

Overcoming the Effects of Correlation in Packet Delay Measurements Using Inter-Packet Gaps[‡]

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Abstract - The end-to-end delay of packets in data streams is characterized with emphasis on effects due to cross traffic, sending rate, and packet size. Measurements indicate that modeling delay of a packet stream with high sending rates, as a fraction of bandwidth, is difficult due to the correlations among the delay values. The correlations among inter-packet gaps (IPG) at these rates, however, are negligible. At lower sending rates, the delay correlations are negligible, and the distribution of delay can be used as a delay model. We exploit the relation between delay and IPG to show that end-to-end delay can be approximated by a Markov process. Thus, a complete solution is presented for modeling delay for all sending rates. Further, a correlation estimation model is provided for delay and IPG values.

Keywords: Internet Measurements, Delay, Inter-packet gaps

1. INTRODUCTION

End-to-end delay of packets is an important characteristic that not only affects the application performance, but also provides information about the state of a network. Real-time applications are concerned with the average one-way delay and jitter [1]. For example, G.114 standard lists 150 milliseconds as the maximum one-way delay for voice-traffic, otherwise, the voice quality is deemed degraded. Internet Service Providers monitor delay characteristics to make routing decisions, e.g., higher delay in an end-end path may be attributed to congestion and the route is altered. Packet reordering and loss are also related to delay values [2].

Deterministic components of the packet delay, e.g., time to transmit and propagation delays depend on parameters such as packet length, line rate and physical distance. However, delays have other components due to queuing and processing that are random in nature. Queuing delays at intermediate nodes may vary due to the presence of cross-traffic, packets from other streams. Processing delays are affected by factors such as heterogeneity among the hardware of the nodes [3], traffic conditions, and variable lookup times in the routers.

Distributions of packet delay have been studied using queuing network models [5], system identification, and time-series approaches [6]. Mathematically, delay has been modeled using exponential, Weibull, and Pareto distributions as well

as time varying exponentials [7]. Delay distributions gathered via measurements have been observed to be gamma-like with heavy tail of Gaussian or triangular lobe [3]. In time-series approach, the model for delay is independent of any recent activity in the network [6].

Our work shows that the distribution of delay by itself does not always result in a complete model, due to correlations between the delay values of different packets in a stream. Network emulators like NISTNet [8] do use such correlation coefficients, to a limited extent, to generate delay values for data streams. For these reasons, we take a systems approach to obtain the delay distributions and study the correlations. Usually, delay measurements are performed either by sending probe packets at random intervals over a time interval, or by sending a continuous stream of packets with a constant inter-packet gap. In the former case, the resulting distribution is used as a model for the delay distribution of packets traversing between the same endpoints; this approach helps in understanding a network's behavior for individual packets. However, we are interested in the latter approach, in which the effect of network on a data stream is captured.

This paper presents a comprehensive study of end-to-end delays of packets in a data stream for different sending rates and different packet sizes. Measurements indicate that the delay distributions for data streams follow a spectrum of distributions ranging from gamma to beta. It is observed that significant correlations exist among delay values of successive packets at high sending rates, as a fraction of the bandwidth. Thus, the delay of any packet in the stream cannot be modeled using the delay distribution alone. On the other hand, it is observed that the inter-packet gaps (IPGs) at the receiver have negligible correlations at higher data rates. Thus, we show that the distribution of IPGs at these rates, by itself, can be used to characterize the end-to-end packet delay as well as the correlation among delays of successive packets. Based on the IPG distributions and using the relation between delay and IPG, delay is shown to approximate a Markov process at high rates, and the transition kernel of this Markov process depends on IPG distribution. At low rates, the delay values of successive packets are independent of each other; therefore, the delay distribution alone can characterize end-to-

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end delay dynamics. In addition, we provide a model to estimate the correlations among delay values and IPGs at high and low rates.

Section 2 discusses the experimental setup used for measurements. Delay distributions and a discussion on correlations between delay values are provided in section 3. In section 4, we discuss IPG distributions along with their correlograms and scatter plots. A delay model for packets in data streams and an estimation model for correlations are presented in section 5. Section 6 presents conclusions and future work.

2. EXPERIMENTAL SETUP

A comprehensive study of delay and IPG distributions of packet streams requires the following capabilities: generate data streams, measure the delay of each packet, measure IPGs, vary the sending rates and packet sizes, fit the measured values into known distributions, and tools to measure the dependence/independence among the values.

Packet delay is measured as the difference between the time stamps taken at the sender and the receiver when the first bit of the packet leaves the sender and when it enters the receiver respectively. A network-monitoring tool such as ‘tcpdump’ can provide the receiver timestamp, and the sending timestamp can be inserted as a part of the data content in the packet. However, using ‘tcpdump’ for delay measurements has several known problems, such as a receiver time stamp occurring only when OS kernel notes the packet. More than one packet could be queued by the time the kernel notes the arrival, and all the packets in the queue may get approximately the same arrival time stamp. Clock synchronization and clock skew can cause problems too. Numerous heuristic based techniques are used to reduce the effects due to clock issues [9], but they cannot eliminate the error. Clock skew is usually in the range of microseconds in an interval of few seconds. Thus, if the measurements are performed over networks within few seconds and the delays are in milliseconds range, most of these errors can be neglected. *Since we are interested in delay distributions, an offset can be used to counter the clock synchronization problem. For measurements, this offset is estimated by setting the first packet’s delay to the average one-way delay (measured by ping application).*

IPG is defined as the difference between the arrival times of the packets with consecutive sequence numbers. To obtain the order at the receiver, sequence numbers are inserted as a part of data in the packet structure.

For traffic generation, we used an Ixia 1600T chassis [10], which provides packet transmission and capture through dedicated hardware, along with a timestamp resolution of 20 nanoseconds with extremely low clock-drift. It also allows GPS based clock synchronization with remote Ixia boxes. The time stamping occurs as soon as the packet leaves/reaches the

customized NIC. It has enough processing power to stamp the departure packet’s first bit and add the value to its data contents at sender’s side. Measurements are presented for two end-to-end network connections (each with a bottleneck capacity of 100 Mbps) as follows:

Net-1: Ixia traffic generator at California Polytechnic (129.65.x.x) destined to another Ixia 1600T at Colorado State University (129.82.x.x). The average one-way delay is 22 milliseconds

Net-2: Ixia traffic generator at Colorado State University (129.82.x.x) destined to a Linux box at University of Massachusetts, Amherst (128.119.x.x). The average one-way delay is 28.5 milliseconds

Six UDP test streams of 20,000 packets each, corresponding to packet sizes 64, 80, 96, 128, 256 and 1024 bytes respectively, were sent one at a time over these networks. Delay and IPG measurements were carried out at sending rates of 0.5, 1, 10, 20, 30, 40, 50, 60, 70, 80 and 90 Mbps, achieved using a constant inter-packet gap at the sender. At the receiver end, in Net-1, Ixia capture-hardware adds the receive-timestamp along with the corresponding packet contents to a buffer. In Net-2, ‘tcpdump’ provides the arrival time stamping. At the same time, ‘Network Estimator’ (also known as ‘netest’) [11] was used to monitor the available bandwidth of the networks.

The measured delay and IPG values are then fitted with a set of standard distributions that includes beta, chi-square, Erlang, exponential, gamma, inverse Gauss, log-logistic, log-normal, Pareto, Pearson, Rayleigh, triangle, uniform and Weibull distributions. The three most commonly used goodness-of-fit (GoF) tests [12] are Chi-Square test (χ^2), Anderson-Darling statistic (A-D) and Kolmogorov-Smirnov statistic (K-S). K-S test statistic does not require binning thereby eliminating the error due to binning as in the χ^2 -test. Though A-D statistic is independent of bin-size, its emphasis is on tail distributions. Bestfit 5.0 software [13] is used to fit distributions, and K-S statistic is used as GoF criteria during analysis. The correlations between the values and the independence are tested using correlograms and scatter diagrams [14] respectively. On Net-1 and Net-2, we measured and modeled delay and IPG values for different rates and packet sizes using each GoF test. Also, the correlograms and scatter plots were taken for each of the cases. The conclusions of the paper are based on the entire set of measurements [15], while only a representative set of results are presented.

3. DELAY MEASUREMENTS

The measurements were taken at 11PM (EST) between Mar. 16, 2004 and Apr. 18, 2004. The process was repeated 20 times over this period to increase the confidence in the observations. During these hours, the cross-traffic (monitored by ‘netest’) remained within a narrow range; the available bandwidth varied between 65-70 Mbps in Net-1, and 60-65 Mbps in Net-2.

TABLE 1. DELAY DISTRIBUTIONS FOR VARIOUS SENDING RATES OVER NET-2, USING DIFFERENT GOF TESTS

Rate (Mbps)	Chi-square test		A-D test		K-S test	
	Fitted curve	Test value	Fitted curve	Test value	Fitted curve	Test value
0.5	Ex* (1155.9) Shift=26818	30488 (98 bins)	G† (33.313, 62.648) Shift=25886.85	Not available	G (9.43, 122.50) Shift=26818	0.0272
10	LL‡ (27483, 1134.5, 41938)	1185 (98 bins)	LL (27483, 1134.5, 41938)	29.10	G (4.99, 245.66) Shift=27510	0.0768
30	lnG§ (2737.6, 6077) Shift=26981.3	1092 (98 bins)	lnG (2737.6, 6077) Shift=26981.3	29.39	G (2.02, 1178.4) Shift=27332	0.0358
50	B** (70.699, 5.9617, -43.28, 41848)	218 (92 bins)	B (70.699, 5.9617, -43.28, 41848)	112.5	B (70.699, 5.9617, -43.28, 41848)	0.0751
70	B (1.12959, 0.66084, 28393, 60398)	202 (84 bins)	R†† (16901) Shift=27964	801.7	B (1.12959, 0.66084, 28393, 60398)	0.1237
90	B (1.1820, 0.83685, 28287, 75255)	333 (80 bins)	R (22911) Shift=26776	343.1	B (1.1820, 0.83685, 28287, 75255)	0.0305

For Net-1 and Net-2, the measured delay values were offset to make the first packet delay equal to 22 and 28.5 milliseconds respectively, (i.e., one-way delays using ping application) thus compensating for the difference in clocks. Since the delays are in the range of milliseconds, as explained earlier, it can safely be assumed that the effect due to clock skew is negligible.

3.1 Effect of GoF criteria

The choice of GoF criteria dictates the kind of distribution that fits the measurements. Table 1 summarizes the fits for Net-2 for different data rates and 64-byte packet size using different GoF tests, with parameters in microseconds. The listed test values correspond to the GoF test that qualifies the fit. The test value for χ^2 -test requires the number of bins for qualification to be specified. Taking an example, the entry for 0.5 Mbps data rate using K-S test led to G (9.43,122.50) Shift=26818, which indicates the standard gamma function with shape parameter 9.43 and scale parameter 122.5, but all the values are shifted by 26818 microseconds. The distributions in the table cover the set of all distributions that other researchers have observed, as discussed in section 1.

3.2 Effect of data rate and packet size

Fig. 1 shows the delay distributions that fit the delay values computed for different sending rates in Net-1, for packet size of 64 bytes. Column graphs represent the input data while the line graphs show the fitted curve. Delay in milliseconds is plotted against the frequency of its occurrence. These results indicate that the delay distribution approaches gamma/Erlang

distribution when the data rate is low. For higher data rates, it approach beta distribution.

Fig. 2(a) and (b) depict the delay distributions for Net-1 and Net-2, with varying packet sizes for different data rates. The plots show the type of distributions in vertical bar that fit the delay values when sent at a rate given on vertical axis, for data stream with packet size in bytes indicated on horizontal axis. For a packet size of 64 bytes in Net-1, the distribution that fits the delays is gamma for data rates 0-30 Mbps, Pareto until 60 Mbps, followed by beta for higher rates. The same distributions fit the delay values for 80 bytes, but the ranges are 0-50 Mbps, 50-80 Mbps, and 80 Mbps or higher for gamma, Pareto and beta respectively. Thus, given a network, the type of distributions that fit the delay values remains the same. However, the type of distribution that fits for a given data rate changes with packet size.

Though the delay distributions in Fig. 2 show a clear demarcation of the distribution regions, we believe that the transition from one distribution to the other is gradual. In case of Net-2, the same set of distributions fits the delay values for varied data rates with changing packet sizes. Nevertheless, the change in distribution regions with packet size for Net-2 is similar to that of Net-1.

Moreover, an interesting observation was made when we computed the gap between the last-bit of the previous packet to the first-bit of the current packet at sender's side. This is termed as packet separation. For the same packet separation, the transition occurs in the type of distribution, even for different packet sizes.

* Exponential (b): b>0 continuous scale parameter

† Erlang (m, b): m > 0 integral shape parameter, b > 0 continuous scale parameter; if m is real, Erlang (E) is Gamma (G)

‡ Log-logistic (s, b, a): s location parameter, b > 0 scale parameter, a > 0 shape parameter

§ Inverse Gauss (x, y): x, y > 0

** Beta (w, x, y, z): w, x > 0 continuous shape parameters, y < z, y - minimum boundary and z - maximum boundary

†† Raleigh (b), b > 0 continuous scale parameter

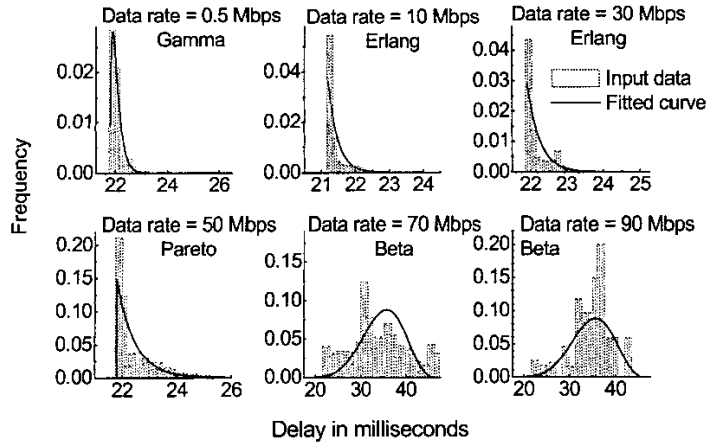


Figure 1. Delay data and distribution fits for 64-byte packets in Net-1 for different data rates

TABLE 2 VARIATION OF DELAY DISTRIBUTION WITH PACKET SEPARATION (GAP IN MICROSECONDS) IN NET-2, FOR DIFFERENT PACKET SIZES

Size/ Rate (Mbps)	64 bytes		80 bytes		96 bytes	
	Fit	Gap	Fit	Gap	Fit	Gap
40	E (1.6278.3) Shift=27883	16.2	G (5.644,149.3) Shift=28200	19.3	G (5.06,177.04) Shift=27835	22.37
50	B (70.699,5.961, -43.28,41848)	12.8	G (3.2414) Shift=27532	15.3	G (2.04,4769.4) Shift=27970	17.73
60	B (1.0885,0.697, 28454,70554)	10.6	B (1.307,0.5689, 28254,80963)	12.6	G (2.03,14589) Shift=27897	14.64
70	B (1.12959,0.66, 28393,60398)	9.0	B (2.6301,1.152, 26843,45024)	10.7	B (1.307,0.5689, 28254,80963)	12.43
80	B (1.1473,0.666, 28256,72533)	7.8	B (1.594,1.083, 27962,54890)	9.3	B (1.307,0.5689, 28254,80963)	10.77

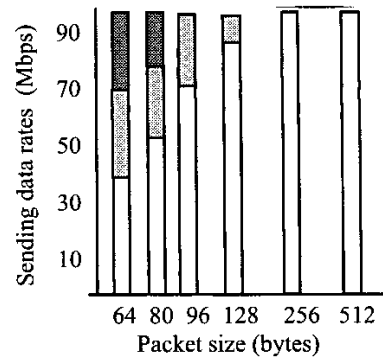
Table 2 shows the packet separations, sending rates and corresponding delay distributions for packet sizes 64, 80 and 96 bytes of Net-2. Here the transition from gamma distribution to beta (shaded) occurs around 12.8 microseconds of packet separation. It is also observed that for the same sending rate, 64-byte packets have more losses than for the 80- byte or higher packet sizes. This phenomenon is quite intuitive. To send at the same rate, the 64-byte frame test stream needs a larger number of packets with smaller gaps compared to 96-byte frame, making the stream more vulnerable to cross-traffic streams. This leads to more congestion while waiting on processing and queuing resources, leading to higher drop rates.

3.3 Correlation and delay model

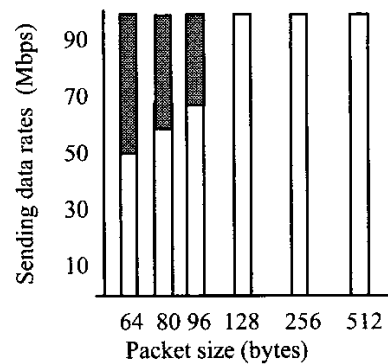
Next, we look at the correlation among delay values in the packet stream. If the delay values are correlated, i.e., the delay of the current packet depends on the delay of the previous packets, then correlation values are required to fully

characterize the packet delay process. Fig. 3 shows the correlogram, i.e., correlation between the delay values for 64-byte packets of Net-1 up to 20 lags. For lag equal to 'j', the correlogram denotes the correlation between delays of all pairs of packets separated by 'j' positions, e.g., packet 'k' and packet 'k+j'. It can be seen that the correlation coefficients are high for consecutive delay values for higher rates, i.e., 80, 60, 40, 20 Mbps. For these rates, the dependency among the delay values extends beyond 20 positions. However, for lower rates, e.g., 0.5 Mbps, it can be observed that the correlation is negligible. In addition, if the packet size is higher the correlations are lower for the same data rate.

To understand the reason for correlations, let us imagine a packet of a data stream being processed at an intermediate node. If more packets of this stream arrive before the first packet's departure, then the delays of new arrivals depend on the current packet's processing component of the delay.



(a)



(b)

□ Gamma ▒ Pareto ■ Beta

Figure 2. Delay distributions spectrums with respect to packet size and data rate (Not to scale) (a) for Net-1 (b) for Net-2

These waiting times produce a cumulative effect at higher data rates, which leads to high correlations. At low rates such as 0.5 Mbps, the correlation is almost zero, and hence the delays can be safely assumed to be independent and identically distributed (i.i.d). Thus, the delay distribution of the packets is sufficient to model the delay at lower data rates. However, for higher data rates, the correlation between the values has to be characterized. These correlations can be computed using IPG as shown in section 5.

4. INTER-PACKET GAP MEASUREMENTS

To measure IPG values from the captured trace, we identify the consecutive packets by using the sequence number fields in the data and then compute the difference between arrival times of consecutive packets. The sender side inter-packet gap is subtracted from this difference to obtain G_i , the random variable that denotes the inter-packet gap between packets 'i' and 'i+1'. Though this offset shifts the curve by an amount equal to the sending gap, it has no effect on the analysis. Using the K-S test, IPG distributions are also observed to form a spectrum of distributions. For Net-1, the distributions range from Pareto to log-logistic. In the case of Net-2, the IPG distributions are always log-logistic. As in the case for delay, the type of GoF test, the packet size and the packet spacing, affect IPG distributions.

Interestingly, the correlation coefficients for IPGs are negligible for higher rates. For lower rates (e.g., 0.5 Mbps, 1 Mbps), there is a correlation between consecutive IPGs for lag one as shown in Fig. 4. When sending rates are very low, the probability of cross-traffic affecting two consecutive packets is very low. Thus, if an IPG of two packets is increased in transit, the next IPG is likely to decrease leading to dependence between two consecutive IPGs. Fig. 5 illustrates scatter plots of consecutive IPG pairs for Net-1 data for sending rates of 90, 60 and 30 Mbps. It can be seen that there is no relation between these values. Thus, IPG can be safely assumed to be i.i.d at higher rates.

5. RELATION BETWEEN DELAY AND IPG

Let $D = \{D_i, i = 1, 2, \dots\}$ denote the random process corresponding to the end-to-end delay, where D_i is the delay of the i^{th} packet. As shown in section 4, at low data rates, the correlation between successive delay values is negligible, and thus D_i is i.i.d. for different 'i'. Let $G = \{G_i, i = 1, 2, \dots\}$ denote the random process where G_i is the IPG between i^{th} and $(i+1)^{\text{th}}$ packets. As shown earlier, for higher data rates, G_i can be considered as i.i.d for different 'i'.

The delay and IPG are related by $D_{i+1} = D_i + G_i$, resulting in $D_{i+1} = D_1 + G_1 + \dots + G_i$. This expression is similar to the 'random walk' problem. Since the increments are i.i.d and D_1 and G_i are independent, at higher data rates, D is a Markov process, i.e., dependence of D_{i+1} on the delays of prior packets is captured by that of the previous packet namely, D_i . Given the mean delay of packets, we can derive the

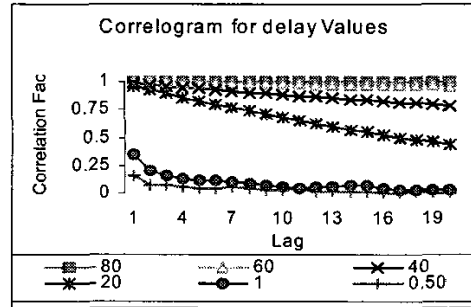


Figure 3. Correlograms for lag = 1 to 20 of delay values in Net-1 for varied data rates (80Mbps – 0.5 Mbps) and 64-byte frame size

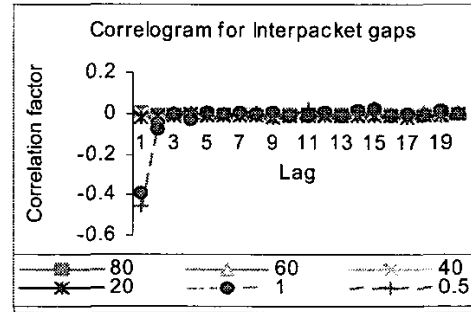


Figure 4. Correlograms for lag = 1 to 20 of IPG values for varied data rates (80 Mbps – 0.5 Mbps) in Net-1

distribution of delay along with the correlation values. Therefore, for higher data rates, the delay can be modeled by using IPG distributions alone. Though the discussion here is limited to delay model, one can exploit the properties of Markov chain to understand the delay random process better.

Next, we derive the relationship between the IPG process, the delay process and the correlation among IPG and delay values. Let $Cov(D_i, D_k)$ and $Cov(G_i, G_k)$ be the covariance between i^{th} and k^{th} samples of delay and IPG respectively. Let $(\sigma_D)^2$ and $(\sigma_G)^2$ be the variances of delay and IPG respectively. The correlation coefficient for D_i and D_k , is given by

$$R_{i,k}^{(D)} = \frac{Cov(D_i, D_k)}{(\sigma_D, \sigma_{D_i})}$$

At low data rates, since D_i, D_k ($i \neq k$) are i.i.d, $R_{i,k}^{(D)} = 0$.

For higher rates, D_i and D_k are dependent; however, the packet gaps are independent. Since $D_k = D_i + G_{i+1} + \dots + G_{k-1}$ (for $k > i$):

$$R_{i,k}^{(D)} = \frac{Cov(D_i, D_i)}{(\sigma_{D_i}, \sigma_{D_i + G_{i+1} + \dots + G_k})} + \sum_{j=i+1}^k \frac{Cov(D_i, G_j)}{(\sigma_{D_i}, \sigma_{D_i + G_{i+1} + \dots + G_k})}$$

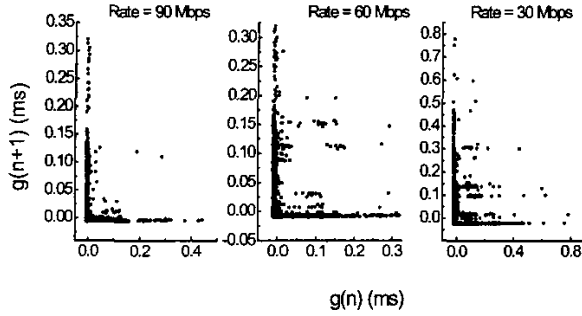


Figure 5. Scatter plots for IPG with lag 1 of Net-2 at different sending rates

The second term on right hand side is equal to zero as D_i and G_j are independent. Therefore,

$$R_{i,k}^{(D)} = \left(\sqrt{1 + k \left(\frac{\sigma_G}{\sigma_D} \right)^2} \right)^{-1/2}$$

Table 3 shows the correlation coefficients calculated with this expression for $R_{i,k}^{(D)}$ for $k=1, 2, \dots, 8$ against the observed correlation through measurements for a data rate of 20 Mbps through Net-1. In addition, with the determination of 'k' for which $R_{i,k}^{(D)}$ is negligible, we can compute the lag for which the delay dependency ceases to exist.

Let $R_{i,k}^{(G)}$ be the correlation coefficient between i^{th} and k^{th} samples of IPG. For low data rates ($i \neq k$),

$$R_{i,k}^{(G)} = \frac{\text{Cov}(D_{i-1}, D_{i-1})}{2\sqrt{(\sigma_{D_{i-1}}^2 + \sigma_{D_{i-1}}^2)}} = -1/2$$

for $k-i = 1$.

As $G_i = D_{i+1} - D_i$, $G_{i+1} = D_{i+2} - D_{i+1}$, and $\{D_i\}$ are i.i.d., $R_{i,k}^{(G)} = 0$ for $k-i > 1$. For higher data rates as $\{G_i\}$ are i.i.d., $R_{i,k}^{(G)} = 0$ for ($i \neq k$). Using Fig. 4, the correlation coefficients for lower rates, 0.5 Mbps and 1 Mbps, are -0.4 and -0.45 respectively as compared to -0.5 computed above.

6. CONCLUSIONS AND FUTURE WORK

Measurements indicate that for a given packet size, the delay distributions of packets in data streams form a spectrum, which ranges from beta (for higher data rates) to gamma (for lower data rates). However, the transition from one distribution to the other depends on the packet separation within the data stream. At low data rates, because of independence in delay values, the delay distribution itself characterizes the delay process completely. On the other hand, delay values have significant correlations at high data rates. Thus, it is necessary to include the correlation values along with the delay distribution for its characterization. Since, the IPG values are not correlated at these rates, the delay process is shown to approximate a Markov process.

TABLE 3. FOR NET-1- MEASURED VS COMPUTED CORRELATION COEFFICIENTS, RATE = 20 MBPS

Lag	Measured Value	Computed $R_{i,k}^{(D)}$
1	0.95	0.95
2	0.92	0.91
3	0.89	0.86
4	0.86	0.83
5	0.79	0.78
6	0.76	0.76
7	0.73	0.73
8	0.70	0.71

Thus, to model delay for higher rates, the IPG distribution and mean delay value are sufficient.

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