IP-layer Bits

IP-layer bits are defined as eight (8) times the number of octets in all IP packets received, from the first octet of the IP header to the last octet of the IP packet payload, inclusive.

IP-layer bits are recorded at the destination D beginning at time T and ending at a time T+I. Since the definitions are based on averages, the two time parameters, T and I, must accompany any report or estimate of the following values in order for them to remain meaningful. It is not required that the interval boundary points fall between packet arrivals at D. However, boundaries that fall within a packet will invalidate the packets on which they fall. Specifically, the data from the partial packet that is contained within the interval will not be counted. This may artificially bias some of the values, depending on the length of the interval and the amount of data received during that interval. We elaborate on what constitutes correctly received data in the next section.

2.3.1.1. Standard or Correctly Formed Packets

The definitions in this document specify that IP packets must be received correctly. The IPPM framework recommends a set of criteria for such standard-formed packets in Section 15 of [RFC2330]. However, it is inadequate for use with this document. Thus, we outline our own criteria below while pointing out any variations or similarities to [RFC2330].

First, data that is in error at layers below IP and cannot be properly passed to the IP layer must not be counted. For example, wireless media often have a considerably larger error rate than wired media, resulting in a reduction in IP link capacity. In accordance with the IPPM framework, packets that fail validation of the IP

header must be discarded. Specifically, the requirements in [RFC1812], Section 5.2.2, on IP header validation must be checked, which includes a valid length, checksum, and version field.

The IPPM framework specifies further restrictions, requiring that any transport header be checked for correctness and that any packets with IP options be ignored. However, the definitions in this document are concerned with the traversal of IP-layer bits. As a result, data from the higher layers is not required to be valid or understood as that data is simply regarded as part of the IP packet. The same holds true for IP options. Valid IP fragments must also be counted as they expend the resources of a link even though assembly of the full packet may not be possible. The IPPM framework differs in this area, discarding IP fragments.

For a discussion of duplicates, please see Section 3.2.

In summary, any IP packet that can be properly processed must be included in these calculations.

2.3.1.2. Type P Packets

The definitions in this document refer to "Type P" packets to designate a particular type of flow or sets of flows. As defined in RFC 2330, Section 13, "Type P" is a placeholder for what may be an explicit specification of the packet flows referenced by the metric, or it may be a very loose specification encompassing aggregates. We use the "Type P" designation in these definitions in order to emphasize two things: First, that the value of the capacity measurement depends on the types of flows referenced in the definition. This is because networks may treat packets differently (in terms of queuing and scheduling) based on their markings and classification. Networks may also arbitrarily decide to flow-balance based on the packet type or flow type and thereby affect capacity measurements. Second, the measurement of capacity depends not only on the type of the reference packets, but also on the types of the packets in the "population" with which the flows of interest share the links in the path.

All of this indicates two different approaches to measuring: One is to measure capacity using a broad spectrum of packet types, suggesting that "Type P" should be set as generic as possible. The second is to focus narrowly on the types of flows of particular interest, which suggests that "Type P" should be very specific and narrowly defined. The first approach is likely to be of interest to providers, the second to application users.

As a practical matter, it should be noted that some providers may treat packets with certain characteristics differently than other packets. For example, access control lists, routing policies, and other mechanisms may be used to filter ICMP packets or forward packets with certain IP options through different routes. If a capacity-measurement tool uses these special packets and they are included in the "Type P" designation, the tool may not be measuring the path that it was intended to measure. Tool authors, as well as users, may wish to check this point with their service providers.

2.3.2. Definition: IP-type-P Link Capacity

We define the IP-layer link capacity, $C(L,T,I)$, to be the maximum number of IP-layer bits that can be transmitted from the source S and correctly received by the destination D over the link L during the interval $[T, T+I]$, divided by I .

As mentioned earlier, this definition is affected by many factors that may change over time. For example, a device's ability to process and forward IP packets for a particular link may have varying effect on capacity, depending on the amount or type of traffic being processed.

2.3.3. Definition: IP-type-P Path Capacity

Using our definition for IP-layer link capacity, we can then extend this notion to an entire path, such that the IP-layer path capacity simply becomes that of the link with the smallest capacity along that path.

$$C(P,T,I) = \min \{1..n\} \{C(L_n,T,I)\}$$

The previous definitions specify the number of IP-layer bits that can be transmitted across a link or path should the resource be free of any congestion. It represents the full capacity available for traffic between the source and destination. Determining how much capacity is available for use on a congested link is potentially much more useful. However, in order to define the available capacity, we must first specify how much is being used.

2.3.4. Definition: IP-type-P Link Usage

The average usage of a link L , $Used(L,T,I)$, is the actual number of IP-layer bits from any source, correctly received over link L during the interval $[T, T+I]$, divided by I .

An important distinction between usage and capacity is that $Used(L,T,I)$ is not the maximum number, but rather, the actual number of IP bits sent that are correctly received. The information transmitted across the link can be generated by any source, including those sources that may not be directly attached to either side of the link. In addition, each information flow from these sources may share any number (from one to n) of links in the overall path between S and D .

2.3.5. Definition: IP-type-P Link Utilization

We express usage as a fraction of the overall IP-layer link capacity.

$$Util(L,T,I) = (Used(L,T,I) / C(L,T,I))$$

Thus, the utilization now represents the fraction of the capacity that is being used and is a value between zero (meaning nothing is used) and one (meaning the link is fully saturated). Multiplying the utilization by 100 yields the percent utilization of the link. By using the above, we can now define the capacity available over the link as well as the path between S and D . Note that this is essentially the definition in [PDM].

2.3.6. Definition: IP-type-P Available Link Capacity

We can now determine the amount of available capacity on a congested link by multiplying the IP-layer link capacity with the complement of the IP-layer link utilization. Thus, the IP-layer available link capacity becomes:

$$AvailCap(L,T,I) = C(L,T,I) * (1 - Util(L,T,I))$$

2.3.7. Definition: IP-type-P Available Path Capacity

Using our definition for IP-layer available link capacity, we can then extend this notion to an entire path, such that the IP-layer available path capacity simply becomes that of the link with the smallest available capacity along that path.

$$AvailCap(P,T,I) = \min \{1..n\} \{AvailCap(L_n,T,I)\}$$

Since measurements of available capacity are more volatile than that of link capacity, we stress the importance that both the time and interval be specified as their values have a great deal of influence on the results. In addition, a sequence of measurements may be beneficial in offsetting the volatility when attempting to characterize available capacity.

3. Discussion

3.1. Time and Sampling

We must emphasize the importance of time in the basic definitions of these quantities. We know that traffic on the Internet is highly variable across all time scales. This argues that the time and length of measurements are critical variables in reporting available capacity measurements and must be reported when using these definitions.

The closer to "instantaneous" a metric is, the more important it is to have a plan for sampling the metric over a time period that is sufficiently large. By doing so, we allow valid statistical inferences to be made from the measurements. An obvious pitfall here is sampling in a way that causes bias. For example, a situation where the sampling frequency is a multiple of the frequency of an underlying condition.

3.2. Hardware Duplicates

We briefly consider the effects of paths where hardware duplication of packets may occur. In such an environment, a node in the network path may duplicate packets, and the destination may receive multiple, identical copies of these packets. Both the original packet and the duplicates can be properly received and appear to be originating from the sender. Thus, in the most generic form, duplicate IP packets are counted in these definitions. However, hardware duplication can affect these definitions depending on the use of "Type P" to add additional restrictions on packet reception. For instance, a restriction only to count uniquely-sent packets may be more useful to users concerned with capacity for meaningful data. In contrast, the more general, unrestricted metric may be suitable for a user who is concerned with raw capacity. Thus, it is up to the user to properly scope and interpret results in situations where hardware duplicates may be prevalent.

3.3. Other Potential Factors

IP encapsulation does not affect the definitions as all IP header and payload bits must be counted regardless of content. However, IP packets of different sizes can lead to a variation in the amount of overhead needed at the lower layers to transmit the data, thus altering the overall IP link-layer capacity.

Should the link happen to employ a compression scheme such as RObust Header Compression (ROHC) [RFC3095] or V.44 [V44], some of the original bits are not transmitted across the link. However, the inflated (not compressed) number of IP-layer bits should be counted.

3.4. Common Terminology in Literature

Certain terms are often used to characterize specific aspects of the presented definitions. The link with the smallest capacity is commonly referred to as the "narrow link" of a path. Also, the link with the smallest available capacity is often referred to as the "tight link" within a path. So, while a given link may have a very large capacity, the overall congestion level on the link makes it the likely bottleneck of a connection. Conversely, a link that has the smallest capacity may not be the bottleneck should it be lightly loaded in relation to the rest of the path.

Also, literature often overloads the term "bandwidth" to refer to what we have described as capacity in this document. For example, when inquiring about the bandwidth of a 802.11b link, a network engineer will likely answer with 11 Mbit/s. However, an electrical engineer may answer with 25 MHz, and an end user may tell you that his observed bandwidth is 8 Mbit/s. In contrast, the term "capacity" is not quite as overloaded and is an appropriate term that better reflects what is actually being measured.

3.5. Comparison to Bulk Transfer Capacity (BTC)

Bulk Transfer Capacity (BTC) [RFC3148] provides a distinct perspective on path capacity that differs from the definitions in this document in several fundamental ways. First, BTC operates at the transport layer, gauging the amount of capacity available to an application that wishes to send data. Only unique data is measured, meaning header and retransmitted data are not included in the calculation. In contrast, IP-layer link capacity includes the IP header and is indifferent to the uniqueness of the data contained within the packet payload. (Hardware duplication of packets is an anomaly addressed in a previous section.) Second, BTC utilizes a single congestion-aware transport connection, such as TCP, to obtain measurements. As a result, BTC implementations react strongly to different path characteristics, topologies, and distances. Since these differences can affect the control loop (propagation delays, segment reordering, etc.), the reaction is further dependent on the algorithms being employed for the measurements. For example, consider a single event where a link suffers a large duration of bit errors. The event could cause IP-layer packets to be discarded, and the lost packets would reduce the IP-layer link capacity. However, the same event and subsequent losses would trigger loss recovery for

a BTC measurement resulting in the retransmission of data and a potentially reduced sending rate. Thus, a measurement of BTC does not correspond to any of the definitions in this document. Both techniques are useful in exploring the characteristics of a network path, but from different perspectives.

4. Security Considerations

This document specifies definitions regarding IP traffic traveling between a source and destination in an IP network. These definitions do not raise any security issues and do not have a direct impact on the networking protocol suite.

Tools that attempt to implement these definitions may introduce security issues specific to each implementation. Both active and passive measurement techniques can be abused, impacting the security, privacy, and performance of the network. Any measurement techniques based upon these definitions must include a discussion of the techniques needed to protect the network on which the measurements are being performed.

5. Conclusion

In this document, we have defined a set of quantities related to the capacity of links and paths in an IP network. In these definitions, we have tried to be as clear as possible and take into account various characteristics that links and paths can have. The goal of these definitions is to enable researchers who propose capacity metrics to relate those metrics to these definitions and to evaluate those metrics with respect to how well they approximate these quantities.

In addition, we have pointed out some key auxiliary parameters and opened a discussion of issues related to valid inferences from available capacity metrics.

6. Acknowledgments

The authors would like to acknowledge Mark Allman, Patrik Arlos, Matt Mathis, Al Morton, Stanislav Shalunov, and Matt Zekauskas for their suggestions, comments, and reviews. We also thank members of the IETF IPPM Mailing List for their discussions and feedback on this document.

7. References

7.1. Normative References

- [RFC1812] Baker, F., "Requirements for IP Version 4 Routers", RFC 1812, June 1995.
- [RFC2330] Paxson, V., Almes, G., Mahdavi, J., and M. Mathis, "Framework for IP Performance Metrics", RFC 2330, May 1998.

7.2. Informative References

- [PDM] Dovrolis, C., Ramanathan, P., and D. Moore, "Packet Dispersion Techniques and a Capacity Estimation Methodology", IEEE/ACM Transactions on Networking 12(6): 963-977, December 2004.
- [RFC3095] Bormann, C., Burmeister, C., Degermark, M., Fukushima, H., Hannu, H., Jonsson, L-E., Hakenberg, R., Koren, T., Le, K., Liu, Z., Martensson, A., Miyazaki, A., Svanbro, K., Wiebke, T., Yoshimura, T., and H. Zheng, "RObust Header Compression (ROHC): Framework and four profiles: RTP, UDP, ESP, and uncompressed", RFC 3095, July 2001.
- [RFC3148] Mathis, M. and M. Allman, "A Framework for Defining Empirical Bulk Transfer Capacity Metrics", RFC 3148, July 2001.
- [V44] ITU Telecommunication Standardization Sector (ITU-T) Recommendation V.44, "Data Compression Procedures", November 2000.

Authors' Addresses

Phil Chimento
JHU Applied Physics Lab
11100 Johns Hopkins Road
Laurel, Maryland 20723-6099
USA

Phone: +1-240-228-1743
Fax: +1-240-228-0789
EMail: Philip.Chimento@jhuapl.edu

Joseph Ishac
NASA Glenn Research Center
21000 Brookpark Road, MS 54-5
Cleveland, Ohio 44135
USA

Phone: +1-216-433-6587
Fax: +1-216-433-8705
EMail: jishac@nasa.gov

Full Copyright Statement

Copyright (C) The IETF Trust (2008).

This document is subject to the rights, licenses and restrictions contained in BCP 78, and except as set forth therein, the authors retain all their rights.

This document and the information contained herein are provided on an "AS IS" basis and THE CONTRIBUTOR, THE ORGANIZATION HE/SHE REPRESENTS OR IS SPONSORED BY (IF ANY), THE INTERNET SOCIETY, THE IETF TRUST AND THE INTERNET ENGINEERING TASK FORCE DISCLAIM ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO ANY WARRANTY THAT THE USE OF THE INFORMATION HEREIN WILL NOT INFRINGE ANY RIGHTS OR ANY IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE.

Intellectual Property

The IETF takes no position regarding the validity or scope of any Intellectual Property Rights or other rights that might be claimed to pertain to the implementation or use of the technology described in this document or the extent to which any license under such rights might or might not be available; nor does it represent that it has made any independent effort to identify any such rights. Information on the procedures with respect to rights in RFC documents can be found in BCP 78 and BCP 79.

Copies of IPR disclosures made to the IETF Secretariat and any assurances of licenses to be made available, or the result of an attempt made to obtain a general license or permission for the use of such proprietary rights by implementers or users of this specification can be obtained from the IETF on-line IPR repository at <http://www.ietf.org/ipr>.

The IETF invites any interested party to bring to its attention any copyrights, patents or patent applications, or other proprietary rights that may cover technology that may be required to implement this standard. Please address the information to the IETF at ietf-ipr@ietf.org.

