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STATISTIC MODEL OF DYNAMIC DELAY AND DROPOUT ON CELLULAR DATA NETWORKED CONTROL SYSTEM

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Abstract

Delay and dropout are important parameters influence overall control performance in Networked Control System (NCS). The goal of this research is to find a model of delay and dropout of data communication link in the NCS. Experiments have been done in this research to a water level control of boiler tank as part of the NCS based on internet communication network using High Speed Packet Access (HSPA) cellular technology. By this experiments have been obtained closed-loop system response as well as data delay and dropout of data packets. This research contributes on modeling of the NCS which is combination of controlled plant and data communication link. Another contribution is statistical model of delay and dropout on the NCS.

Keywords: Network delay, Data dropout, Network model, NCS, HSPA.

1. Introduction

In recent two decades, wireless data communication network have been implemented in control system to integrate the system components such as sensors, actuators and controllers. The advantage of wireless technology enables simple installation of large scale area systems, and allows controller and plant to be placed at different locations. This system is currently known as a Wireless Networked Control System (NCS) [1].

As Internet technology becomes more advantages at low-cost and wide coverage for many applications of remote system, the Internet usage in NCS has been more promising [2]. Internet-based NCS, therefore, could be a promised application on the Internet of Things.

Nomenclatures

a	Delay on C-A link, s
$A_{(.)}$	System matrix of (.)
b	Delay on S-C link, s
$B_{(.)}$	Input matrix of (.)
$C_{(.)}$	Output matrix of (.)
$D_{(.)}$	Input-output matrix of (.)
$H(q^{-1})$	Closed loop transfer function
K_I	Integral coefficient
K_P	Proportional Coefficient
$L(q^{-1})$	Denominator polynomials of transfer function
$M(q^{-1})$	Numerator polynomials of transfer function
$O_{(k)}$	Observation at k
O_{seq}	Hidden observation sequence
p_{ji}	Probability of state changes (from state j to state i)
$P(q^{-1})$	Plant transfer function
q^{-1}	Backwards shift operator
$S_{(k)}$	State at k
$\mathrm{S_{seq}}$	State sequence
$U_{(.)}$	Control input of (.)
$\hat{U}$	Estimated control input
$X_{(.)}$	State variable of (.)
$Y_{(.)}$	Output signal of (.)
$\hat{Y}$	Estimated output signal
(.)	(P: plant, C : Controller, CA : C-A Link, SC : S-C Link)

Greek Symbols

α	Dropout on C-A link
β	Dropout on S-C link
$\varepsilon(t)$	White noise

Abbreviations

ADSL	Asymmetric Digital Subscriber Line
ARX	Autoregressive Exogenous
BR	Bit Rate, bps
C-A	Controller to Actuator
HMM	Hidden Markov Model
HSPA	High Speed Packet Access
MIMO	Multi-Input Multi-Output
M2M	Machine to Machine
NCS	Networked Control System
OPC	OLE for Process Control
PI	Proportional Integral
RTT	Round Trip Time, s
SISO	Multi-Input Multi-Output
S-C	Sensor to Controller
TCP	Transmission Control Protocol
TTI	Transmission Time Interval, s
UDP	User Datagram Protocol

Nowadays, there are several options of Internet access technology such as cellular technology, Satellite, ADSL (Asymmetric Digital Subscriber Line), and optic communication [3]. Cellular technologies have advantages in the availability of extensive coverage network area, affordable prices of modem and in particular, continuous evolution to increase the Internet speed [4]. Moreover, the speed of data transmission over cellular technology has met the needs of data streaming applications by 3G technology and beyond.

However, there is an inherent problem in application of an NCS that is data communication networks may generate random delay and random dropout. Delay and dropout influence overall control system performance and therefore should not be ignored in design procedure of an NCS [5 - 7]. In an NCS, delay is defined as a time needed by data packet go from transmitter to receiver. If the delay is longer than life time allowed in network, the data packet will be dropped out. Hence in an NCS, Packet Loss is defined as a percentage of data dropouts [1].

Many papers discussed design of the control system with delay and dropouts in network were considered as disturbances. Implementation of various observers such as Periodic Observer and Robust Fuzzy Observer has been proposed such as by Simon et al. [8] and Jing et al. [9] respectively. Other papers considered the knowledge of network condition to improve NCS implementation has been proposed by estimating parameters of the network [10, 11].

Delay and dropout on a cellular network are important parameters which are needed to realize the NCS. A number of papers have reported performance of 3G and 3.5G cellular network were conducted by simulation [12, 13]. In the NCS applications, it is necessary to have an accurate model of the network delay and dropout in network using empirical data [14]. Jurvansuu et al. [15] have completed an experimental with UDP (User Datagram Protocol) and TCP (Transmission Control Protocol) test over HSPA (High Speed Packet Access) network to obtain the delay and dropout. Meanwhile, Jang et al. [16] and Soto et al [17] have conducted experiments with high speed vehicle to obtain the network parameters including delay and dropout. Popovic et al. [18] have completed experiments to obtain a live HSPA network performance on two types of traffic patterns, M2M and online Gaming. Moreover, there are other papers considering the same subject [19, 20]. Larson et al. [19] has measured end-to-end delay as RTT (Round Trip Time) over 3G and 4G networks. The experiment has been conducted by sending a 20 bytes UDP packet to an echo server every second. The measurement data has been divided into 1-minute duration bins. This papaer has studied characterisation of excessive RTT delays. Hu et al. [20] analysed massive traces from large cellular data networks in several major cities in China and in Southeast countries. They have analysed aggregate traffic, throughput, RTT, and loss rate, and how they were affected by cellular modes, applications, time, and geographic locations.

Several of mentioned research discuss delay as RTT [12, 18-20], and some of them have one way uplink delay and downlink delay on average [15-17, 20], and some with dropout represented as packet loss rate [13, 16, 19, 20]. Particularly, Refs. [13, 16, 19, 20] also discuss cumulative distribution function from measurement data. However, they did not discuss modelling of data to regenerate delay.

The mentioned researchers mostly measure time of delay from user equipment to server, where used a file or traffic generator to generate data to be uploaded to server and to be downloaded from the server. Other papers were using echo server or ping to measure RTT delay. Meanwhile, this papaer proposes a measurement scenario to measure delay from one user equipment, in this case is a controller, to other user equipment, where in this case are sensor and actuator. In this real time experiment, the traffic was generated by the implemented NCS.

Feedback signal from Sensor and control signal on NCS will be transmitted on one way, respectively from sensor to controller and from controller to actuator. Therefore, NCS implementation needs information of delay and dropout on one-way communication. Murti et al. [21] tested an HSPA network to get information of delay and dropout occurred during transferring data packets partially in both directions of communication. The test was carried out specifically using simulated data transmission without a controller element in the network.

This research has realized a NCS of water level control of BDT921 boiler using Internet communication which is based on HSPA cellular technology. In this research we obtained response of the closed-loop system (NCS) as well as one-way delay and dropout in the network which were caused by data packet. The results of this research are the model of plant with internet communication link and model of probability distribution of delay for each communication direction.

Structure of this paper is organized as follows. Section 2 discusses a proposed system model of an NCS. Section 3 discusses the experiment method which is conducted in this research. Section 4 discusses the results of experiment and analysis, and conclusions will be given in Section 5.

2. Model of the Networked Control System

In general a NCS may be explained by a block diagram as shown by Fig. 1. A controller is connected to plant and sensor by data communication links. Data communication system from controller to actuator is called C-A Link, while S-C Link is data communication system from sensor to controller.

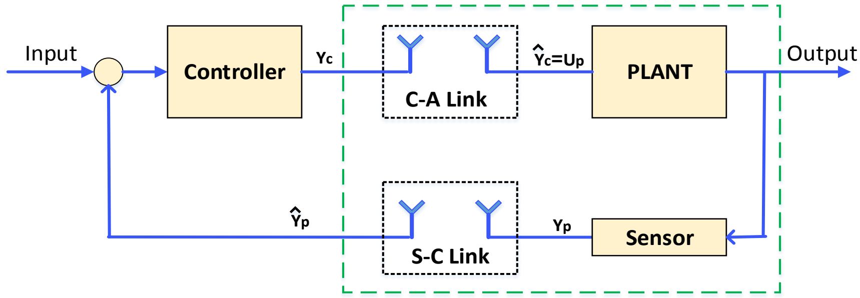


Fig. 1. NCS block diagram.

Referring to Fig. 1, output signal of the controller, called control signal, Y_C, is sent to actuator through C-A Link. The data packet of Y_C may be experienced a delay or lost, and to be represented as $U_P = \hat{Y}_C = f(Y_C, a, \alpha)$. Likewise, feedback signal from sensor, that is output of the plant, is sent to controller through the S-C Link. The data packet of Y_P may also experience a delay or lost, and it is represented as $U_C = \hat{Y}_P = f(Y_P, b, \beta)$. By those background, the controller shown in Fig. 1 is facing a plant system including the networks as shown in Fig. 2.

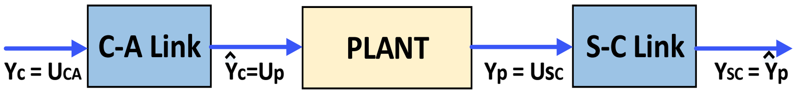


Fig. 2. Plant with data communication.

Referring to Fig. 2, consider the plant has a state-space model as:

$$X_P(k+1) = A_P X_P(k) + B_P U_P(k)$$
$$Y_P(k) = C_P X_P(k) + D_P U_P(k) \quad (1)$$

Meanwhile, C-A link has a state-space model as:

$$X_{CA}(k+1) = A_{CA} X_{CA}(k) + B_{CA} U_{CA}(k)$$
$$Y_{CA}(k) = C_{CA} X_{CA}(k) \quad (2)$$

and S-C link has a model of:

$$X_{SC}(k+1) = A_{SC} X_{SC}(k) + B_{SC} U_{SC}(k)$$
$$Y_{SC}(k) = C_{SC} X_{SC}(k) \quad (3)$$

In Fig. 2, the control signal U is sent to the plant through C-A link. Y_C will be the input signal for block C-A or $Y_C = U = U_{CA}$. Meanwhile output of the block C-A, Y_{CA}, will be a control signal that is received by the plant, $\hat{U} = Y_{CA} = U_P$. Similarly, plant output of the feedback signal Y_P will be sent to the controller through S-C link and become input signal for S-C link, $Y_P = U_{SC}$. The output signal from S-C link is the estimated output of the plant, $\hat{Y}_P = Y_{SC}$.

Output of plant, $Y_P(k)$, will experienced a delay of b seconds and if the delay is greater than time allowed, the data will be dropped out. When the network is in good condition and data from the plant is received in controller then $\beta = 0$. Conversely, if the data network is in a bad condition due to some reasons and it causes the dropout at S-C link, then $\beta = 1$. Similar to the data output from the controller, $Y_C(k)$ will be delivered to the plant through internet, and it will be delayed for a seconds. $\alpha = 0$ when the data was arrived at the plant and $\alpha = 1$ in case of dropout at C-A link.

Using basic concept of delay and dropout given in [1], the received control signal through C-A link can be written as:

$$U_P(k) = (1-\alpha)U_{CA}(k-a) + \alpha U_P(k-1) \quad (4)$$

We assumed that $X_{CA}(k) = U_P(k)$ and $Y_{CA}(k) = U_P(k)$

Thus, state space model of C-A link can be written down as:

$$X_{CA}(k+1) = \alpha X_{CA}(k) + (1-\alpha)U_{CA}(k+1-a)$$
$$Y_{CA}(k) = 1.X_{CA}(k) \quad (5)$$

Since $X_{CA}(k) = U_P(k)$, therefore Eq. (1) can be rewritten to be:

$$X_P(k+1) = A_P X_P(k) + B_P X_{CA}(k) \tag{6}$$
$$Y_P(k) = C_P.X_P(k) + D_P X_{CA}(k)$$

Similarly, the feedback signal from sensor to controller through S-A link can be written as:

$$\hat{Y}_P(k) = (1-\beta)Y_P(k-b) + \beta\hat{Y}_P(k-1) \tag{7}$$

We assume that:

$X_{SC}(k) = \hat{Y}_P(k)$ and $Y_P(k) = U_{SC}(k)$

and $Y_P(k) = U_{SC}(k)$ therefore Eq. (3) can be rewritten to be:

$$X_{SC}(k+1) = \beta.X_{SC}(k) + (1-\beta)C_P.X_P(k+1-b) + (1-\beta)D_P X_{CA}(k+1-b) \tag{8}$$

Equations (5), (6) and (8) show that block of plant which is included data communication link has input signal $U_{CA}(k+1-a)$ and has states $X_{CA}(k)$, $X_P(k)$, $X_{SC}(k)$.

Let's assume:

$$X(k) = \begin{bmatrix} X_{CA}(k) \\ X_P(k) \\ X_{SC}(k) \end{bmatrix}$$

Thus, Eqs. (5), (6) and (8) can be rewritten to be :

$$X(k+1) = A_0 X(k) + A_1 X(k+1-b) + BU(k+1-a) \tag{9}$$
$$Y(k) = C\,X(k)$$

where

$$A_0 = \begin{bmatrix} \alpha & 0 & 0 \\ B_P & A_P & 0 \\ 0 & 0 & \beta \end{bmatrix} \quad A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ (1-\beta)D_P & (1-\beta)C_P & 0 \end{bmatrix} \quad B = \begin{bmatrix} (1-\alpha) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ D_P & C_P & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Equation (9) shows that the model of the system is not only constructed by plant parameters, but it also has parameters that were influenced by the values of a, b, α, and β, which are the delay and dropout on the network.

3. Delay and Dropout Measurement

To get a statistical model of the delay and dropout, an experiment has been performed as illustrated by Fig. 3. A Boiler Drum Tank of type BDT 921 was connected by an interface to an OPC Server. The OPC Server software from KEPServer was running on a computer at side A. The controller with OPC Client by IGNATION was connected to the OPC Server through Internet using HSPA modem. OPC Client was running on another computer at side B. The data communication that takes place between computer A and B was recorded using Wireshark on both sides.

The closed-loop system has implemented a PI controller to control water level in the boiler tank. Using Ziegler-Nicholas method and manual adjustment as fine tuning, then we have parameters of PI controller of *Kp* = 4 and *Ki* =0.181 with input reference from 33 cm to 83 cm. The Experiments were conducted with two scenarios to obtain data set of response system without Internet network, data set of response system with Internet network, and data set of delay and dropout.

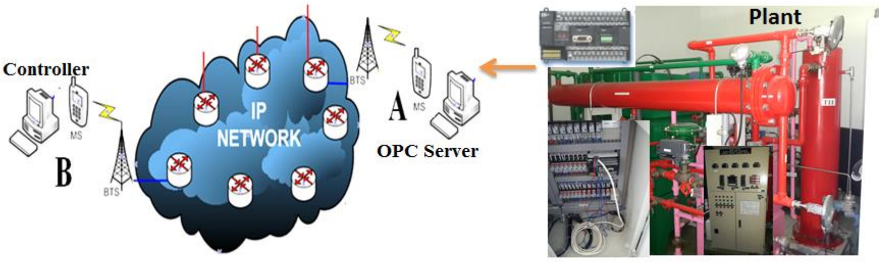


Fig. 3. Structure diagram of NCS experiment.

4. Result and Discussion

4.1. Control system without internet network

No Internet network in this case. Among elements of control system, they are plant including sensor and actuator, and controller are connected directly. To get a plant model, test has been carried out without Internet. Closed loop system was implemented using PI Controller. The water level in the tank was changed abruptly (step change) from 33 cm to 83 cm. The result has been obtained as shown in Fig. 4. Figure 4 shows the step response of system in percentage.

Using system identification tool of MATLAB, the model of the closed-loop system with ARX (Autoregressive Exogenous) structure has been obtained as shown in Fig. 5. ARX model is well suited for control design since this class of linear model is associated with a convex parameter estimation problem for both SISO and MIMO systems. A linear, discrete time, single input single output ARX model could be represented by the following equation:

$$L(q^{-1})y(t) = M(q^{-1})u(t) + \varepsilon(t), \; \varepsilon \in N(0, \sigma^2) \tag{10}$$

where $L(q^{-1})$ and $M(q^{-1})$ are polynomials of order n in the backwards shift operator q^{-1} and $\varepsilon(t)$ is white noise.

$$L(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + \cdots + a_n q^{-n} \tag{11}$$

$$M(q^{-1}) = b_1 q^{-1} + b_2 q^{-2} + \cdots + b_n q^{-n}$$

Figure 5 shows the simulated output of several ARX models. The index in ARX model are indicating a number of poles, number of zeros, and number of input samples that occur before the input affects the output. The best fits of each estimated ARX model is shown by Table 1. The ARX model of closed loop system of order 4 (ARX441) has the best fit value of 88.47 %. The input-output model of the closed loop system is given by

$$H(q^{-1}) = \frac{M(q^{-1})}{L(q^{-1})} \quad (12)$$

where

$L(q^{-1}) = 1 - 1.834\, q^{-1} + 0.8268\, q^{-2} + 0.02958\, q^{-3} - 0.009794 q^{-4}$

$M(q^{-1}) = 0.04062\, q^{-1} - 0.037333 q^{-2} - 0.02129 q^{-3} + 0.03059 q^{-4}$

Therefore, the plant model can be calculated and written as:

$$P(q^{-1}) = \frac{M(q^{-1})}{L(q^{-1})} \quad (13)$$

where

$L(q^{-1}) = 4.181 - 23.69\, q^{-1} + 55.78\, q^{-2} - 69.56 q^{-3} + 47.66\, q^{-4} - 15.77\, q^{-5} + 0.5841\, q^{-6} - 0.9632 q^{-7} - 0.1459\, q^{-8} - 0.01001\, q^{-9} - 0.001582\, q^{-10}$

$M(q^{-1}) = 0.04062\, q^{-1} - 0.1931\, q^{-2} + 0.345\, q^{-3} - 0.2334\, q^{-4} - 0.07439\, q^{-5} + 0.2154\, q^{-6} - 0.1241\, q^{-7} + 0.0225\, q^{-8} - 0.001713\, q^{-9} - 0.0002996\, q^{-10}$

It is strightforward to show that the plant is a stable system because all poles are inside of unit circle.

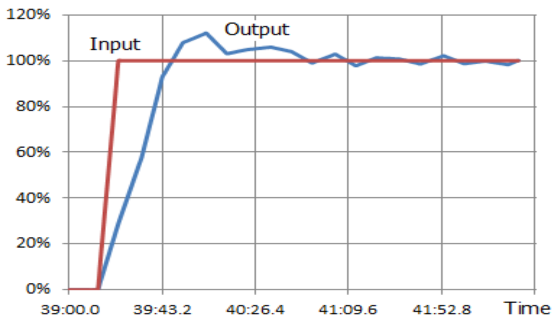


Fig. 4. Step response without network.

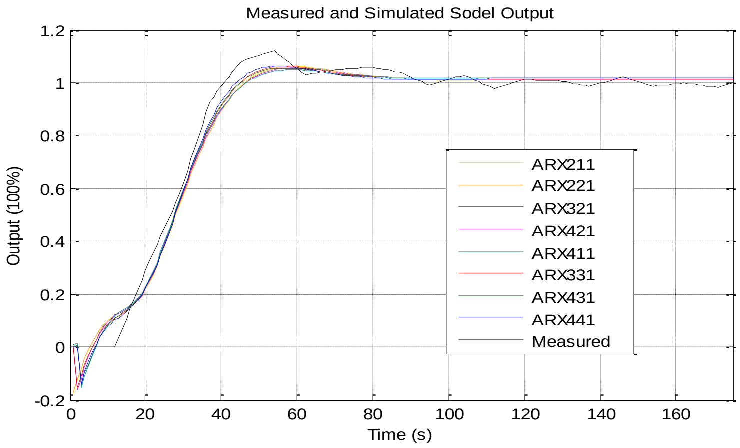


Fig. 5. Measured and simulated model output.

Table 1. Best Fit of simulated model to measured output.

ARX Model	Best Fits (%)
ARX441	88.47
ARX431	87.62
ARX331	87.3
ARX411	86.55
ARX421	86.55
ARX321	86.22
ARX221	85.72
ARX211	85.66

4.2. Control system with Internet network

This is an NCS, where connections of sensor to controller and controller to actuator are used internet networks. In this case the plant under controlled is included sensor and actuator as interfaces to the controller (See Figs. 1 and 2). To obtain set of data of delay and dropout, an experiment is conducted upon an NCS as shown in Fig. 3. Equation (12) with additional delay on network can be written as:

$$Y(k) = N(\tau)\frac{M(q^{-1})}{L(q^{-1})}U(k) \tag{14}$$

where N(τ) consists of delay on C-A link (a) and delay on S-C link (b). In condition of perfect model Eq. (14) should be equal to Eq. (9). But it is not necessary since Eq. (9) is the proposed model which consists of plant and network models as a system. The main issue is to obtain model of delay and dropout on the network.

Figure 6 shows the response of system has 4.95% of overshoot, and settling time was achieved in 23 seconds with steady-state error of 0.45%. Based on the test results, we concluded that the system is stable and works normally. Therefore, the captured data traffic over NCS with PI controller will be used to analyse the delay and dropout on the network.

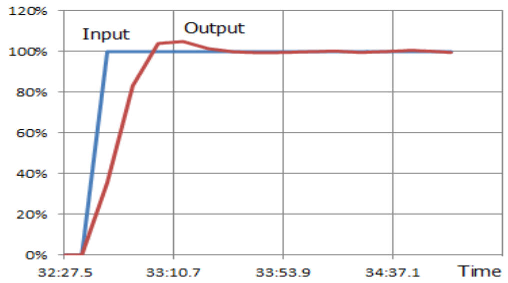


Fig. 6. Response of NCS with controller PI.

4.3. Data traffic record

During experiment of the closed-loop system with network, data traffic has been recorded. Data packet size has average of 188 bytes with the largest size is 454 bytes for C-A link.

As for S-C link, it has average of 332 bytes with the largest packet size of 662 bytes. The delay and dropout caused by each packet can be seen in Fig. 7. The delay varies with average delay of 0.1324 seconds for C-A Link and 0.3599 seconds for S-C link. Compare to [19] with 20 bytes of packet size, the average RTT delay is 100ms, but 40% of packet bins have maximum RTT delay more than 1 second.

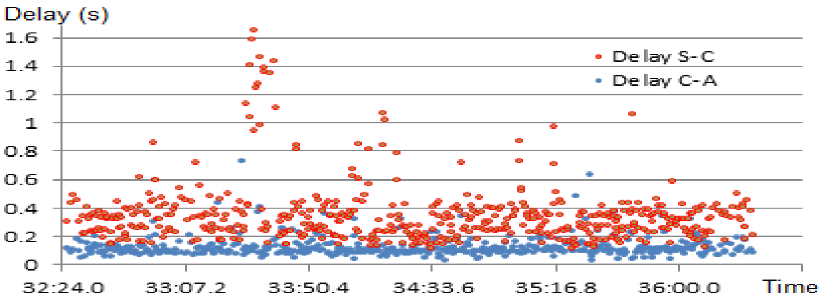
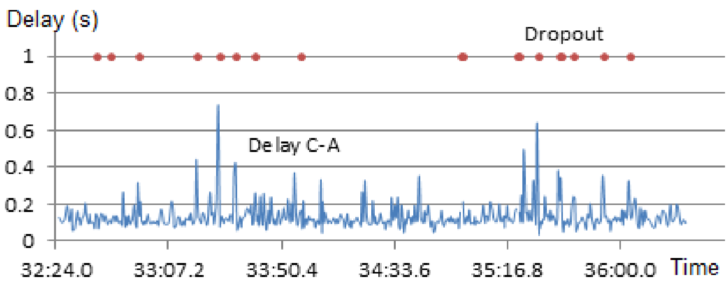


Fig. 7. Data traffic record.

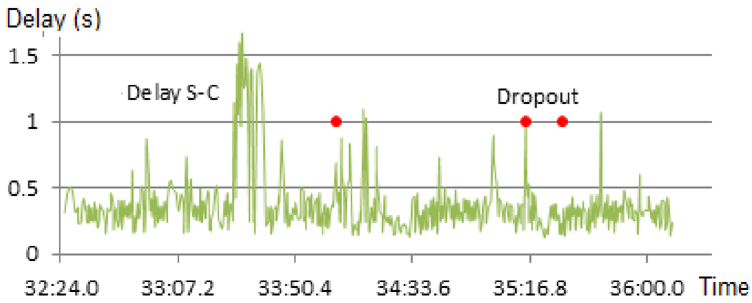
4.4. Dropout

Figure 8 shows dropout occurred several times for both directions. About 500 data packets of data have been sent with 15 dropouts in the direction of C-A link and 3 dropouts in S-C link. Packet Loss can be calculated using the following equation [21]:

$$Packet\ loss = \frac{Drop\ out}{total\ packet} \tag{15}$$



(a). Delay and dropout in C-A link.



(b). Delay and dropout in S-C link.

Fig. 8. Delay and dropout.

Therefore, the resulted packet losses are 3% and 0.6% respectively for the communication direction of C-A link and S-C link. If we consider both C-A link and S-C link have upload at transmitter side and download at receiver, as shown in Fig 3, then the result is lower than reported in [20], which is the packet loss rate is 1.95% for uplink and 2.18% for downlink.

Packet Loss is very low because the data packet size is small and TTI (Transmission Time Interval) is longer relatively to the data rate capacity of Internet connection with HSPA technology. The experiment is conducted with TTI = 1 second and the largest packet size is 662 bytes, and then data is with highest rate as [21]:

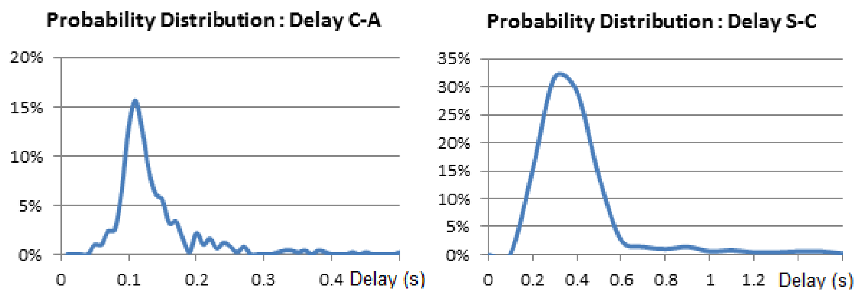
$$BR = \frac{\text{packet size}}{\text{TTI}} = \frac{662 \times 8}{1} = 5{,}296 \text{ bps} \tag{16}$$

Therefore, it requires Internet data rate less than 6 kbps. It is a significantly low data rate in contrast to Internet capacity of HSPA technology which is up to 14 Mbps.

4.5. Probability distribution of delay

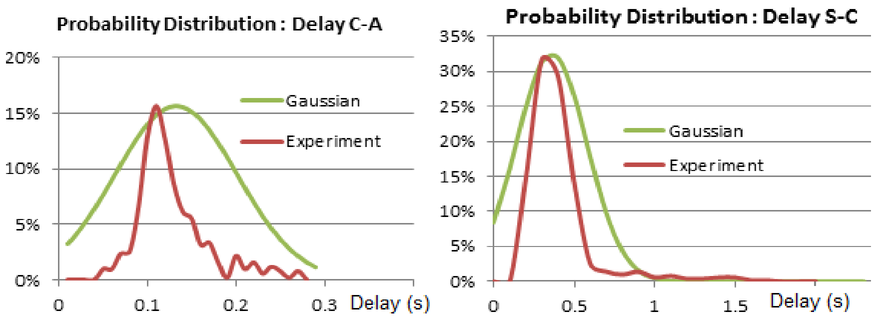
Statistical model of delay could be modelled by probability distribution [21]. Figure 9 shows an empirical distribution of delay in C-A link and S-C link.

Probability distribution of delay shown by Fig. 9 is close to Gaussian distribution function. Gaussian distribution is one of common delay models. We use basic Gaussian distribution as basic approach on delay modelling and compare with experiment data. Therefore, using statistical data of mean and standard deviation, we obtained Gausian like probability distribution shown by Fig. 10. The mismatch between simulation and experiment is because there are 10% of data packets undergo high delays as shown in Fig. 9. Although the number of events is very small, it increases the average value of delay. To avoid the anomaly, the distribution can be recalculated by excluding 10% of the very long time delay. We propose Gaussian distribution with corrected data and Hidden Markov Model.



(a) C-A link. **(b) S-C link.**

Fig. 9. Probability distribution of delay.



(a) C-A Link. **(b) S-C Link.**

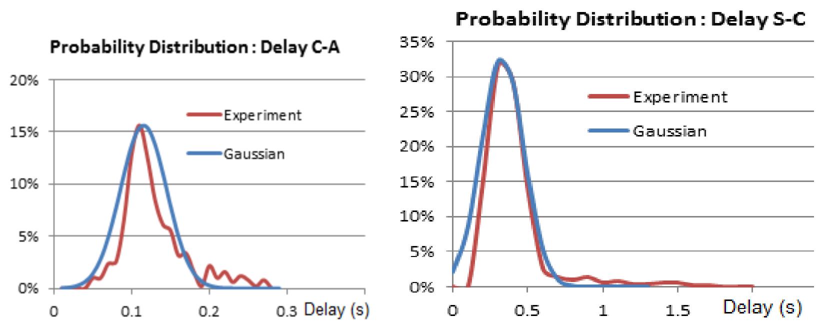
Fig. 10. Gaussian distribution of delay.

4.6. Corrected Gaussian distribution

If we assume a small amount of event with very long time delay that rarely appear and can be ignored, it will obtain better results. As shown in Table 2, for the direction of C-A link, in the case of which the delay greater than 0.2 seconds is ignored, then average of delay is shifted from 0.132 seconds to 0.11 seconds. Similarly, for the S-C link, the average of delay is changed from 0.36 seconds to 0.33 seconds. The distribution using average and standard deviation can be shown in Fig. 11.

Table 2. Time delay statistical data.

	C-A Link Delay (s)		**S-C Link Delay (s)**	
	100% data	***90% data***	***100% data***	***90% data***
Mean	0.132	0.115	0.360	0.331
Min	0.041	0.040	0.123	0.123
Max	0.739	0.200	1.661	1.027
Standard Deviation	0.069	0.030	0.219	0.141



(a) C-A link. **(b) S-C link.**

Fig. 11. Corrected Gaussian distribution of delay.

Using such modification, Correlation value and RMSE (Root Mean Square Error) between the experimental data distribution and modified data distribution are shown in Table 3.

As shown in Table 3, the modified Gaussian distribution models with 90% data packet has a correlation of 0.937 and 0.969 for the direction of C-A link and S-C link respectively, while the RMSE values are 0.020 and 0.023 for the direction of C-A link and S-C link. It shows that removing a small portion of data packet can represent a substantial delay distribution that occurred in the experiment.

4.7. Hidden Markov Model (HMM)

The Markov model is a finite state model that describes the probability distribution by a sequence of possibility. Figure 12 shows a Markov chain with two states, S_1 and S_2. The probability of state changes from state j to state i is p_{ji}, where $p_{ji} < 0$ and $\sum_i p_{ji} = 1$.

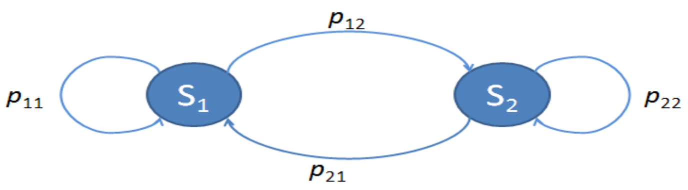


Fig. 12. Markov chain 2 states.

Sequential delay incident in Fig. 7 is a sequence of observations O_{seq} with n data. O_{seq} is assumed as a hidden sequence of S_{seq}, corresponding to the following equation [19]:

$$O_{seq}=O_{(1)}\ , O_{(2)}\ , \ \ldots, O_{(k-1)}\ , O_{(k)}\ , O_{(k+1)}\ ,\ldots, O_{(n)} \tag{17}$$

$$S_{seq}=S_{(1)}\ , S_{(2)}\ , \ \ldots, S_{(k-1)}\ , S_{(k)}\ , S_{(k+1)}\ ,\ldots, S_{(n)}$$

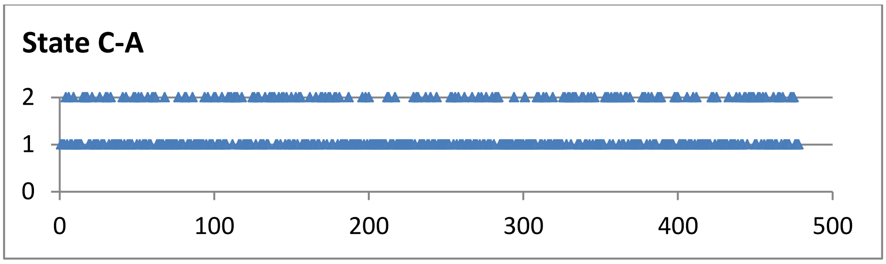
where $O_{(k)}$ and $S_{(k)}$ are delay observation and corresponding state at sample time k. State S_1 represents condition with short delay, and S_2 represents condition with long delay, therefore the discrete state set is $S_{(k)} \in S = \{S_1, S_2\}$ with discrete observation set is $O_{(k)} \in O = \{O_1, O_2, \ldots, O_n\}$. Let's use mean values on Table 2 as threshold between short delay and long delay for each communication link. Furthermore, the sequence of observations O_{seq} in Fig. 7 has sequence of states S_{seq} as shown in Fig. 13 for C-A link and S-C link.

Using maximum likelihood estimation of the transition with data sequence O_{seq} and S_{seq}, the transition matrices for C-A link and S-C link are:

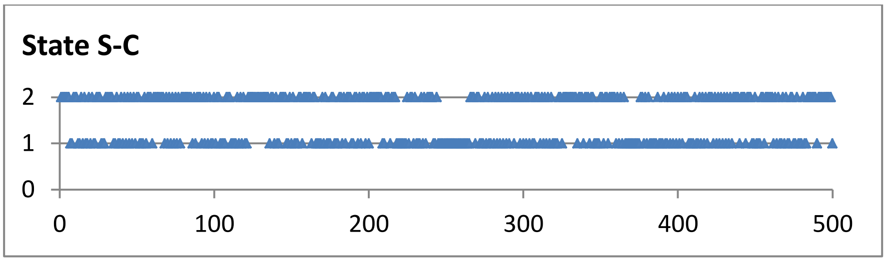
$$P_{SC} = \begin{bmatrix} 0.432 & 0.568 \\ 0.496 & 0.504 \end{bmatrix}$$

$$P_{CA} = \begin{bmatrix} 0.67 & 0.33 \\ 0.66 & 0.34 \end{bmatrix}$$

Transition matrix along with emission matrix can estimate the next state with specific delay. Then let's generate a number of delays by Hidden Markov Model and investigate the probability distribution of generated delay as shown in Fig. 14.

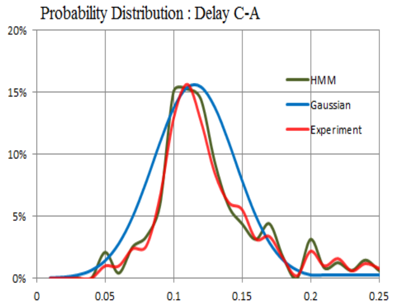


(a) C-A link.

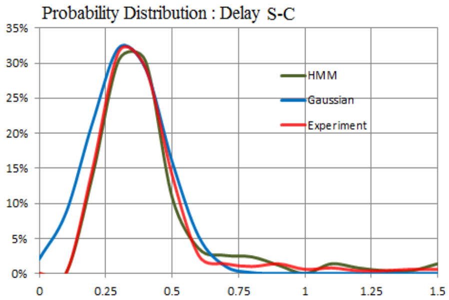


(b) S-C link.

Fig. 13. Sequence of states S_{seq}.



(a) C-A link.



(b) S-C link.

Fig. 14. Probability distribution of HMM.

As shown in Fig. 14 and Table 3, probability distribution of HMM has better correlation compared with Gaussian distribution model, they are 0.988 for C-A link and 0.995 S-C link. Furthermore, HMM also has better RMSE with 0.0199 for C-A link and 0.023 for S-C link.

Table 3. Correlation and RMSE of distribution models.

	C-A Link		S-C Link	
	Correlation	***RMSE***	***Correlation***	***RMSE***
Gaussian	0.730	0.0334	0.867	0.0535
Corrected Gaussian	0.939	0.0199	0.969	0.0230
HMM	0,988	0,0056	0,995	0,0096

5. Conclusions

An investigation has been performed to obtain the statistical model of delay and dropout on NCS with HSPA technology. This paper has discussed a model of plant with a data communication network for both directions C-A link and S-C link in the form of state space equations. In addition, an experiment has been carried out to obtain an ARX model of plant in discrete transfer function. Dropouts occur with 3% of packet loss rate resulting from NCS experiment conducted with data packet size of 600 Bytes and TTI of 1 second. It also has been shown that Gaussian distribution model can be used to represent delay probability distribution with correlation of 0.93 and RMSE of 0.02. These results were obtained when a small amount of data packet delay with high values is excluded from the calculation. Hidden Markov Models with two states for low and high delay may be used to estimate the delay. Probability distribution of delay by the HMM delay estimator has correlation of 0.988 and 0.995, while RMSE values are 0.0056 and 0.0096 respectively for the C-A link and S-C link.

Actually the Gaussian delay model and the Hidden Markov delay model did not considered dropout since the experiment shows there were very low of packet loss rate. threfore, the delay models are only suitable for system with low packet loss. It is an important for future work to find a model of delay and dropout on both communication directions simultaneously as interactive model. This model will be suitable for higher packet loss.

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