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Fault Detection with MAC Delay Compensation in Wireless Sensor Actuator Networks

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***Abstract*—Although the Wireless Sensor and Actuator Networks (WSANs) have many advantages than the wired networks, the nature of sharing wireless media and the complicated behavior of Media Access Control (MAC) introduce adverse impacts on the control system. In contrast to most work on networked control systems using simplified models of network induced delays, this paper considers the study the random access delay caused by a contention-based MAC scheme slotted ALOHA in WSANs. An improved fault detection observer with access delay compensation is proposed to improve the fault detection performance against the MAC delays.**

I. Introduction

As one of the main challenges in Wireless Sensor Actuator Networks (WSANs) and Networked Control Systems (NCSs), the network-induced delay degrades the fault detection performance [1], [2],[3], [4] and much of attention have been paid on designing a fault detection system robust to network-induced delays [5], [6]. In most existing studies, the characteristics of a communication network are usually represented by simplified analytical models without considering the details of different communication protocols. For instance, it is popular to adopt a finite state Markov chain to represent the dynamics of the network-induced delays $\{\tau_k\}$, without consideration of the complicated behaviours of various communication protocols. As a result, the control system is modelled as a Markov Jumping System (MJS) [7] and various methods were proposed to design the fault detection filters, including Riccati equation methods [3] and linear matrix inequalities (LMIs) for H_∞ fault detection observer design. In [8], [3], a Takagi-Sugeno (T-S) is built to represent network-induced delays and a fuzzy fault detection observer is proposed. [9] models the delay as a stochastic process with known mean and variance, and treats the impacts of delay as a parameter change in the framework of stochastic systems. Paper [10] used the Taylor approximation to analysis the impacts of delay and proposed a parity space-based residual generator. Eigen-decomposition and the Pade approximation were used in [11] under the assumption that the state matrix is diagonal.

However, the communication network is a complicated dynamic system and the simplified model of network delays cannot represent the communication network behaviour very well. The network-induced delays are caused by many reasons and there have been studies on the estimate the packet delays in a network [12]. For instance, paper [13] adopted the network calculus theory to determine the bounds of delays and adjust the threshold of fault detection observer's residual accordingly. In wireless networks, the contention-based MAC schemes are widely adopted to support multiple access. Unfortunately, it is still not clear how a random MAC scheme and its associated delay statistics influence the FD performance of NCSs. To bridge this gap between the communication protocols and fault detection observer designs, this paper brings the statistical properties of the access time of a contention-based MAC scheme (the so-called slotted-ALOHA) into the FD observer design. The main contribution of this paper are, (1) According to the analysis of the slotted ALOHA MAC scheme and its associated access delay (namely MAC-delay), a statistical estimation of the MAC-delay in slotted ALOHA induced is proposed. (2) With the estimate of MAC-delays, a new FD observer is proposed to compensate the MAC-delay such that the adverse impacts of the delays are attenuated and the fault detection performance is improved.

The rest of this paper is organized as follows: Section II is an introduction to a industrial WSAN. The slotted ALOHA is analyzed and its MAC-delay is estimated in Section III, followed by the proposal of a novel FD observer design with MAC-delay compensation in Section IV. The fault detection performance is then optimised in Section V. Finally, Section VI evaluates the performance of the proposed FD observer on a MATLAB/OMNeT hybrid simulation platform.

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II. System Model and Problem Formulation

As shown in Fig. 1, this paper considers a WSAN consisting of a set of distributed sensors and controllers organized in a group of control loops, an access point (AP) linking together the wireless network and the wired Ethernet and a Fault Detection (FD) system. All controllers and sensors are connected through the wireless network with a star topology, and the wireless network takes two non-overlapped radio channels, namely uplink and downlink channels, in 2.4G ISM band.

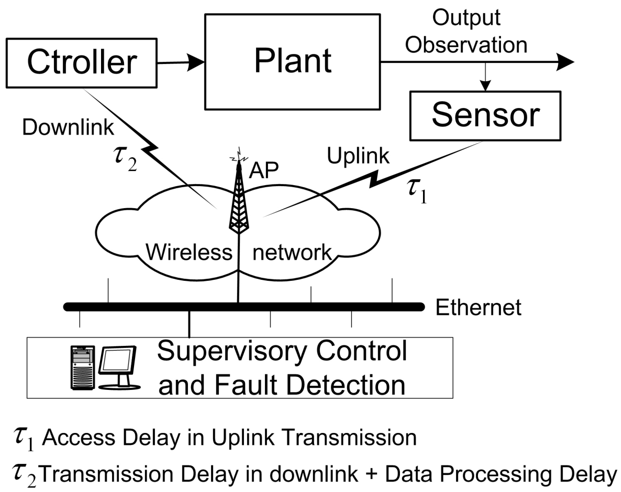

Fig. 1. A wireless sensor actuator network for supervisory control

Consider a plant working at some operation point

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_f f(t) + B_d d(t) \\ y(t) = Cx(t) + v(t) \end{cases} \quad (1)$$

where $x(t) \in \mathbb{R}^n$ is the state variable of the plant, $u(t) \in \mathbb{R}^m$ the input, $y(t) \in \mathbb{R}^p$ the output. $v(t)$ and $d(t)$ are unknown inputs with appropriate dimensions. $f(t) \in \mathbb{R}^q$ is the fault to be detected. A, B, C, B_f and B_d are known constant matrices with appropriate dimensions, and C is of full row rank.

The output y_k measured by the sensor at sampling interval T_s is sent to the AP through the uplink channel by using the slotted ALOHA media access protocol [12]. Once receiving a packet of y_k, the AP forwards it to the corresponding controller (via downlink channel) and to the remote FD system (via Ethernet). And the controllers reply with its control signal u_k to the AP. When a packet of u_k arrives from a controller through the downlink channel, the AP forwards it to the FD system only. The sensors S_i are time-driven with local sampling interval T_s and the controllers Ctr_i is event-driven.

Remark 1 The uplink is shared by all sensors, and a sensor has to compete for the use of the uplink channel. Several sensors may send their packets at the same time, which results in a 'collision'. Thus the transmission fails, re-transmission has to be scheduled and some delay is introduced. As one of the widely used random access scheme, a slotted ALOHA protocol is considered in this paper. In the downlink communication, however, the access to the downlink is fully coordinated by the AP, there is no competition for the use of downlink and the collision is avoided.

It is further assumed that the disturbances and fault components have slow dynamics $f(t) = f_k$, $d(t) = d_k$ and $v(t) = v_k$ for all $t \in [kT_s, (k+1)T_s]$. Similar to the discretization of dynamic system, at the k-th sampling instants, an equivalent discrete system of (1) can be represented by [10][14]

$$\begin{cases} x_{k+1} = \bar{A}x_k + B_0(\tau_k)u_k + B_1(\tau_k)u_{k-1} + \bar{B}_f f_k + \bar{B}_d d_k \\ y_k = Cx_k + v_k \end{cases} \quad (2)$$

where $\bar{A}$, $B_0(\tau_k)$, $B_1(\tau_k)$, $\bar{B}_f$ and $\bar{B}_d$ are defined in a similar way as [10].

Let

$$\bar{B} = \int_0^{T_s} e^{At} B dt = B_0(\tau_k) + B_1(\tau_k), \quad (3)$$

and

$$\Delta u_k = u_k - u_{k-1}, \quad (4)$$

system (2) can be rewritten under the following form:

$$\begin{cases} x_{k+1} = \bar{A}x_k + \bar{B}u_k - B_1(\tau_k)\triangle u_k + \bar{B}_f f_k + \bar{B}_d d_k \\ y_k = Cx_k + v_k \end{cases} \quad (5)$$

Note that $B_1(\tau_k) \in \mathbb{R}^{n\times m}$ is a matrix of functions with respect to τ_k. Due to the fact that τ_k is a stochastic process determined by the communication network behaviors, the input matrix $B_1(\tau_k)$ varies at different time instants and the system under consideration actually behaves as a stochastic system,

III. MAC Delay Analysis and Estimation

The network-induced delay τ_k is the delay relating the sensor sending out y_k to the controller receiving it. Due to the nature of media sharing in wireless communication, if two or more devices sends their packet to the radio media during the transmission, a collision occurs, the receiver cannot receive the packet successfully, and the packets have to be re-transmitted. Thus a significant delay is induced. Such a delay is refereed to as 'MAC delay' or 'access delay'. In this section, it is our main interests to study the characteristics of MAC delay, and to estimate its mean value.

Let τ_1 denote the MAC-delay in the uplink, τ_1 is a stochastic variable and can be decomposed into two parts:

$$\tau_1 = E(\tau_1) + \Delta\tau_1 \quad (6)$$

where $E(\tau_1)$ is the mean value of the MAC-delay, and $\Delta\tau_1$ represents the jitter (the variation in the time between packets arriving at the AP). Generally, $\Delta\tau_1$ is a stochastic process with zero mean and variance $var(\Delta\tau_1) = \sigma^2$. Considering the reality of canceling re-transmissions in case of a too many re-transmissions, $\Delta\tau_1$ will be bounded.

Since the access to the downlink is fully coordinated by the AP, the delay from the AP to controllers consists of the transmission delay and data processing delay only. Let τ_2 denote the downlink delay from the AP to controllers, τ_2 is a deterministic constant value.

$$\tau_2 \approx T \tag{7}$$

where T is the transmission time of a packet. Here, we have implicitly assumed that the the sum of processing time at the AP and corresponding controller is smaller and can be ignored. When this is not true, only a fixed constant term needs to be added to the final delay expression.

Let τ_k denote the network-induced delay relating the sensor to the actuator during sampling period $[kT_s, (k+1)T_s)$, τ_k can be expressed as

$$\tau_k \approx \tau_1 + T = T + E(\tau_1) + \Delta\tau_1 \tag{8}$$

and the mean value of the network-induced delay is

$$\bar{\tau} = E(\tau_k) \approx T + E(\tau_1) \tag{9}$$

In the followings, the focus is on the analysis of the slotted ALOHA scheme and the estimation of the mean value of access delay τ_1 in the uplink channel. Borrowing the models and notations of the slotted ALOHA scheme in [12], the slotted ALOHA MAC protocol is summarized as follows:

1) When a sensor generates a new packet y_k, it accesses the uplink channel at the beginning of the next slot. This is called immediate-first transmission (IFT). Let D_0 be the access delay from the sampling time to the end of the initial transmission.
2) All packets are of the same size with transmission time T and the length of a time slot is equal to T.
3) For a given sampling interval T_s, the total number of available slots for packet re-transmission n is determined by:
$$n = \lfloor \frac{T_s}{T} \rfloor - 3 \tag{10}$$
4) A retransmission is scheduled after a random *backoff delay*, when a packet transmission fails. Let W_i be the i-th backoff delay in unit of slots, that is refereed to as *backoff window size*. Then, the i-th retransmission takes place at the beginning of the W_i-th available slot. Note that $W_i \geqslant 1$. In this paper, a *uniform backoff* (UB) policy is adopted. That is all W_i's are uniformly distributed in the same range , say $[1, w]$. The statistics of W_i under UB policy are
$$\begin{aligned} P\{W_i = j\} &= \frac{1}{w}, \quad j = 1, 2, \ldots, w && (11)\\ E[W_i] &= \frac{1+w}{2} && (12)\\ \text{var}[W_i] &= \frac{[w^2-1]}{12} && (13) \end{aligned}$$
5) Let R denote the number of retransmission needed for a successful packet transmission, and D_i be the delay time due to the i-th unsuccessful transmission.

Thus, the access delay τ_1 in the uplink is the time duration from its generation to the moment it is successfully transmitted to the AP, that is

$$\tau_1 = \sum_{i=0}^{R} D_i \tag{14}$$

and

$$D_i = (W_i + 1)T, \qquad i = 1, 2, ... \tag{15}$$

As required by the control criteria, the total network-induced delay should be less than T_s, that is $\tau_1 + \tau_2 < T_s$. Since the delay τ_2 in the downlink is always T, the access delay τ_1 should less than $T_s - T$. This requirement implies that the up bound of the access delay in the slotted ALOHA is $D_0 + nT$, where n is given by (10). Hence, the value of τ_1 can only be selected from the following set

$$\{D_0,\ D_0 + 2T,\ D_0 + 3T, \ldots, D_0 + nT\} \tag{16}$$

It is worth noting that τ_1 can not be $D_0 + T$, because at least two slots are required for retransmission. According to the delay distributions of Slotted ALOHA [12] with some modification, the mean value of the access delay τ_1 with the upper bound $D_0 + nT$ can be estimated as

$$\mathrm{E}(\tau_1) = D_0 + \frac{-1 + \sum_{i=1}^{n} \mathrm{P}\{\tau_1 \geqslant D_0 + iT\}}{\mathrm{P}\{\tau_1 \leqslant D_0 + nT\}} + 1 \tag{17}$$

where $\mathrm{P}\{\bullet\}$ represents the possibility of an event. For instance, $\mathrm{P}\{\tau_1 \leqslant D_0 + nT\}$ denote the possibility of $\tau_1 \leqslant D_0 + nT$ [12].

Hence, by selecting a proper initial backoff window size w, the distribution of the re-transmission R can be calculated and the mean value of the access delay $E(\tau_1)$ in the uplink channel can be computed as (17). Thus the mean value of the total network-induced delay can be estimated as

$$\hat{\bar{\tau}} = T + E(\tau_1) \tag{18}$$

IV. Fault Detection Observer design

Recalling the model of delay (4), one can rewrite (2c) as

$$\begin{aligned} B_1(\tau_k) &= \int_{T_s - \bar{\tau} - \Delta\tau_k}^{T_s} e^{At} B dt \\ &= A^{-1}[I - e^{-A(\bar{\tau} + \Delta\tau_k)}] e^{AT} \cdot B \end{aligned} \tag{19}$$

Applying the Taylor approximation of $e^{At} = [I + At] + g(t)$ to (19) gives

$$\begin{aligned} B_1(\tau_k) &= A^{-1}\big[I - [I - A(\bar{\tau} + \Delta\tau_k) + g(\bar{\tau} + \Delta\tau_k)]\big]\bar{A} \cdot B \\ &= \bar{A}(\bar{\tau} + \Delta\tau_k) - g(\tau_k)] \cdot B \\ &= \bar{A} \cdot \bar{\tau} \cdot B + \bar{A} \cdot \Delta\tau_k \cdot B - \bar{A} g(\tau_k) \cdot B \\ &= \bar{A}B \cdot \bar{\tau} + \bar{A}B \cdot \Delta\tau_k - \bar{A} g(\tau_k) B \end{aligned} \tag{20}$$

Substitute (20) into the state equation of (5), the system model can be written as

$$\begin{cases} x_{k+1} = \bar{A}x_k + [\bar{B} \quad -\bar{A}B\bar{\tau}] \begin{pmatrix} u_k \\ \Delta u_k \end{pmatrix} \\ \qquad\qquad +[-\bar{A}B\Delta u_k \quad \bar{B}_d\ ] \begin{pmatrix} \Delta\tau_k \\ d_k \end{pmatrix} + \bar{B}_f f_k + \bar{g}(\tau_k) \\ y_k = Cx_k + D_2 v_k \end{cases}$$

where $\bar{g}(\tau_k) = -\bar{A}g(\tau_k)B\Delta u_k$ denotes modeling errors due to the approximation. Define

$$\begin{matrix} \Gamma(\bar{\tau}) = [\bar{B} \quad -\bar{A}B\bar{\tau}], & \bar{u}_k = \begin{pmatrix} u_k \\ \Delta u_k \end{pmatrix} \\ \Gamma_d = [-\bar{A}B\Delta u_k \quad \bar{B}_d], & \bar{d}_k = \begin{pmatrix} \Delta\tau_k \\ d_k \end{pmatrix} \end{matrix}, \tag{21}$$

the system model now is expressed in the following form:

$$\begin{cases} x_{k+1} = \bar{A}x_k + \Gamma(\bar{\tau})\bar{u}_k + \Gamma_d\ \bar{d}_k + \bar{B}_f f_k + \bar{g}(\tau_k) \\ y_k = Cx_k + v_k \end{cases} \tag{22}$$

A networked fault detection observer in the following discrete Luenberger observer form is used:

$$\begin{cases} \hat{x}_{k+1} = \bar{A}x_k + \Gamma(\hat{\bar{\tau}})\bar{u}_k + L(y_k - \hat{y_k}) \\ \hat{y}_k = C\hat{x}_k \\ r_k = W(y_k - \hat{y}_k) \end{cases} \tag{23}$$

where $r_k \in \mathbb{R}^l$ is the so-called residual for indicating the fault occurrence, $L \in \mathbb{R}^{n\times p}$ and $W \in \mathbb{R}^{l\times p}$ are the observer gain matrix and weighting matrix to be designed, respectively.

Let the observer error be $e_k = x_k - \hat{x_k}$ and $\hat{\bar{\tau}}$ the estimation of $\bar{\tau}$, the the overall dynamics of residual generator (23) is governed by

$$\begin{cases} e_{k+1} = (\bar{A} - LC)e_k + (\Gamma(\bar{\tau}) - \Gamma(\hat{\bar{\tau}}))\bar{u}_k \\ \qquad\qquad +\Gamma_d\bar{d}_k + \bar{B}_f f_k - Lv_k + \bar{g}(\tau_k) \\ r_k = WCe_k + Wv_k \end{cases} \tag{24}$$

In equation (24), it appears that the residual dynamics depends on the amplitude of the terms $\Gamma(\bar{\tau})$, $\Gamma(\hat{\bar{\tau}})$ and $\Delta\tau_k$ which are functions of network-induced delay τ_k.

Recalling $\Gamma(\bar{\tau}) = [\bar{B} \quad -\bar{A}B\bar{\tau}]$ in (21), one can get

$$\begin{aligned} & [(\Gamma(\bar{\tau}) - \Gamma(\hat{\bar{\tau}}))]\bar{u}_k \\ = \ & \left[[\bar{B} \quad -\bar{A}B\bar{\tau}] - [\bar{B} \quad -\bar{A}B\hat{\bar{\tau}}]\right] \begin{bmatrix} u_k \\ \Delta u_k \end{bmatrix} \\ = \ & \left[0 \quad \bar{A}B(\hat{\bar{\tau}} - \bar{\tau})\right]\Delta u_k \\ = \ & \bar{A}B(\hat{\bar{\tau}} - \bar{\tau}) \cdot \Delta u_k \end{aligned} \tag{25}$$

Then $(\Gamma(\bar{\tau}) - \Gamma(\hat{\bar{\tau}}))\bar{u}_k + \Gamma_d\bar{d}_k$ in (24) can be re-formed as

$$[\bar{A}B\Delta u_k \quad \bar{A}B\Delta u_k \quad \bar{B}_d] \begin{bmatrix} (\hat{\bar{\tau}} - \bar{\tau}) \\ \Delta\tau_k \\ d_k \end{bmatrix}, \tag{26}$$

and the state estimation error (24) now is

$$\begin{cases} e_{k+1} = (\bar{A} - LC)e_k + [\bar{A}B \quad \bar{A}B \quad \bar{B}_d] \begin{bmatrix} (\hat{\bar{\tau}} - \bar{\tau})\Delta u_k \\ \Delta\tau_k\Delta u_k \\ d_k \end{bmatrix} \\ \qquad\qquad +\bar{B}_f f_k - Lv_k + \bar{g}(\tau_k) \\ r_k = WCe_k + Wv_k \end{cases} \tag{27}$$

It shows that the network-induced delay introduces an extra unknown input $\begin{bmatrix} (\hat{\bar{\tau}} - \bar{\tau})\Delta u_k \\ \Delta\tau_k\Delta u_k \end{bmatrix}$ into the dynamics of the residual generator, and the residual may deviate from zero even if no fault has happened. If this unknown input is not carefully taken into account in the fault detection observer design, residual r_k could not reflect the fault's occurring properly. This phenomenon causes either false alarms or failure to detect faults.

Different from the decoupling unknown inputs in some fault detection observer designs, in this paper, the FD observer design problem is turned into an eigenvalue assignment and performance optimization problem. The objectives are to select an gain matrix $L \in \mathbb{R}^{n\times p}$, such that the following three criteria are met:

- Stability: The poles of $\bar{A} - LC$ in (27) is within the unit circle in the z-plane;
- Sensitivity to faults: The residual r_k should be sensitive to faults f_k, that is the transfer function matrix (TFM) relating f_k to r_k should be maximized;
- Robustness to disturbances and delays: The residual r_k should be insensitive to disturbances d_k and network-induced delays τ_k. That is the TFM relating d_k and τ_k to r_k should be minimized.

V. Fault Detection Performance Optimisation

In the following, the impacts of the delays on the residual r_k is analyzed in terms of TFMs and an the gain matrix L in (27) is optimised to ensure the residual's sensitivity to the faults and enhance the robustness against the delays.

The z-transform of (27) gives the following transfer function matrices (TFMs)

$$\begin{cases} G_1(z) = G_2(z) = C(zI - \bar{A} + LC)^{-1}\bar{A}B \\ G_f(z) = C(zI - \bar{A} + LC)^{-1}B_f \end{cases} \tag{28}$$

where $G_1(G_2)$ and G_f are TFM relating r_k to $(\hat{\bar{\tau}} - \bar{\tau})\Delta u_k$, $(\Delta\tau_k\Delta u_k)$ and f_k , respectively.

A. Optimization in the frequency domain

As shown in the FD problem definition, there are two objective functions, namely sensitivity index and robustness index. Considering the access delays of the ALOHA in section III, we propose the following two performance indices.

1) Robustness Index: Observe that the TFMs $G_1(G_2)$ relating r_k to $\Delta\tau_k\Delta u_k$ ($[\hat{\bar{\tau}} - \bar{\tau}]\Delta u_k$) are the same, but the signals $\Delta\tau_k$ and $(\hat{\bar{\tau}} - \bar{\tau})$ have different characteristics in the frequency domain. By optimizing the fault detection performance at the frequency of interest, instead of the whole frequency range, our observer is tailored for attenuating the network-induced delay.

$$\min_L J_1 = \sum_{z\in\Omega} \|\beta(z)G_1(z)\| \quad (29)$$

where Ω is the frequency range of interest, and $\beta(z)$ is a weighting function for $G_1(z)$ over the frequency range Ω. Ω and $\beta(z)$ depend on the frequency characteristics of the MAC-delay τ and the the difference between successive input samples Δu. Generally, since it is the residual we are interested in, Ω and $\beta(z)$ are determined by finding the significant frequency components of r_k.

2) Sensitivity Index: Not like a random noise, a fault signal is usually associate with some pattern, and, its energy distribution is not uniformly distributed over the whole frequency range of interest. In general, two common faults are considered, namely, the incipient fault (a ramp signal) and the abrupt fault (a step signal). A ramp fault mainly consists of low-frequency components. For an abrupt fault, high-frequency contents exist only at the time instant when the fault starts, and it is almost constant (zero frequency) content thereafter. In order to increase the fault significance in residual r, it is proposed that the sensitivity index is maximized at $z = 1$ (corresponding to zero frequency in the continuous frequency domain).

$$\max_L J_2 = \|G_f(z)\|_{z=1} \quad (30)$$

Combining robustness index (29) and sensitivity index (30) yields the performance index

$$\min_{Q,\Lambda} J = \frac{J_1}{J_2} = \frac{\sum_{z\in\Omega} \|\beta(z)G_1(z)\|}{\rho + \|G_f(z)\|_{z=1}} \quad (31)$$

where ρ is an arbitrary small positive number to ensure a non-zero denominator. Since the frequency information has now incorporated into the new index (31), the resulting FD observer is optimal for attenuating the negative impacts caused by the MAC-delay. In most applications, such a FD observer has a better performance in terms of attenuating the MAC-delay induced disturbance.

VI. Simulation Platform and Results Analysis

In order to demonstrate the the proposed delay compensation approach, the hybrid simulation platform and fault detection results are presented in this section. The control system and the FD system are programmed in MATLAB/SIMULINK, and the wireless network is emulated by using OMNeT++. Compared with MATLAB/SIMULINK, the open source OMNeT++ platform is able to mimic the detailed behaviour of a wireless network, and imitate the features, such as SNIR(Singal-Noise-Interference-Ratio), SNR(Singal-Noise-Ratio), MAC-delay and packet loss due to either low SNR or collision.

In the simulation, the system matrices of the plant are as follows:

$$A = \begin{bmatrix} 30.7643 & 36.0164 \\ -30.8287 & -35.9486 \end{bmatrix}, \quad B = \begin{bmatrix} 2.2991 \\ -0.0668 \end{bmatrix},$$

$C = [1 \quad 0]$ and $B_d = B_f = B$. The sampling interval $T_s = 0.03$ sec. The control input and plant output are subject to input disturbances d_k and output measurement noises v_k, respectively, where d_k and v_k are independent bounded noises uniformly distributed between $[-0.2, 0.2]$ and $[-2, 2]$. Two kind of faults are concerned in the simulation, namely, step fault and slope fault. The step fault associated with the actuator occurs at time $t_1 = 10s$ with magnitude 0.2, and the slope fault starts at 10 s with slope rate 0.05.

As shown in Figure 1, we consider a networked control system composed with five local control loops in total and one AP. The total number of clock-driven sensors is ten and there are five event-driven controllers. A FD observer is to be designed for one of the control loops. All the communication devices works at 2Mbps on 2.4GHz ISM band. Data, either from sensors or from controllers, is transmitted with a single packet whose length is 1712 bits including physical premier(192 bits), protocol header length (272bits for MAC, 32bits for Network layer), which gives an air frame with a transmission duration of 856*us*.

The simulation results of packet delay given by OMNeT++ are shown in Figure 2. The mean value of the packet delay from sensor to controller is $\bar{\tau} = 0.0136$s. With the aid

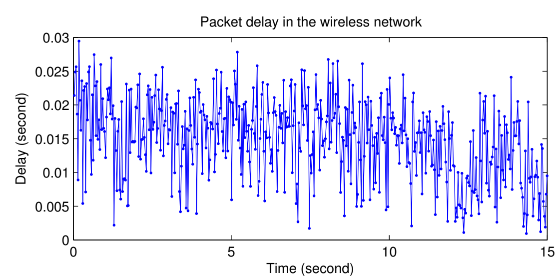

Fig. 2. Packet delay τ_k from sensor to controller

of the MAC-delay estimate, a MAC-delay compensated FD observer can be constructed as (23) and the optimisation of index (31) yields the optimal gain matrix

$$L = \begin{bmatrix} 0.1123 \\ -0.1027 \end{bmatrix} \quad (32)$$

The residuals of the proposed FD observer are given by Figure 3 (for step fault) and Figure 4 (for slope fault), respectively. From Figure 3-4, one can seen that the proposed delay compensation techniques is able to detect these faults clearly.

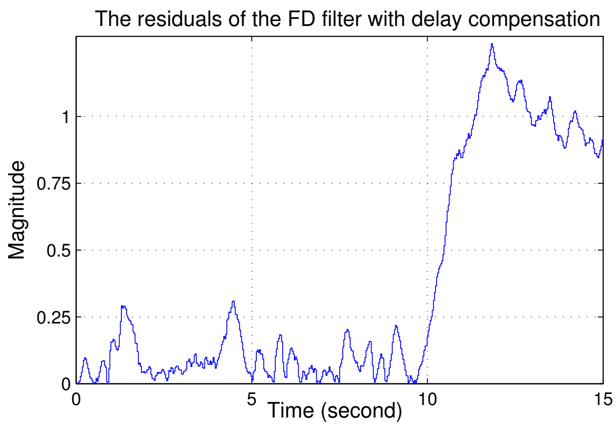

Fig. 3. Residuals r_k subject to step fault occurring at 10 second with step size 0.2

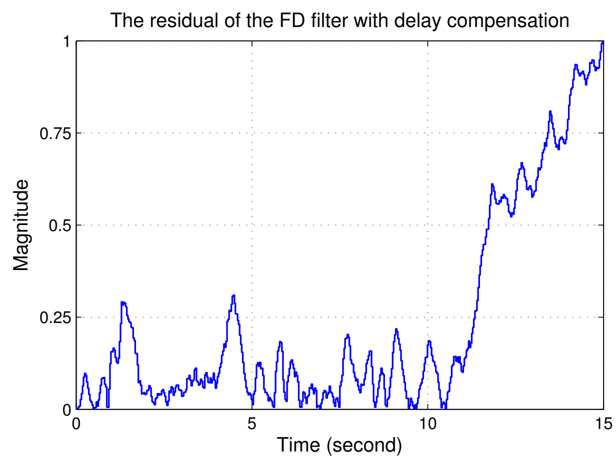

Fig. 4. Residuals r_k subject to slope fault occurring at 10 second with rate of 0.05

VII. Conclusions

This paper addresses the fault detection problem of WSANs-based wireless networked control systems, where the MAC-access delay of the slotted ALOHA is considered. With the aid of the MAC-access delay estimation, a FD observer with MAC-delay compensation is proposed. These advantages of the proposed FD observer with MAC delay compensation have been demonstrated through extensive computer simulations. As to future work, it is certainly possible to extend our cross-discipline analytical approach by considering more sophisticated MAC schemes (such as Carrier Sense Multiple Access(CSMA) and 802.11 Distributed Coordination Function), random backoff policies (such as geometric backoff and binary exponential backoff) and physical channel models.

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