Internet Traffic Periodicities and Oscillations: 
A Brief Review

Reginald D. Smith

Bouchet-Franklin Research Institute, PO Box 10051, Rochester, NY 14610

Abstract

Internet traffic displays many persistent periodicities (oscillations) on a large range of time scales. This paper describes the measurement methodology to detect Internet traffic periodicities and also describes the main periodicities in Internet traffic.

Key words: internet traffic, packets, FFT, wavelets, periodicities

1 Introduction

Internet traffic has exploded in the last fifteen years as an area of intense theoretical and experimental research. As the largest engineered infrastructure and information system in human history, the Internet’s staggering size and complexity are reinforced by its decentralized and self-organizing structure. Using packets of encapsulated data and a commonly agreed protocol suite, the Internet has far outgrown its origins as ARPANET whose traffic has demanded new models and ways of thinking to understand and predict.

Amongst the earliest discoveries were the researches of Leland and Wilson [1] who identified the non-Poisson nature of Internet traffic. This was followed by the seminal paper of Leland, Taqqu, Willinger, and Wilson [2] which proved that Internet packet interarrival times are both self-similar and portray long-range dependence. Though self-similarity is present at all time scales, it is most well-defined when traffic is stationary, an assumption that can only last a few hours at the most. The lack of stationarity on long time scales is due to one of the most widely known periodicities (or oscillations) in Internet traffic, the diurnal cycle with 12 and 24 hour peaks.

Email address: rsmith@bouchet-franklin.org (Reginald D. Smith).
Internet periodicities are not new and have been well-studied since the earliest days of large-scale measurements of packet traffic, however, they rarely receive primary attention in discussions of traffic and are often mentioned only as an aside or a footnote. Gradually, however, they are gaining more attention. This new area of research has been dubbed *network spectroscopy* [3] or *Internet spectroscopy*. In this paper, they will take front and center as the most important periodicities, as well as the techniques to measure them, are described.

2 Detection Methodologies

Identifying periodicities in Internet traffic is, in general, not markedly different from standard spectral analysis of any time series. The same cautions apply with sampling rates and the Nyquist theorem to determine the highest identifiable frequency as well as to be aware of possible aliasing. In addition, the sampling period is important due to the large ranges of magnitudes the periods of Internet periodicities occupy.

The standard method is covered in [4,5]. A continuous time series is collected and binned with a sampling rate $p$ where the number of packets arriving every $p$ interval seconds are counted. Next, to remove the DC component of the signal, every time step has the mean of the entire time series subtracted from it. Next you calculate the autocovariance (ACVF) of the adjusted time series. where for a time series of $N$ sampling periods (total sampling time $pN$) the ACVF, $c$ at lag, $k$ is defined as

$$c(k) = \sum_{t=0}^{N-k-1} (X(t) - \bar{X})(X(t+k) - \bar{X})$$

(1)

with a typical lag range chosen of $0 < k < N/2$. Finally, a Fourier transform is taken of the ACVF with maximum lag $M$ and the periodogram created from the absolute value (amplitude) of the Fourier series

$$P(f) = \left| \sum_{k=0}^{M-1} c(k)e^{-i2\pi fk} \right|$$

(2)

A resulting periodogram (see figure 1) has several typical features. First, low frequency $1/f$ noise can be present, again testifying to the self-similar nature of the traffic. This can sometimes obscure low-frequency periodicities in the data. Second, are any periodicities, their harmonics, and occasionally even small peaks perhaps representing nonlinear mixing of a sort between two periodicities, often with periods of different orders of magnitude.
2.1 Wavelet methods

Given the nonstationary nature of Internet traffic and the frequent presence of transients, methods based on the Fourier transform can only give an incomplete view of the periodic dynamics of Internet traffic. In particular, especially for rapidly changing periodicities such as those caused by RTT of flows, periodicities may only be temporary before shifting, disappearing, or being displaced. Wavelet methods have been developed in great theoretical and practical detail in the last several decades to allow for the analysis of a signal’s periodic nature on multiple times scales. Wavelet techniques will not be covered here in detail though there are many good references \[6,7,8,9\]. The continuous wavelet function on the signal \(x(t)\), here an Internet traffic trace, is given for a mother wavelet, \(\psi\) with \(a\) representing a stretching coefficient (scale) and \(b\) represents a translation coefficient (time)

\[
T(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^* \left( \frac{t - b}{a} \right) dt
\]

In figure 1 alongside the FFT of the signal is a contour plot generated by plotting \(T(a, b)\) using the Morlet mother wavelet over 12 octaves. One of the key advantages of wavelets is seeing the periodic variation over time. The y-axis represents the period of the signal represented and the x-axis is the time of the traffic trace in seconds. A first feature is the continuous strong periodicity at 30 seconds as a result of the update packets. A second and more intriguing feature are the inverse triangular ‘bursts’ of high frequency traffic with an average period close to one hour. These are update packets generated by route flapping, which are damped for a maximum period of one hour according to the most common presets for route flapping damping. The packets with the most pernicious flapping routers announcing withdrawals were removed in the third figure where the hourly oscillation largely disappears.

3 Traffic oscillations/periodicities

There are a plethora of traffic periodicities that represent oscillations in traffic over periods of many orders of magnitude from milliseconds to weeks. Broido, et. al. \[10\] believe there are thousands of periodic processes in the Internet. The sheer range of the periods of the periodicities means that many times, only certain periodicities appear in packet arrival time series due either to the sampling rate or sampling duration. This is one of the reasons why a comprehensive description of all Internet periodicities has rarely been done.
Internet periodicities have origins which broadly correspond to two general causes: first, there are protocol or data transmission driven periodicities. These range on the time scale from microseconds to seconds, or in rare cases, hours. These periodicities can again be broken down into two smaller groups, periodicities driven by packet data transmission on the link layer and periodicities
Fig. 2. A rough breakdown of the major periodicities in Internet traffic showing the responsible protocols and their period in seconds. The periodicities span over 12 orders of magnitude and different protocol layers tend to operate on different time scales.

driven by protocol behavior on the transport layer.

Second are application driven periodicities. Their periods range on the time scale of minutes to hours to weeks, and quite possibly longer. These are all generated from activities at the application layer, either by automated applications such as BGP or DNS or user driven applications via HTTP or other user application protocols.

The major known periodicities are summarized in figure 2 and will be described in detail in the next two subsections.
3.1 Key Periodicities: Link and Transport Layer

A key link level periodicity due to the throughput of packet transmission of a link and can be deduced from the equation:

\[ f = \frac{T}{s} \]  

(4)

Where \(T\) is the average throughput of the link and \(s\) is the average packet size at the link level. The base frequency is the rate of packet emission across the link at the optimum throughput and packet size. The base frequency for data transmission is given by

\[ f_{\text{max}} = \frac{B}{\text{MTU}} \]  

(5)

where \(B\) is the bandwidth of the link and the packet size is the MTU packet size. Therefore for 1 Gigabit, 100 Mbps, and 10 Mbps Ethernet links with MTU sizes of 1500 bytes, the theoretical optimal base frequencies are 83.3 kHz, 8.3 kHz, and 833 Hz respectively. Other technologies have their own specific periods such as SONET frames identified with periods of 125µs\[3\].

These are among the most difficult traffic to identify due to the need for high sampling rates of packet traffic. At a minimum, a microsecond sampling rate is usually necessary to make sure you can identify all link-layer periodicities. It is rare that both link layer and other periodicities are displayed together since the massive memory overhead of recording the timestamp of almost every packet is necessary.

The link layer periodicities are receiving much of the attention in the research, however, due to their possible use in inferring bottlenecks and malicious traffic. The main practical applications being researched are inferring network path characteristics such as bandwidth, digital fingerprinting of link transmissions, and detecting malicious attack traffic by changes in the frequency domain of the transmission signal. [13][14] use analysis of the distribution of packet interarrival times to infer congestion and bottlenecks on network paths upstream. In [4][15][16][17][18] various measures of packet arrival distributions, particularly in the frequency domain, are being tested to recognize and analyze distributed denial of service or other malicious attacks against computer networks. Inspecting the frequency domain of a signal can also reveal the fingerprints of the various link level technologies used along the route of the signal as is done in [10][19].

The transport layer also produces its own periodicities. In particular, both TCP and ICMP often times operate bidirectional flows with the interarrival
of ACK packets corresponding to the RTT between the source and destination
[10,15,20], often in the range of 10 ms to 1 s. Instead of just frequency peaks
there usually are wide bands corresponding to the dominant RTT in the TCP
or ICMP traffic measured. According to most equations of TCP throughput
such as that by Semke et. al. [21] the throughput of TCP depends inversely on
the RTT so that the TCP RTT periodicities often can give a relative estimate
of throughput of the flows producing them and the distribution of RTT for
flows in the traffic trace. Exact estimates are difficult though since packet loss
and maximum segment size are usually unknown. ICMP, though a connection-
less protocol also has echo replies which can also appear as periodicities if
they are persistent through time.

3.2 Key Periodicities: Application Layer

Once you rise to periods above one second, application layer periodicities dom-
inate the spectrum. These come from a variety of sources including software
settings and human activity. At the low end are the 30s and sometimes 60s
periodicities in BGP traffic. The 30s oscillation, shown in figure 1, is the most
common set time for routers to advertise their presence and continuing func-
tion to neighboring routers using KEEPALIVE BGP updates. These are the
strongest periodicities present in BGP traffic. Large-scale topological pertur-
bations such as BGP storms can also produce transient periodicities in traffic
such as large-scale route flapping which is shown in figure 1.

UDP traffic periodicities are rarely consistent and large-scale and are generally
generated by DNS, the largest application using UDP. Claffy et. al. identified
periodicities of DNS updates transmitted with periods of 75 minutes, 1 hour,
and 24 hours due to default settings in Windows 2000 and XP DNS software[3].
They warn that such software settings could possibly cause problems in Inter-
net traffic if they lead to harmful periods of traffic oscillations and congestion.
Large numbers of usually source and software specific UDP periodicities were
also identified by Brondman [22].

User traffic driven periodicities were the first known and most easily recog-
nized. The first discovered and most well-known periodicity is the 24 hour
diurnal cycle and its companion cycle of 12 hours. These cycles have been
known for decades and reported as early as 1980 and again in 1991 as well
as in many subsequent studies [23,24,25,26,27,28,29]. This obviously refers to
the 24 hour work-day and its 12-hour second harmonic as well as activity
from around the globe. The other major periodicity from human behavior is
the week with a period of 7 days [25,26,30] and a second harmonic at 3.5
days and barely perceptible third harmonic at 2.3 days. There are reports as
well of seasonal variations in traffic over months [12], but mostly these have
not been firmly characterized. Long period oscillations have been linked to possible causes of congestion and other network behavior related to network monitoring [27,28]. One note is that user traffic driven periodicities tend to appear in protocols that are directly used by most end users. The periodicities appear TCP/IP not UDP/IP and are mainly attributable to activity with the HTTP and SMTP protocols. They also often do not appear in networks with low traffic or research aims such as the now defunct 6Bone IPv6 test network.

4 Discussion

These periodicities range in roughly 12 orders of magnitude. However, they share one particular characteristic. Namely, the longer the period of the periodicity, the less likely it is to betray variations in period or phase over time. For example, the diurnal and weekly periodicities have their roots in human activity and are based on the Earth’s rotation and the seven week social convention. These do not vary appreciably over long-time periods and since they help drive human behavior which drives traffic, these could be considered the most permanent of all periodicities and this is partially why these were the earliest known. The BGP KEEPALIVE updates and DNS updates are based on commonly agreed software settings. These also do not vary appreciably and only change by user preference. However, the transport and link layer periodicities are much more variable. The RTT of TCP or ICMP varies depending on the topological distance and congestion between two points. Hardly, stable variables. Assuming the bandwidth of the link layers is steady, the average packet size, which depends on both the maximum transmission unit (MTU) software settings can cause large variability to be seen in actual network traffic. Understanding the range of these periodicities is more important than memorizing a distance frequency value since it is always different depending on the time and place of measurement. Internet periodicities will likely play a large role in full characterization and simulation of Internet traffic. Hopefully further work will put them in their rightful place as fundamental phenomena of data traffic.

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