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# Empirical Network Jitter Measurements for the Simulation of a Networked Control System

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***Abstract*—Delay variation or jitter is an inherent feature of packet switched communication networks due to bottlenecks. In communication systems buffering is commonly used to mitigate in real time multimedia applications at the expense of an additional delay. This method is therefore not suitable for control systems implemented over packet switched communication networks due to the additional delay which can make the system unstable. Hence, jitter modelling and management is necessary. This paper focuses on the development and experimental verification of a suitable jitter model for wireless and wired network bottlenecks. The effects of jitter are then investigated by quantifying the performance of a simulated Networked Control System (NCS). According to the results, the reduction in attenuation due to jitter compared to a jitter free benchmark ranges from approximately 0.01-0.04dB depending on the encoding type.**

***Index Terms*—Networked control systems, cyber-physical systems, delay variation, self similarity, communication networks**

## I. INTRODUCTION

A Networked Control Systems (NCS) is a control system where the medium of a communication network is used to interconnect at least part of a control loop consisting of sensors, the controller and actuators. Due to numerous factors such as as low infrastructure costs, versatility and ease of deployment they are highly desired in industrial automation [1] [2]. Packet switched NCS have a long history of use for discrete event systems such as industrial automation [3] [4] [5] and electric substation automation [6] [7].

The use of a packet switched communication network as the medium of connection can have undesirable effects such as delay and delay variation (jitter) [8] [9]. In a discrete event system, the system can be designed to tolerate a delay. For example in the electric substation automation protocol IEC61850, a Generic Object Oriented Substation Event (GOOSE) packet with critical information such as a message for tripping an overcurrent relay has an acceptable maximum delay of 4ms [10].

In the case of systems with continous or hybrid (combined discrete and continuous) dynamics al network induced delay less than the sampling time (i.e., small delay case) can be neglected [11]. Delays larger than the sampling time induce an error that can affect the stability of the sytem [12].

The mitigation of jitter is an essential requirement to maintain the Quality of Service (QoS) in communication networks [13]. Studies have shown the possible effects of sampling jitter in a control system [14] [15] [16]. These effects would inevitably manifest themselves in a NCS due to inherent jitter of the communication network. For critical multimedia applications such as video streaming and voice communication, it can be controlled by buffering [17]. The downside of this strategy is the introduction of a significant time lag that can affect the stability of the control system [12].

### A. Contribution

Numerous models have been proposed for jitter analysis, these include models based upon the Laplacian distribution [18] [19], the Cauchy distribution [20] and self similar attribute of network traffic [21]. Such models are based upon traffic data obtained from WANs where significant path differences occur due to routing. In Local Area Network (LAN) based control systems, such events would not take place. Hence, there is a need to obtain the jitter model of such a network using experimental data. The effects of jitter are then investigated by quantifying the performance of a simulated NCS.

## II. PRELIMINARIES

### A. Notations

In this paper, the symbol $*$ is used to denote a convolution operation while the terms pdf and pmf are used to denote the probabilitiy density function and probabilty mass function of a random variable respectively. The symbols $\mathbb{R}$ and $\mathbb{Z}^+$, represent the set of real numbers and positive integers (excluding zero) respectively.

### B. Delay Causing Factors

When data is transmitted over a communication network, delays are inevitable. Modelling of this can be done by decomposing the delay into its constituent delay causing factors [22] [23] between the source and the destination. This allows the delay $(\tau)$ to be expressed as,

$$\tau = \tau_T + \tau_P + \tau_Q + \tau_A + \tau_F \qquad (1)$$

where $\tau_T$ is the transmission delay, $\tau_P$ is the propagation delay, $\tau_Q$ is the queuing delay and $\tau_A$ is the channel acquisition delay in a packet mode mulitiple access network. The framing delay $\tau_F$ is due to framing of the samples into a packet. In a LAN, the significant jitter causing factors are $\tau_Q$ and $\tau_A$ because $\tau_T$

can be neglected because the medium bitrate, $B \ll T_S$[1] where $T_S$ is the sensor sampling rate.

For wireless networks, the signals propagate at the speed of light ($c$). In a coaxial cable, the signal propagation velocity is around 0.78c [24]. At such speeds, the signal would have to travel around 200km to incur a delay of 1ms which is comparable to the sampling rate of a typical control system. Thus, for wireless LAN interfaces and NCS running over interconnected LANs, the delay ($\tau_P$ ) and delay variation due to path propagation differences can be neglected.

### C. *Traffic Generation Process*

Studies have shown that network traffic has Long Range Dependance (LRD) [25] [26] with self similarity. The network traffic can be represented as a time series ($X(t)$) which consists of the series of packet arrival times $\{t_i\}$ where $i \in \mathbb{Z}^+$ and the series of packet sizes $\{x_i\}$.

$$X(t) \quad = \quad \sum_{i \in \mathbb{Z}^+} x_i \delta(t - t_i) \qquad (2)$$

where $\delta$ is the Kroneker delta function. From this, different series can be derived depending on the service time requirement for the packets once queued. For example, a tunneling protocol or intrusion detection system might have a service time dependant on the size of the packet. A router will only need the destination address of the packet. Hence, the service time ($t_c \doteq 1/\mu$) can be considered constant. A simple renewal process can be used to model the arrival of packets at the queue based upon the interarrival time pdf $f_\tau$. Proposed and experimentally verified distributions for $f_\tau$ include approximately exponential [27], Pareto [28] [26] and inverse Gaussian [29].

### D. *Queue Delay Model*

Consider a $G/G/1$ queue with a service time distribution, $f_S$. Let $n \in \mathbb{Z}^+$ and define $u_n$ as the time difference between the service time for packet $n$ and the interarrival time of packet $n+1$.

$$u_n \quad = \quad t_n - \tau_{n+1} \qquad (3)$$

$$f_U(t) \quad = \quad f_S(t) * f_\tau(-t) \qquad (4)$$

Where $f_U$ is the pdf of $u_n$. The traffic generation process is stationary and $t_n$ and $\tau_{n+1}$ are independant. The waiting time for packet $n+1$ is given by the Lindley equation,

$$w_{n+1} \quad = \quad (w_n + u_n) \vee 0 \qquad (5)$$

The pdf for $w_{n+1}(t)$ is obtained from the nonlinear operation,

$$w_{n+1}(t) \quad = \quad [w_n(t) * f_U(t)]u(t) \qquad (6)$$

The queue approaches steady state as $n \longrightarrow \infty$. When this is reached the condition $E[u_n] < 0$ is necessary for stability and the pdf of the waiting time converges (i.e. $w_{n+1}(t) = w_n(t)$). Analytic solutions for (5) using transform methods have been around for a long time [30] but have limited application. In most cases a numerical solution of (6) is required [31] with the initial condition being $w_1(t) = \delta(t)$, corresponding to an empty queue with zero delay.

## III. NETWORK BOTTLENECK JITTER MODELS

A network bottleneck is a link in with a severe bandwidth constraint that leads to network traffic congestion. During congestion, queue occupancy near the bottlneck increases resulting in longer delays. The self similar nature of network traffic results in variation of queue occupancy which translates into delay variation (jitter). In this section the models of Section II are used to derive jitter models for wired and wireless bottlenecks.

### A. *Wireless Bottleneck Jitter Model*

In a packet switched wireless network, the air interface is taken as the bottleneck. Jitter occurs due to the variable time taken for a transmitting station to acquire the wireless channel. Due to high attenuation and the hidden terminal problem, detecting a collision is not feasible. Collision avoidance is used instead with the receiving station sending an acknowledgment to indicate successful transmission. If the transmitting station does not receive the acknolwedgment packet, a collision is assumed and the random exponential backoff algorithm is used to retransmit the packet.

In IEEE 802.11 (WiFi) when a new packet is ready for transmission (Figure 1), the transmitter initializes a clock using a random value $c_0 \in (0, W_0 - 1)$ ($c_0 \in \mathbb{Z}^+$ and $W_0 \in 2^n$) and decrements the clock for each time slot. The clock is frozen if the channel is sensed busy. The probability of the channel being busy is taken as $p$.

The packet is transmitted once the clock reaches zero. If a collision occurs, the clock is restarted using a larger random value which is given by $c_i \in (0, W_i - 1)$ where $W_i = 2^i W_0$ for the $i^{th}$ collision. This continues until $b$ collisions have passed after which $W_i = 2^b W_0$. The station will give up after $m$ collisions where $0 < b < m$.

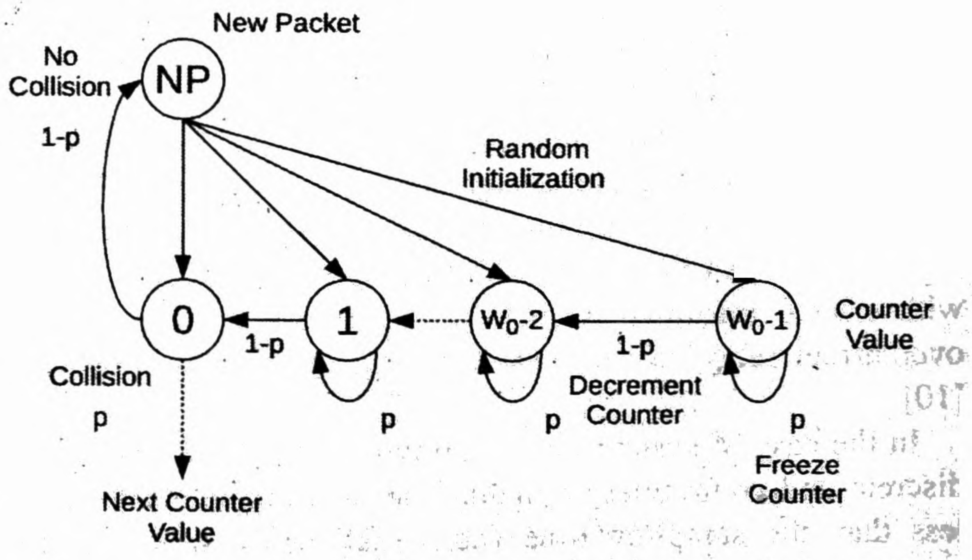

Fig. 1. IEEE 802.11 (WiFi) Random Exponential Backoff Algorithm

**Assumption 1.** *The channel occupancy is approximated to,*

$$p \quad = \quad \frac{s_0}{E[T]} \qquad (7)$$

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[1] For a network transmitting at 10Mbps, $B = 100ns$ while the typical sampling time of the sensors of the NCS would be $> 1ms$.

*where $s_0$ is the slot duration.*

In [32], the number of wireless nodes is necessary to determine $p$. From this assumption, it is only necessary to know the statistical properties of the wireless network traffic.

To simplify the model, counter freezes are not considered. The delay in transmitting a packet for a single stage is given the random counter value $C_i$. Hence the total delay for the $i^{th}$ collision in terms of time slots is given by,

$$D_i = \sum_{j=0}^{i} C_j \tag{8}$$

where $C_i$ a discrete random variable with a pmf of,

$$f_{C_i}[k] = \begin{cases} c[k] & 1 \leq k \leq W_i \\ 0 & \text{elsewhere} \end{cases} \tag{9}$$

Therefore the total delay for the $i^{th}$ collision is given by,

$$f_{D_i}[k] = \begin{cases} f_{C_0}[k] * f_{C_1}[k] * \cdots * f_{C_i}[k] & 0 \leq i < b \\ f_{C_0}[k] * f_{C_1}[k] * \cdots * f_{C_b}[k] & b \leq i \leq m \\ 0 & \text{elsewhere} \end{cases} \tag{10}$$

resulting in a channel acquisition delay distribution with pmf,

$$f_{CA}[k] = (1-p) \sum_{i=0}^{m-1} p^i f_{D_i}[k] + p^m f_{D_m}[k] \tag{11}$$

Thus, the jitter distribution due to channel acquisition in a wireless network is given in terms of time slots by,

$$J_{CA}[k] = f_{CA}[-k] * f_{CA}[k] \tag{12}$$

For the sample parameters $W_0 = 8$, $b = 8$ and $m = 16$, Figure 2 gives the channel acquisition jitter when $C_i$ is uniformly distributed.

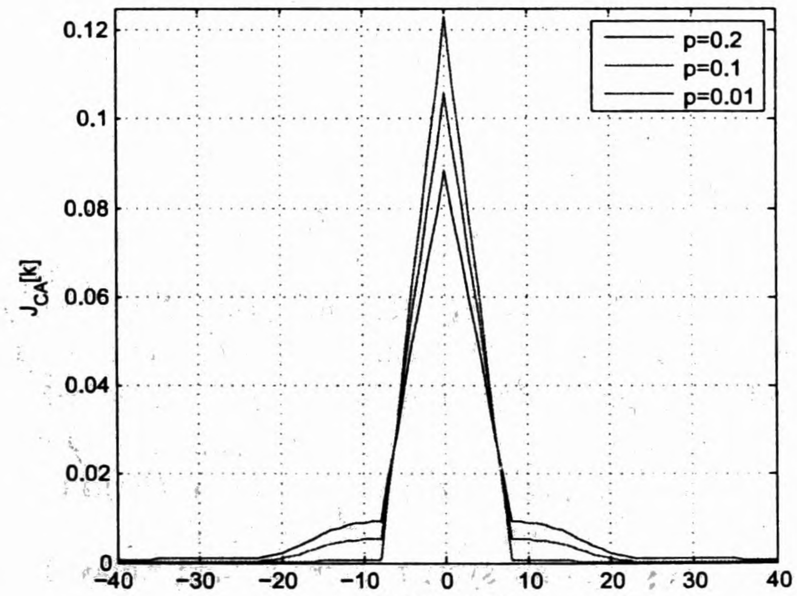

Fig. 2. Jitter Distribution for Uniformly Initialized Counters

## *B. Wired Bottleneck Jitter Model*

The IEEE 802.3 (Ethernet) wired network protocol was originally developed with explicit collision detection [33]. However, this mechanism became inefficient with increased bitrates and impractical when devices with different speeds (*i.e.* 10Mbps, 100Mbps and Gigabit Ethernet) are used in the same network. Therefore, modern IEEE 802.3 networks are point to point with buffering at switches.

In the bottleneck, the switch of the NCS is approximated as a $G/G/1$ queue with a constant service time since only routing takes place. The jitter distribution for the router will be given by the pdf of the difference of two succesive delays,

$$J_R(t) = w_{n+1} - w_n \tag{13}$$

The jitter can be modelled for three types of traffic,

1) *Stable traffic* when $E[S] > E[T]$ excluding the trivial case when $min(T) > max(S)$ for which no accumulation of packets will take place within the queue and the delay will equal the service time.
2) *Critical traffic* for $E[S] \approx E[T]$
3) *Unstable traffic* where $E[S] < E[T]$ and tail drop occurs.

Figure 3 shows sample jitter distributions for the above three types of traffic obtained for uniform interarrival distributions. From this, the anticipated result would be for the jitter distribution to spread out with increased traffic.

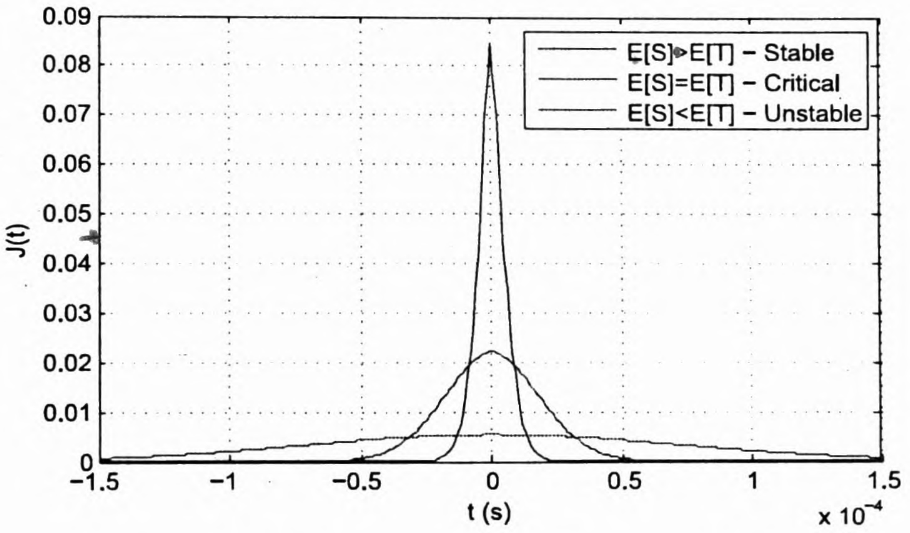

Fig. 3. Sample Jitter Distributions for a $G/G/1$ Queue

## IV. EMPIRICAL MEASUREMENTS

In this section the theoretical models of the previous section (Section III) are verified using experimental data. The best model and appropirate parameters will be subsequently used to simulate the ship roll stabilizer NCS in Section V.

## *A. Wireless Bottleneck Jitter Model*

The wireless bottleneck jitter model is experimentally verified by analysing the jitter statistics of Beacon Frames (BF) of WiFi Wireless Access Points (WAP). A BF is a special packet transmitted by a WAP without buffering at a specific interval to indicate its presence to a wireless node. The BFs transmitted by two WAPs located at the Department of Electronic and Telecommunication Engineering, University of Moratuwa were captured during a 320 minute period. The two WAPs, AP1 and AP2 transmit BFs at intervals of 0.1s and 0.2s respectively resulting in 192406 and 76064 packets being captured. The minimum time increment of the traffic capture using Airmon and Wireshark is $1\mu s$. The normalized jitter distributions for both WAPs (Figure 4) differs from that of a uniformly initialized counter (Figure 2) due to the existence of two prominant peaks on either side of the main peak.

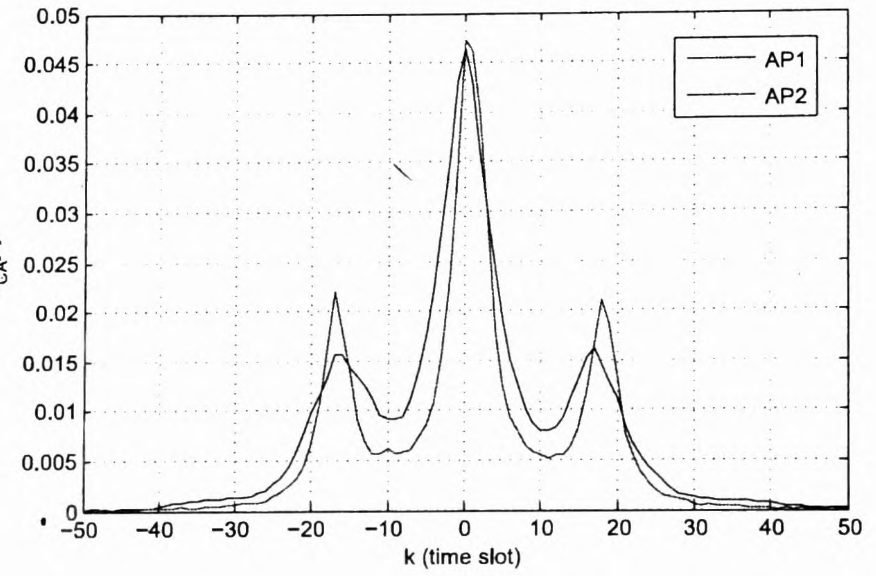

Fig. 4. Measured Wireless Jitter Distribution

### *B. Wired Bottleneck Jitter Model*

The wired bottleneck jitter model was verified using an experimental setup located at the Department of Mechanical Engineering, University of Melbourne. A total of 100000 packets were transmitted at a 0.1s interval through a network switch under simulated minimal, heavy and unstable traffic. The results (Figure 5) do not show a clear spreading for unstable traffic as in Figure 3 due to packet drops.

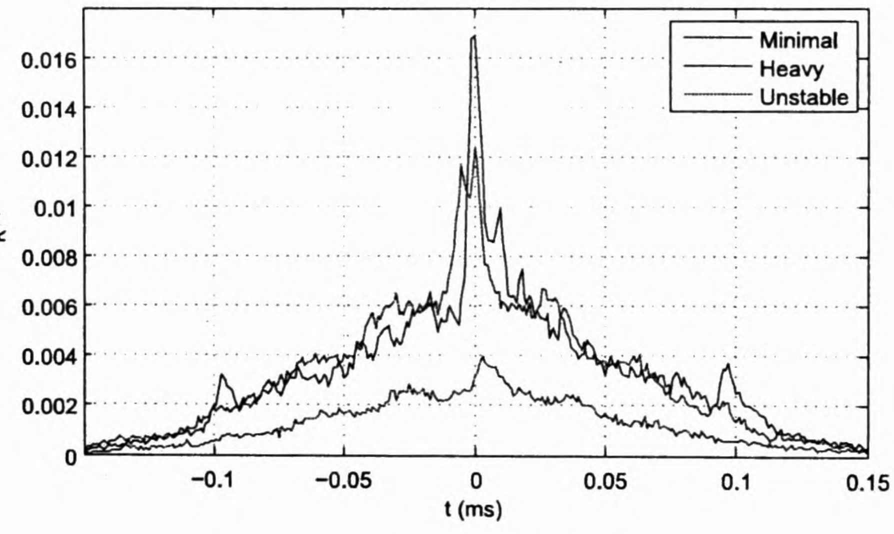

Fig. 5. Measured Wired Jitter Distribution

In order to determine the best zero centered statistical jitter distribution, the MATLAB Curve Fitting Toolbox is used to fit the observed data into a Gaussian (14), Laplace (15) and Cauchy (16) distributions using the Nonlinear Least Squares (NLS) method. These distributions are given by,

$$f_G(x) = ae^{-\left(\frac{x}{b}\right)^2} \tag{14}$$

$$f_L(x) = ae^{-\frac{|x|}{b}} \tag{15}$$

$$f_C(x) = \frac{a}{\left(\frac{x}{b}\right)^2+1} \tag{16}$$

Table I gives the estimates of the distribution parameters and Table II gives the goodness of fit of each distribution. According to the results, the best fit is obtained for the Laplacian distribution for both minimal and heavy traffic while all three distributions have a very similar score when the traffic is unstable.

TABLE I

NLS PARAMETER ESTIMATION (95% CONFIDENCE)

| Parameter | | Minimal | Heavy | Unstable |
|---|---|---|---|---|
| Gaussian | a | 0.007111 | 0.00725 | 0.00274 |
| | b | 0.07582 | 0.07478 | 0.07729 |
| Laplacian | a | 0.009779 | 0.00946 | 0.00345 |
| | b | 0.05287 | 0.05615 | 0.06142 |
| Cauchy | a | 0.008437 | 0.008092 | 0.002987 |
| | b | 0.04452 | 0.04878 | 0.05271 |

TABLE II

HYPOTHESIS $R^2$ SCORE

| Hypothesis | $R^2$ Score | | |
|---|---|---|---|
| | Minimal | Heavy | Unstable |
| Gaussian | 0.7297 | 0.8944 | 0.9396 |
| Laplacian | 0.8358 | 0.9327 | 0.9331 |
| Cauchy | 0.7858 | 0.9079 | 0.9377 |

## V. APPLICATION TO A NETWORKED CONTROL SYSTEM

The example considered is a simplified ship roll stabilizer (Fig. 6) of [34] which attenuates a bounded wave disturbance ($w$) on a linear hull using a saturating stabilizing fin. The deflection angle of the hull ($x_1$) is remotely measured by an inclination sensor, encoded and transmitted along a communication network with a delay. This results in an error $e_1$. This error cannot be directly measured but its effect can be indirectly observed in terms of the disturbance attenuation of the system. The sampling time is set to 0.1ms.

For the system $K, K_0, a, b > 0$ and $x \in \mathbb{R}^2, u \in \mathbb{R}, w \in \mathbb{R}$, the system dynamics are given by,

$$\begin{pmatrix} \dot{x}_2 \\ \dot{x}_1 \end{pmatrix} = \begin{pmatrix} -a & -b \\ 1 & 0 \end{pmatrix} \begin{pmatrix} x_2 \\ x_1 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} (sat(-KK_0(x_1 - e_1)) + w). \tag{17}$$

The origin is the only equilibrium point for (17). Global asymptotic stability for (17) can be shown using the radially unbounded Lyapunov function $V$.

$$V(x) = \frac{KK_0}{2}(bx_1^2 + x_2^2) + \int_0^{KK_0x_1} sat(u)du$$

Similar to [34], the system gain $K$ and delay $\tau$ form a constraint equation

$$3\tau KK_0 < 1. \tag{18}$$

Taking $K_0 = b = 4$, $a = 0.35$ and $|sat(r)| \leq 0.2$ for a delay of up to $0.4ms$ (four samples), $K = 4$ would be sufficient to satisfy (18). The system is subjected to a bounded wave disturbance of Fig. 7 with an amplitude of 0.2 units which is superimposed with Gaussian noise. It is repeated with a period of 16s and each simulation is run for a total of 100s.

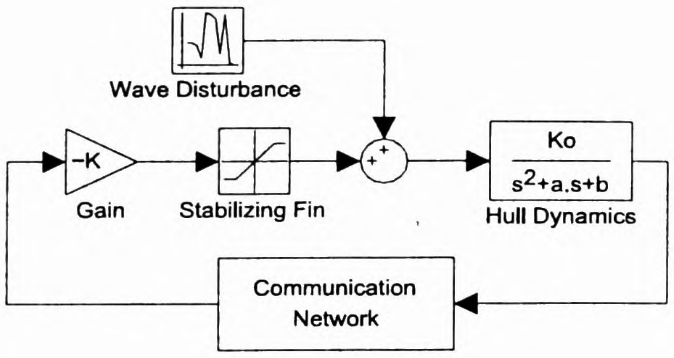

Fig. 6. Nonlinear Ship Roll Stabilizer

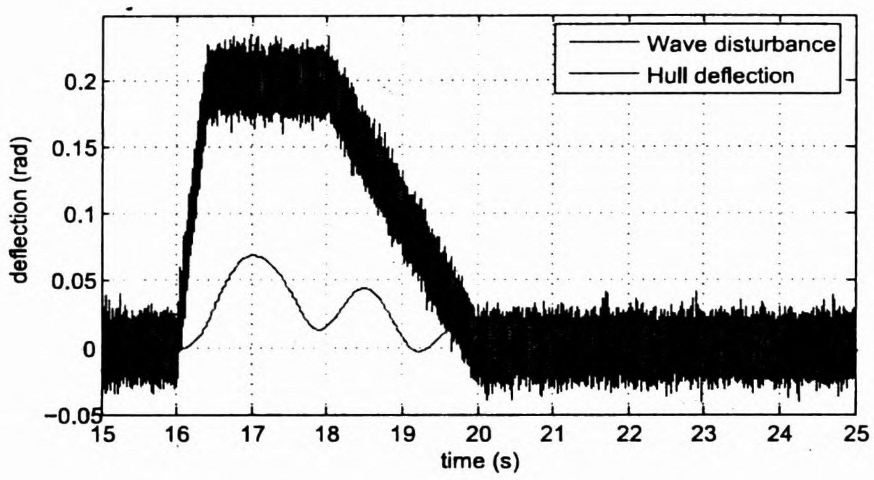

Fig. 7. Wave Disturbance and Sample Hull Deflection

### A. Jitter Model

From the results of Section IV, the jitter for a wireless bottleneck is small when compared to the sampling time of 0.1ms. Hence, regardless of whether a wired or wireless LAN is used for the feedback path, only the queuing delay needs to be considered. The jitter distribution is approximated by the discretized distribution of Table III. The performance is compared by running benchmarks for periodic sampling and each encoding scheme. This is then compared with the jittered case.

TABLE III
DERIVED NETWORK JITTER DISTRIBUTION

| t (ms) | -0.2 | -0.1 | 0 | 0.1 | 0.2 |
|---|---|---|---|---|---|
| J(t) | 0 | 0.025 | 0.95 | 0.025 | 0 |

The purpose of the encoding scheme is to reduce the bandwidth of a signal by minimizing signal redundancy. The encoding schemes used are Memory Based Event Triggering (MBET) [35] with an event triggering threshold $e_T$ and ETADM [34]. For ETADM, the main parameters are the maximum step size $S_{\max}$, the minimum step size $S_{\min}$ (which also equals the event triggering threshold $e_T$ for an accurate signal reconstruction) and the step increment $\Delta S$. The parameters of each encoding scheme are given in Table IV. Both encoding schemes minimize signal redundancy by *sporadic sampling*. In the case of MBET, the periodically sampled input is transmitted over the communication network only if the difference between it and the previously transmitted value exceed $e_T$. In ETADM, the difference between two periodic samples is encoded into an adaptive step size and transmitted if the encoded value exceeds the minimum step size $S_{\min}$.

TABLE IV
ENCODING SCHEME PARAMETERS

| Encoding | Parameters | | | |
|---|---|---|---|---|
| | $S_{\max}$ | $S_{\min}$ | $\Delta S$ | $e_T$ |
| MBET | – | – | – | 0.001 |
| ETADM | 0.001 | 0.004 | 0.001 | – |

### B. Performance Results

The simulation results for each system are given in Table V. In all cases the presence of jitter reduces the disturbance attenuation by approximately 0.01-0.04dB. This reduction is less than the reduction of performance due to the encoding scheme which is 0.32dB for MBET and 0.18dB for ETADM. The reason for ETADM having better disturbance attenuation compared to MBET is due to the passive (dissipative) nature of the reconstructed estimate of ETADM due to the use of a lossy integrator. In MBET, the reconstructed estimate is obtained using a Zero Order Hold (ZOH) which is marginally stable (i.e., non-passive).

TABLE V
DISTURBANCE ATTENUATION COMPARISON

| Encoding | Disturbance Attenuation (dB) | |
|---|---|---|
| | Benchmark | Jitter |
| Benchmark | 12.7568 | 12.7408 |
| MBET | 12.4370 | 12.4105 |
| ETADM | 12.5728 | 12.5575 |

## VI. CONCLUSIONS

This paper focuses on the development and experimental verification of a suitable jitter model for wireless and wired network bottlenecks. The effects of jitter are then investigated by quantifying the performance of a simulated Networked Control System (NCS). According to the results, the reduction in attenuation due to jitter compared to a jitter free benchmark ranges from approximately 0.01-0.04dB depending on the encoding type. This is less than the reduction due to the attenuation itself which is 0.32dB for MBET and 0.18dB for ETADM. In terms of future work, the main focus should be in the direction of a suitable theoretical model for better understanding of the effects of error induced by jitter on stability and performance. The incorporation of statistical properties of network traffic is another promising avenue of research.

## VII. ACKNOWLEDGEMENT

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