Stabilization for Wireless Sensor/Actuator Networks with Reordering-Based Sample Rate Adaptation

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Abstract—A novel sample rate adaptation technique is proposed for the wireless sensor/actuator networks with packet reordering. Considering network-induced delay and packet loss, a new technique for adapting the sampling interval to network parameters is studied in terms of the Reorder Density, such that a closed-loop switched delay system is presented by constructing state feedback controller. Furthermore, a criterion for stochastic stability of WSANs is derived based on the stochastic theory due to the subsystems subject to Markov chain. An adaptive controller is designed by solving linear matrix inequalities (LMI). An example is given to show the effectiveness of the proposed method.

Introduction

Wireless sensor networks (WSNs), wireless communication tools equipped sensor nodes, have been applied in the industry field increasingly. Sensors are emplaced to detect the physical world in the spatially distributed control systems, and actuators, carrying out appropriate actuation according to sensors measurements, are also introduced into the WSNs, which forms up the wireless sensor/actuator networks (WSANs)\textsuperscript{1, 2}. In the WSANs, the controllers are introduced to make up the closed-loop control systems, they can be also called wireless networked control systems and have potential use in the practical industry control fields. The wireless transmissions are subject to obstacles, reflections, multi-path effects, and fading, all of which affects the quality of transmissions\textsuperscript{3}, and conspires to long or unbounded delay, severe packet reordering and high packet loss rate, such that packets are received much more unreliable than in wired media. So, WSANs provide many new challenging control problems. Then, it is the most urgent problem to how to analyze and control the WSANs by the approaches that are sensitive to the wireless networks, such that the WSANs can be applied in the practical application preferably.

Sample rate adaptation is a form of improving the performance of networks and control systems. The sampling policy determines the choice of sampling interval, and the appropriate sampling interval should be deduced based on the appended Quality of Service of the networks (QoS), as well as knowledge about the control Quality-of-Performance (QoP). Up to date, the sampling interval is generally regulated based on the delay and loss rate. The early attempts have been made [4-6]. An LMI ‘girding’ approach was proposed in [7], wherein the controller was designed so that the system is robust to variations in sampling period.

Traffic trends over the Internet indicate a significant increase of packet reordering, out-order packet. In addition, ad hoc routing and heterogeneous hand-off technologies in wireless domain introduce additional parallelism. All these point to an increasing trend of packet reordering\textsuperscript{8}. However, noted that packet reordering is not analyzed in the above literature. To the best of the authors' knowledge, packet reordering and controller design of the WSANs have not been fully investigated to date. Especially for sample rate adaptation of the WSANs in terms of packet reordering, no results have been available in the literature so far, which motivates the present study.
In this paper, reordering-based sample rate adaptation technique is investigated for the WSANs with packet reordering. Considering network-induced delay and packet loss, a sampling interval variation strategy based on Reorder Density (RD) in the WSANs is put forward, which is a contribution in this paper. A sufficient condition for the stochastic stability and an adaptive controller design method of the WSANs are derived by the approach combining Markov theory and LMI. The example and simulations demonstrate the effectiveness of the proposed method.

Reorder Density

Several metrics have been proposed for packet reordering, such as Percentage of Reordered Packets, Reorder Density (RD), Reorder Buffer-occupancy Density (RBD), the Reordering Extent and N-Reordering. These metrics face multiple challenges that include spatial and time complexities, real-time evaluation, robustness, etc. RD can capture both the amount and extent of reordering of packets in an arrival sequence. Since RD uses a discrete density that represents the fractions of the sequence size with respect to packet displacements. As pointed by in [8], RD fares better than the other metrics in all categories. Here, RD is chosen to evaluate the out-order packets.

Considering the following system given by

\[ x(t) = Ax(t) + Bu(t) \]

where \( x(t) \in \mathbb{R}^n \) and \( u(t) \in \mathbb{R}^m \) are the state vector and control input vector, respectively; \( A \) and \( B \) are some constant matrices of appropriate dimensions. The state feedback controller can be expressed as

\[ u(t) = Kx(t) \]

where \( K \) is some constant matrix of appropriate dimensions. Since system \((1)\) is controlled over a wireless network, the signal transmitting delay, packet loss and packet reordering will exist inevitably.

In this paper, a sensor samples a plant and transmits the sampled information to a remote controller at a particular sampling frequency, that is, the sensor is time-driven. The actuator receives the control action, and waits to apply the output at the next sampling instant, that is, the actuator is also time-driven, and the controller is event-driven, that is, the controller compute control action whenever it receives the signal from the sensor. \( T \) denotes the sampling period (sampling interval) of the sensor, and we assume that the network-induce delay is bounded, that is \( 0 < t^k = t^k_1 + t^k_2 \leq kT \), and the maximum value of consecutive packet loss is \( h = h_1, h_2 \) (\( h_1, h_2 \) are positive integers, and \( t^k, t^k_1, t^k_2 \) denote sensor to controller delay and controller to actuator delay, respectively). Set \( h = h_1 + h_2 \).

**Remark 1.** Bounded network-induced delay and the maximum value of consecutive packet loss in the wireless networks can be guaranteed by adapting sampling interval to the changes of RD.

At each sampling instant, the current states are known by, e.g., the time-stamping technique. By the time-driven actuator, the newest control input can be executed by actuator. There are \( h+1 \) cases, control action \( u(k) \) acts on the controlled process at sampling instant \( t_k \), or \( u(k-1) \) acts on the controlled process at sampling instant \( t_{k-1} \) by analogy, or \( u(k-h) \) acts on the controlled process at sampling instant \( t_{k-h} \). Recent studies of packet reordering based on measurements over the Internet validate reordering is an increasingly common phenomenon. It is important to address the packet reordering proactively, especially for the WSANs. Without loss of generality, we consider a sequence of packets \( x_{i-p}, x_{i-h}, \ldots, x_i \) transmitted over the wireless network. For packets \( x_{i-p}, x_{i-h}, \ldots, x_i \), it is well known that the corresponding expected arrival sequence numbers are \( 1, 2, \ldots, h+1 \). Then, it is easily obtained that the expected arrival sequence number of packet \( x_{i-p} \) is \( h+1-i \) \( (i = 0, 1, \ldots, h) \). A receive_index \((1, 2, \ldots, h+1)\) is assigned to each non-duplicate packet as it arrives at the point of measurement, which we refer to as the destination (actuator). For an arrival sequence in which no loss or duplication of packets occur over the wireless networks, in the absence of reordering, the expected sequence number of the packet and the receive_index value are the same for each packet. If the receive_index assigned to packet with expected arrival sequence number \( m \) \( (m=1, 2, \ldots, h) \) is \( m + d^m \), with \( d^m \neq 0 \), then a `reordering event' has occurred in communication. Packet with expected arrival sequence number \( m \) is late if this displacement \( d^m > 0 \),
early if \( d_n^m < 0 \), and in order if \( d_n^m = 0 \). For the presence of packet loss, one can wait till the arrival process is completed to assign receive_index values, so that receive_index values can be assigned correctly\(^8\). RD is defined as the histogram of \( d_n^m \) values, normalized with respect to the total number of packets, which has been adjusted for loss and duplication of packets. Table I illustrates the expected arrival sequence numbers, assigned receive_index values, displacements and RD for a sequence \((x_{k-4}, x_{k-3}, x_{k-2}, x_{k-1}, x_k)\) transmitted over the network. Noted that packet \( x_{k-3} \) has dropout and \( x_k \) has no arrived at \( t_k \) instant in the wireless communication.

**Remark 2.** A packet whose sequence number has existed in early-arrival buffer is classified as a duplicate one, no receive_index value is assigned to it when it arrives the actuator. At sampling instant \( t_k \), the receive_index of \( x_k \) is not assigned if it is not received at the actuator, which will not effect the measures of the packet reordering.

<table>
<thead>
<tr>
<th>TABLE I WITH PACKET LOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Packets</strong></td>
</tr>
<tr>
<td><strong>Expected</strong> (m)</td>
</tr>
<tr>
<td><strong>Corrected</strong> (m)</td>
</tr>
<tr>
<td><strong>received index</strong> (m + ( d_n^m ))</td>
</tr>
<tr>
<td><strong>Displacement</strong> (( d_n^m ))</td>
</tr>
<tr>
<td><strong>RD</strong></td>
</tr>
</tbody>
</table>

**Sample Rate Adaptation**

Sample rate is varied according to either control performance, network performance or a combination of the two. In general, poor network conditions are usually implied by long delay, high dropout rate and high degree of reordering. Observed from the experiments that the frequency of higher displacement increases, indicating higher degree of reordering, with increase in mean delay and packet loss rate, which means that RD may be used for network diagnosis purpose as well\(^{11}\). In other words, if \( RD_k[0] \) is small, indicating higher degree of reordering, long delay and high packet loss rate may happen in the network communication, if \( RD_k[0] \) is large, indicating lesser amount of reordering, there exist better network traffic conditions. Then, the sample rate adaptation can be derived based on the \( RD_k[0] \). As an example, the sampling period is updated using the following policy

\[
T(t_{k+1}) = G(RD_k[0])
\]

\[
= \begin{cases} 30ms & RD_k[0] \geq 0.8 \\ 120 - 10u ms & 0.1(u - 1) \leq RD_k[0] < 0.1u \\ 90ms & RD_k[0] < 0.3 \end{cases}
\]

where \( 4 \leq u \leq 8 \). For the sample rate adaptation technique proposed in this paper, \( RD_k[0] \) is measured at the actuator node, and the controller node calculates the sampling interval and control action based on the sampling policy and controller design, respectively.
Remark 3. In fact, the upper and lower bounds (0.8, 0.3, etc.) of \( R D_k[0] \) and corresponding sampling interval should be determined by the distribution characteristics of \( R D_k[0] \) in the practical wireless network communication, which can be implemented by examining the wireless networks.

Remark 4. By the sampling policy applied, the sampling interval is required to adapt to \( R D_k[0] \). As \( R D_k[0] \) decreases, the sampling interval is increased to reduce the number of packets in the transmitting, such that QOS in the wireless networks is improved.

In this policy, the WASNs can be modeled as the discrete-time switched systems.

Modelling the Markov Jumping Systems
Due to the sample rate adaptation applied in the WSANs, the bounded network-induced delay and the maximum value of consecutive packet loss can be guaranteed. We have

\[
    u_k = \sum_{i=1}^{b} \theta^i(l)x_{k-i} + n_k 
\]

where \( u_k = u(t_{k-i}) \), \( \theta^i(l) = 0 \) or 1, \( \sum_{i=1}^{b} \theta^i(l) = 1 \), and \( n_k \) is additive noise. Under the sample rate adaptation in Section 3 and combining (3), the system (1) can be discretized as

\[
    x_{k+1} = \phi(T_k) x_k + \Gamma(T_k) \sum_{i=1}^{b} \theta^i(l) K x_{k-i} 
\]

where \( \phi(T_k) = e^{iT_k} \), \( \Gamma(T_k) = \int_{T_k}^{T_{k+1}} e^{-i(t-r)} B ds \), and \( T_k = t_{k+1} - t_k \). Set \( m(k) = [\theta^0(l), \theta^1(l), \ldots, \theta^b(l)]^T \), we know that \( m_k \) takes values on the finite set with \( (9 - 3 + 1)(h+1) \). For notational convenience, we define a vector-valued function \( f: m(k) \rightarrow \sigma(k) \) to map the vector \( m(k) \) into a scalar number \( \sigma(k) \in \mathcal{S} = \{1, 2, \ldots, r\} \), where \( r = (9 - 3 + 1)(h+1) \).

It is desired to design a real-time controller \( K_{\sigma(k)} \) depending on the newest signals received, such that the closed-loop WASNs system is stochastic stable. Then, the system (4) is rewritten as

\[
    x_{k+1} = \phi(\sigma_k) x_k + \sum_{i=1}^{r} \Lambda_{\sigma_k, \sigma(i)} K_{\sigma(i)} x_{k-i} 
\]

where \( \phi_{\sigma(i)} = \phi(T_k) \), \( \Lambda_{\sigma, \sigma(i)} = \Gamma(T_k) \theta^i(l) \). It is well known it is possible to the newest signals received by nodes (actuator) subject to some probability distribution\(^{12}\), therefore, we may just as well assume that the newest signals transmitted over the wireless channel subject to Markovian chain, and define transition probability \( \pi_{ij} = P[\sigma(k+1) = j | \sigma(k) = i] \). \( \sigma(k) \) is the No. \( i \) subsystem of WASNs (5). Obviously, \( \pi_{ij} \geq 0 \) and \( \sum_{i=1}^{r} \pi_{ij} = 1 \).

Set \( \xi_k = [x_k^T, x_{k-1}^T, \ldots, x_{k-L}^T]^T \), we obtain the following augmented system

\[
    \xi_{k+1} = \Phi_{\sigma(i)} \xi_k 
\]

where

\[
    \Phi_{\sigma(i)} = \phi_{\sigma, \sigma(i)} + \phi_{\sigma, \sigma(i)} K_{\sigma(i)}, \quad \phi_{\sigma, \sigma(i)} = \begin{bmatrix} \phi_{\sigma(0)} & 0 \\ 0 & \phi_{\sigma(i)} \end{bmatrix}, \\
    \phi_{\sigma, \sigma(i)} = \begin{bmatrix} \Lambda_{\sigma(i), \sigma(i)} & \cdots & \Lambda_{\sigma(i), \sigma(i)} \\ \cdots & \cdots & \cdots \\ 0 & \cdots & \Lambda_{\sigma(i), \sigma(i)} \end{bmatrix}, \\
    K_{\sigma(i)} = diag(K_{\sigma(i)}, \ldots, K_{\sigma(i)}) 
\]

Stability Analysis and Controller Design
In this section, we will present the sufficient condition for the stochastic stability of the systems and the method of controller design.

Lemma 1\(^{13}\) For matrices \( A, P > 0 \) and \( Q > 0 \), the inequality

\[
    A^TQA - P < 0 
\]
holds if and only if there exists a matrix $Y$ such that
\[
\begin{bmatrix}
-P & A^TY^T \\
YA & -Y^T + Q
\end{bmatrix} < 0
\]

**Theorem 1** For a given scalar $h$, matrices $K_i$, if there exist matrices $P > 0$ and $P_j > 0 \ (i, j \in \mathbb{S})$, such that
\[
\sum_{j \in \mathbb{S}} \pi_j \Phi_j^T P_j \Phi_j - P_j > 0
\]
then the closed-loop system (6) is stochastically stable. Where $\Phi_i = \phi_{i(1)} + \phi_{i(2)} \bar{K}_i$.

**Proof.** Choosing a Lyapunov-Krasovskii functional which is given by $V_i = \xi_i^T P_i \xi_i$, and assuming $\sigma(k) = i$, we can obtained
\[
EV_{i+1} - V_i = \sum_{j \in \mathbb{S}} \pi_j \xi_i^T \Phi_j^T P_j \Phi_j \xi_i - \xi_i^T P_i \xi_i
\]
\[
= \xi_i^T (\sum_{j \in \mathbb{S}} \pi_j \Phi_j^T P_j \Phi_j - P_i) \xi_i
\]
(8)

If (7) is satisfied, the stochastic stability is obtained. This completes the proof.

Note that Theorem 1 cannot be directly used to obtain the control law of the system (6). Therefore, we should design feedback gain $K_i$, which makes system (6) stochastically stable corresponding to the dynamic changes of the wireless network.

**Theorem 2** For a given scalar $h$, if there exist matrices $Q > 0$, $X_{i(1)}$, and $Y_{i(0)} \ (i \in \mathbb{S})$, such that
\[
\begin{bmatrix}
-Q_i & \sqrt{\pi_i} Y_i^T \\
* & \Delta_{i(1)} \\
* & * \\
* & * & \Delta_{i(1)} \ \\
\end{bmatrix} < 0
\]
(9)
then $K_i = V_i X_i^{-1}$ are real-time controller gains guaranteeing the stochastic stability of the WASNs. Where $Y_i^T = (X_{i(0)} \Phi_{i(1)} + V_i \Phi_{i(2)})$, $\Delta_{i(1)} = -X_{i(1)} - X_{i(1)}^T + Q_i$, $\Delta_{i(0)} = -X_{i(0)} - X_{i(0)}^T + Q_i$, $X_{i(0)} = \text{diag} (X_{i(0)}, \ldots, X_{i(0)})$, $V_{i(0)} = \text{diag} (V_{1(0)}, \ldots, V_{i(0)})$, $V_i = K_i X_i$.

**Proof.** By Lemma 1, (9) is true if there exists a matrix $Y_{i(0)}$ such that the following matrix inequality
\[
\begin{bmatrix}
-P_i & \sqrt{\pi_i} \Phi_{i(0)}^T Y_{i(0)}^T \\
* & -Y_{i(0)} - Y_{i(0)}^T + P_i \\
* & * \\
* & * & -Y_{i(0)} - Y_{i(0)}^T + P_i
\end{bmatrix} < 0
\]
(10)
holds. (10) implies that $Y_{i(0)}$ is invertible, $X_{i(0)} = X_{i(0)}^T$ is defined and $X_{i(0)}$ is restricted to be a block-diagonal matrix. By pre- and post-multiplying (10) by $\text{diag} (X_{i(0)}, \ldots, X_{i(0)})$ and $\text{diag} (X_{i(0)}^T, \ldots, X_{i(0)}^T)$, respectively. Set $Q_i = X_{i(0)} P_i X_{i(0)}^T$, (9) is obtained. The proof is completed.

**Remark 5.** Noted that adaptive controller obtained by Theorem 2 can be varied according to the subsystems switched.

**A Numerical Example**

To illustrate the effectiveness of the main results, a numerical example is presented. Here, the single WASN contained the following unstable plant
\[
\dot{x}(t) = \begin{bmatrix}
-0.8 & -0.1 \\
1 & 0.1
\end{bmatrix} x(t) + \begin{bmatrix}
0.4 & 1 \\
0.1 & 0
\end{bmatrix} u(t)
\]
The plant has an equal chance to transmit as there is no priority in IEEE 802.11 b ad hoc networks. Typically, data communication networks often experience delay, packet loss and packet reordering. For convenience of investigation, we take no account of packet loss. Packet reordering is captured here by \( RD_k[0] \).

For convenience of study, \( T_{k+1} \) is updated using the following sampling policy based on the \( RD_k[0] \).

\[
T(t_{k+1}) = G(RD_k[0])
\]

\[
\begin{align*}
30\text{ms}, & \quad RD_k[0] \geq 0.8, \\
40\text{ms}, & \quad 0.3 \leq RD_k[0] < 0.8, \\
50\text{ms}, & \quad RD_k[0] < 0.3.
\end{align*}
\]  

A comparison of the network-induced delay in Fig. 1(a), under constant sampling interval \( T = 50\text{ms} \) and adaptive sampling, shows the significant reduction in delay with sample rate adaptation.

Since the upper bound of the network-induced delay is \( h = 2 \), we have \( h = 2 \). The mapping \( f : m(k) \rightarrow \sigma(k) \in \mathcal{S}, \ \mathcal{S} = \{1, 2, \ldots, 9\} \ (m(k) = [I, \mathcal{J}^t(0) \mathcal{J}^t(1) \mathcal{J}^t(2)]) \) is given in detail as follows:

\[
\begin{align*}
[30 \ 1 \ 0 \ 0] & \rightarrow 1, [30 \ 0 \ 1 \ 0] \rightarrow 2, \\
[30 \ 0 \ 0 \ 1] & \rightarrow 3, [40 \ 1 \ 0 \ 0] \rightarrow 4, \\
[40 \ 0 \ 1 \ 0] & \rightarrow 5, [40 \ 0 \ 0 \ 1] \rightarrow 6, \\
[50 \ 1 \ 0 \ 0] & \rightarrow 7, [50 \ 0 \ 1 \ 0] \rightarrow 8, \\
[50 \ 0 \ 0 \ 1] & \rightarrow 9.
\end{align*}
\]

A comparison of the network-induced delay in Fig. 1(a), under constant sampling interval \( T = 50\text{ms} \) and adaptive sampling, shows the significant reduction in delay with sample rate adaptation.

Under the adaptive sampling policy (10) and the network-induced delay shown in Fig. 1(a), the subsystems are switched in the approach in Fig. 1(b). We assume that the subsystems of the WSAN subject to the Markovian process, whose state transition matrix is given in the following

\[
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\]

where

\[
Y_{11} = \begin{bmatrix}
0.3 & 0.3 & 0 & 0.2 & 0.2 \\
0.2 & 0.3 & 0.15 & 0.1 & 0.15 \\
0.2 & 0.1 & 0.2 & 0.1 & 0.25 \\
0.3 & 0.1 & 0 & 0.2 & 0.1 \\
0.02 & 0.03 & 0.05 & 0.1 & 0.08
\end{bmatrix}
\]

\[
Y_{12} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0.1 & 0 & 0 & 0 & 0 \\
0.15 & 0 & 0 & 0 & 0 \\
0 & 0.2 & 0.1 & 0 & 0 \\
0.12 & 0.1 & 0.2 & 0.3 & 0
\end{bmatrix}
\]

\[
Y_{21} = \begin{bmatrix}
0.11 & 0.12 & 0.06 & 0.11 & 0.1 \\
0.4 & 0.15 & 0 & 0.2 & 0.02 \\
0.09 & 0.1 & 0.11 & 0.15 & 0.05 \\
0.07 & 0.07 & 0.14 & 0.15 & 0.05
\end{bmatrix}
\]
By Theorem 2, the adaptive controller gains of the WSAN are obtained and shown in Table II. At the initial state value \( x_0 = [1 \ 2]^T \), the state response of the WSAN with adaptive sampling are shown in Fig. 2. As illustrated in Fig. 2, the real-time controller obtained by the approach of sample rate adaptation in this paper can stabilize the systems easily.

### TABLE II. CONTROLLER GAINS OF THE WSNA WITH SAMPLE RATE ADAPTATION

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Controller gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( K_1 = \begin{bmatrix} -4.9825 &amp; -333.8311 \ -30.9417 &amp; 133.5825 \end{bmatrix} )</td>
</tr>
<tr>
<td>2</td>
<td>( K_2 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
<tr>
<td>3</td>
<td>( K_3 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
<tr>
<td>4</td>
<td>( K_4 = \begin{bmatrix} -4.9767 &amp; -250.4970 \ -22.6111 &amp; 100.2486 \end{bmatrix} )</td>
</tr>
<tr>
<td>5</td>
<td>( K_5 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
<tr>
<td>6</td>
<td>( K_6 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
<tr>
<td>7</td>
<td>( K_7 = \begin{bmatrix} -4.9708 &amp; -200.4963 \ -17.6139 &amp; 80.2482 \end{bmatrix} )</td>
</tr>
<tr>
<td>8</td>
<td>( K_8 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
<tr>
<td>9</td>
<td>( K_9 = \begin{bmatrix} 0 \ 0 \end{bmatrix} )</td>
</tr>
</tbody>
</table>

### Conclusions

In this paper, stability analysis and controller design are discussed for the WSANs with reordering-based sample rate adaptation. Based on the dynamic characteristic of RD in the WSANs, a novel sampling interval variation strategy is obtained, such that a closed-loop switched system is constructed. Combining Markov theory and LMI, the stochastic stability is analyzed and the adaptive controller is designed. The simulation results are given to illustrate the effectiveness of the proposed method.
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