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Optimal bandwidth scheduling of networked control systems (NCSs) in accordance with jitter*

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Abstract: Network-induced delay and jitter are key factors causing performance degradation and instability of NCSs (networked control systems). The relationships between the sampling periods of the control loops, network-induced delay and jitter were studied aimed at token-type networks. A jitter-dependent optimal bandwidth scheduling algorithm for NCSs is proposed, which tries to achieve a tradeoff between bandwidth occupancy and system performance. Simulation tests proved the effectiveness of this optimal scheduling algorithm.

Key words: NCSs (networked control systems), Network-induced delay, Jitter, Deadline, Loop delay
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INTRODUCTION

Compared with point-to-point control, the major advantages of networked control (NC) include flexibility of operation, integrated diagnostics, quick and easy maintenance and monitoring, small wiring volume, low cost. There are also many disadvantages due to the limited bandwidth resources shared by all nodes. Two major consequences are the network-induced delay and the jitter, the transmission fluctuations of successive instances of a data, both of which can degrade the dynamic performance of the NCSs inevitably, even cause instability (Ray and Halevi, 1988; Stothert and Macleod, 1998; Walsh *et al*., 1999; Zhang, 2001). Therefore the key issue in the analysis and design of the NCSs is to assign the limited bandwidth so that the network influence on the controlled plant is minimal and the requirements of timeliness and control performances are both satisfied.

Ray and Halevi (1988) provided fundamental concepts on the analysis and design of NCSs. Chow and Tipsuwan (2001) presented the basic details of networked control and recent networked control techniques for handling the network-induced delays. These NCSs techniques are based on various concepts such as state augmentation (Lian *et al*., 2002), scheduling (Hong, 1995; Hong and Kim, 2002), hybrid system theory (Zhang, 2001), queuing and probability theory (Chan and Özgüner, 1995; Nilsson and Bernhardsson, 1997), nonlinear control and perturbation theory (Walsh *et al*., 1999; 2001), etc. Most of the studies emphasized particularly the control performance (Walsh *et al*., 1999; 2001; Stothert and Macleod, 1998; Zhang, 2001) from the viewpoint of control or bandwidth utilization (Raja and Ulloa, 1993; Coutinho *et al*., 2003) or from the viewpoint of network scheduling. Only few papers touched on the relationship between the control performance and the bandwidth utilization, Hong (1995) and Hong and Kim (2002)'s work being prominent. Based on the window model of the bandwidth resources, Hong

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(1995) and Hong and Kim (2002) developed a non-jitter sampling scheduling algorithm for multiple control loops with cyclic service discipline. Through configuring the sampling period of each control loop to 2^k (k=0,1,2…) multiples of T_1, the minimum period of the NCSs, and determining the initial phases, the amount of periodic data generated in each primary period T_1 is restricted within a constant and the network-induced delays of all periodic data are constrained not to exceed T_1, which not only satisfies the control performance, but also utilizes the bandwidth efficiently. Although very simple and effective, it is not always economical and optimal because of the exponential scalar configuration of the sampling periods at the cost of much more of the bandwidth resource being occupied. As a result, on one hand, some control loops that could be served originally may not be served now because some others occupy the bandwidth resource too much. On the other hand, when all control loops of the NCSs must be served simultaneously as a requirement, the above configuration should pay for the excessive bandwidth resource.

Aimed at these drawbacks, an algorithm of jitter-dependent optimal bandwidth scheduling for the token-type based NCSs is proposed, where the jitter caused by scheduling is considered only. In this algorithm, jitter is used as a connecting bridge between the bandwidth occupancy and the control performance. Through choosing the jitter, the permitted range of the sampling period of each control loop is constrained according to the requirement of the control performance. Choices of the sampling period and the jitter for each control loop not only affect the achievable control performance, but also affect the bandwidth utilization. Therefore a tradeoff between bandwidth occupancy and control performance could be determined.

CHARACTERISTICS OF TOKEN-TYPE NETWORKS

Because of the cyclic service property of the token-type networks, the sampled data generated by each node cannot be transmitted but wait in the transmitter queue until the token arrives. It causes the network-induced delay that is defined as the time interval from the instant when a data arrive at the transmitter queue of the sender node to the instant when the same data is completely received by the receiver queue of the destination (Hong, 1995). In practical systems, different control loops (nodes) may generate data at different periods and the network has to support a large variety of applications requiring these data. Therefore an important requirement is to support different nodes generating periodic data at different frequencies. This means that periodic data generated at different periods have to be served exactly once within fixed deadlines. In the classical approach, only one cycle (basic cycle) is used and each periodic node is allocated to a particular time slot in a basic cycle. This restricts the network-induced delay of all the periodic data to time of not more than one cycle and has no jitter. However its disadvantage is that each node with different period is allocated averagely yet, where the nodes with larger period occupy more bandwidth than required so that the bandwidth is wasted. An alternative solution is to organize the periodic data transfer in multi-cycles (Raja and Ulloa, 1993). The basic idea of the multi-cycles scheduling is to allocate the necessary bandwidth to each corresponding periodic node, that is, to allocate only one particular time slot to satisfy the system requirements. The network-induced delay is not limited to one cycle time any more but to not exceed the corresponding maximum allowable time delay, which causes the larger jitter consequently. Therefore, this achieves higher bandwidth utilization by increasing the network-induced delay and jitter.

Let us consider the NCSs with M control loops that share the network medium. The controller for each control loop is assumed to be designed in advance without considering the effect of the network. Each control loop has two data transmitting nodes of sensor and controller, while the actuator node is not included because it does not transmit its data through the medium. Therefore there are a total of $N=2M$ data transmitting nodes in the network. Before the discussion, some basic assumptions (Hong, 1995) used in this paper are listed first as follows.

1. The sensors and the controllers are time-triggered and synchronized while the actuators work in the event-driven mode. That is, the sensors and controllers will not transmit the data in the transmitter queue until the new period time comes,

while the actuators act on the plant immediately as long as the actuator command arrives.

2. The sensor node and the controller node in the same control loop i sample their data with an identical sampling period T_i. The sampling time skew between the nodes is limited to a negligibly small value compared to the sampling period.

3. The processing time at the nodes is negligibly small compared to the sampling period.

4. The periodic data generated from each node are packetized to the fixed length L', which is identical to all the nodes in the medium. If the data rate of the network medium is B, the packetized data transmission time is $L=L'/B$. The case that different nodes may have different data length is not considered.

Let τ_{i1} be the sensor-controller delay and τ_{i2} be the controller-actuator delay of control loop i in the NCSs, as shown in Fig.1. Based on the above assumptions, the bounds on the network-induced delay can be determined as follows.

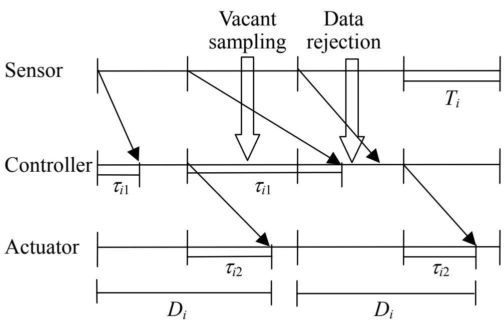

Fig.1 Loop delay of the *i*th control loop

The best case of τ_{im} (m=1,2) for data transmitted without any waiting delay is

$$\min \tau_{im} = L, \quad (m = 1,2) \tag{1}$$

The worst case of τ_{im} (m=1,2) occurs when the node m in control loop i releases the token immediately before a data enters in its transmitter queue, after which the data cannot be transmitted until the token finishes n_i cycles visiting and in the (n_i+1)th cycle, the node m gets the token again after visiting all the other nodes. Therefore the worst case of τ_{im} is expressed as

$$\max \tau_{im} = n_i T_1 + rL + N\sigma, \quad (m = 1,2) \tag{2}$$

where T_1 is the time of one basic cycle; r is the maximum allowable number of data that can be transmitted during one cycle service; σ is the overhead of the token, which includes the token processing time and its maximum propagation delay. When n_i=0, it is the maximum delay bound in the classical bandwidth allocation scheme, i.e. one-cycle scheduling scheme.

CONTROL PERFORMANCE ANALYSIS OF NCSs

Ray and Halevi (1988) showed that the performances of a feedback control loop directly depend on the loop delay, which is defined as the interval between the instant when the sensor node samples a data from the plant to the instant when the actuator command generated based on the same data acts on the plant (Fig.1). The loop delay of the control loop i is expressed as

$$D_i = \lceil \tau_{i1}/T_i \rceil T_i + \tau_{i2} \tag{3}$$

The time-variant network-induced delay can cause data rejection in one sampling interval and vacant sampling in some other sampling intervals; then the control performance is degraded and the distortion of the controller signal is introduced. This distortion of the controller signal will cause high frequency noise in the actuator and thus lead to excessive wear (Ray and Halevi, 1988; Hong, 1995). Therefore every sensor data should arrive at the controller node before the next sensor data is sampled, i.e. the data deadline of every node is one sampling time of its own. The control loop D_i is time-varying too because of the time-variant τ_{i2}. Hong (1995) showed that the stability is still guaranteed when D_i is replaced by its constant supremum D_i'

$$D_i' = 2T_i + (\max \tau_{i2} - \min \tau_{i2}) \tag{4}$$

Let ϕ_i, i=1,2,…,M (where $\phi_i \le \phi_{i+1}$) be the predetermined maximum allowable loop delay of control loop i, which can be obtained from the conventional stability criterion and/or by considering the response smoothness. The following conditions are then the requirements of the control performance that control loop i must satisfy:

C1: $\tau_{im} \le T_i$ (m=1, 2) to eliminate data rejection and sampling vacancy;

C2: $D_i' \le \phi_i$ to maintain the control performance;

C3: $\max\tau_{im} < (n_i+1)T_1$ (m=1, 2) to limit jitter not to exceed the permitted bound.

C1 and C3 are the real-time requirements of the control loops.

Determination of Φ_i

In order to guarantee system stability and control performance, two control measures can be used to determine the best sampling period: phase margin φ and the control loop bandwidth $\omega_{\rm bw}$ (Lian *et al.*, 2002) (or equivalently the rise time $T_{\rm rise}$ of the control loop). The primary effects of the sampling period $T_{\rm s}$ and the network-induced delay $T_{\rm d}$ on the system stability are additional phase lag, expressed respectively as

$$\Delta\varphi_{\rm s} = \omega T_{\rm s}/2 \text{ and } \Delta\varphi_{\rm d} = \omega T_{\rm d} \quad (5)$$

where ω is the system frequency. Therefore the total additional phase lag should be less than the phase margin such that the system stability is guaranteed, that is

$$\varphi > \omega T_{\rm s}/2 + \omega T_{\rm d} \quad (6)$$

In order to guarantee acceptable control performance, that is, to consider the response rapidness and smoothness, the "rule of thumb" for selecting the sampling periods in digital control (DC) is that the reasonable sampling rates are 20~40 times the control loop bandwidth $\omega_{\rm bw}$ (Lian *et al.*, 2002) or 4~10 per rise time $T_{\rm rise}$ (Tou, 1959), i.e.

$$20 \le \omega_{\rm s}/\omega_{\rm bw} \le 40 \ (1/40 \le T_{\rm s}/T_{\rm bw} \le 1/20)$$
$$\text{or} \quad 4 \le T_{\rm rise}/T_{\rm s} \le 10 \quad (7)$$

In network control (NC), the network-induced delay unavoidably degrades the control performance further. To maintain the acceptable control performance as that in DC, the network-induced delay should be considered when choosing the sampling periods. Suppose both DC and NC have the same phase lags (Lian *et al.*, 2002), Eq.(7) could be revised for NC as follows

$$1/40 \le (T_{\rm s} + 2T_{\rm d})/T_{\rm bw} \le 1/20$$
$$\text{or} \quad 4 \le T_{\rm rise}/(T_{\rm s} + 2T_{\rm d}) \le 10 \quad (7')$$

Therefore the maximum allowable loop delay ϕ_i of control loop i could be determined by Eq.(7')

$$\phi_i \le [T_{i,\rm bw}/40, T_{i,\rm bw}/20]$$
$$\text{or} \quad \phi_i \le [T_{i,\rm rise}/10, T_{i,\rm rise}/4] \quad (8)$$

OPTIMAL SAMPLING PERIODS SCHEDULING

Based on the idea of the multi-cycles scheduling scheme, an algorithm of jitter-dependent optimal bandwidth scheduling is proposed to find a tradeoff between the control performance and the bandwidth utilization under the constraint of jitter.

Configuring the sampling periods

When the sampling period of each control loop in the NCSs is configured with a whole number times of the basic cycle under the conditions of C1, C2 and C3, the mathematical relationships between the scales of the NCSs (the number of the nodes), the sampling periods of the control loops and the cost of the bandwidth described by the window concept (Hong, 1995; Hong and Kim, 2002) are constructed easily to smooth the path of the next optimal scheduling.

To satisfy the minimum requirement of the maximum allowable loop delay of the control loops in the NCSs, i.e. control loop 1 with ϕ_1, the basic cycle time must not exceed the determined sampling period of control loop 1 and the shorter the basic cycle time, the better the control performance. However, the basic cycle time cannot be chosen too small because the overhead wasted is constant and so the effective bandwidth is decreased.

Let $T_i, i = 1, 2, \cdots M$ be the sampling periods of the M control loops of the NCSs and $T_i \le T_{i+1}$, $\forall i$. Because the basic cycle is equal to T_1, the data with the sampling period T_1 must be transmitted within the basic cycle (i.e. n_1=0) to satisfy the conditions of C1, C2 and C3, and when $D_i' = \phi_1$, T_1 is determined as

$$T_1 = (\phi_1 + L)/3 \quad (9)$$

Similarly, T_i is determined as

$$T_i < \frac{\phi_i - (n_i + 1)T_1 + L}{2} \quad (10)$$

Assuming that $T_i = k_i T_1$ ($k_i \geq 1$), $\forall i > 1$, then

$$k_i \leq \left\lfloor \frac{\phi_i - (n_i + 1)T_1 + L}{2T_1} \right\rfloor \quad (11)$$

where $0 < (n_i + 1) \leq k_i$ is required to satisfy the conditions C1 and C3.

From the control point of view, the choice of n_i constraints the choice of the sampling period $T_i(k_i)$ directly. The large n_i means the permitted data transmission delay is long, so in order to guarantee the control requirement such that the total loop delay is limited to the maximum allowable range, $T_i(k_i)$ should decrease to compensate the large loop delay caused by the large data transmission delay. From the network point of view, with the increase of the n_i, $T_i(k_i)$ decreases, network traffic load increases. Hence, the required bandwidth increases. If the sampling period $T_i(k_i)$ is constant, increasing n_i means to permit the larger jitter range, which degrades the control performance but relaxes the limitation of the bandwidth scheduling and as a result it is more possible to promote the bandwidth utilization.

When the network parameters are fixed, the number of the maximum allowable transmission data (i.e., the number of windows) in one basic cycle that the network medium could provide is determined by Eq.(2) and C1 as

$$r = \left\lfloor \frac{T_1 - N\sigma}{L} \right\rfloor = \left\lfloor \frac{(\phi_1 + L)/3 - N\sigma}{L} \right\rfloor \quad (12)$$

N nodes in the NCSs dynamically share the r windows during any interval of T_1, so that the number of data transmitted during any interval of T_1 does not exceed r. If $r \geq N$, the network traffic is lightly loaded, the network could provide the data transmission for all N nodes with the maximum network-induced delay T_1. If $r < N$, it should be decided whether the designed NCSs are schedulable and if it does, how to schedule the data of every node. The interval of interest for observing the network schedulability and jitter-dependent scheduling is the macro-cycle, the least common multiple (LCM) of all control loops in the NCSs with $T = LCM[T_i, i=1, 2, \ldots, M]$. During the macro-cycle interval of T, there is a total constant number of data, $\sum_{i=1}^{N} T/T_i = 2(T/T_1)\sum_{i=1}^{M}(1/k_i) = \beta(T/T_1)$ with $\beta = 2\sum_{i=1}^{M}(1/k_i)$, generated from all nodes and there is a fixed number of windows, $(T/T_1)r$, offered by the network. Therefore, if $\beta > r$, the limited bandwidth cannot accommodate all of the input traffic in the NCSs, i.e. the network is overloaded or cannot be scheduled.

Jitter-dependent optimal sampling periods scheduling

Based on the analysis above, the jitter-dependent optimal bandwidth scheduling algorithm for the NCSs is shown in Fig.2, which is a repetitive searching process dependent on the practical requirements. Given the network with fixed parameters, it is used to search for the most attainable optimal control performance of the NCSs. Given the required control performance of the NCSs, it is used to search for the minimum or the most economical bandwidth occupa-

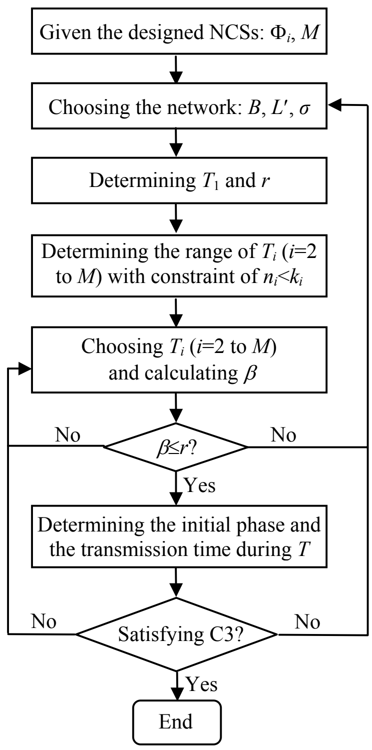

Fig.2 Jitter-dependent bandwidth scheduling

ncy. It is also to search for the tradeoff between the control performance and bandwidth utilization to obtain the whole system performances including the network part and the control part.

The first step is to choose the proper network such as the H1 fieldbus with 31.25 kbps or the H2 fieldbus with 1 Mbps/2.5 Mbps in FF and then to determine the basic cycle time and the corresponding maximum number of windows. The second step is to determine the allowable range of the sampling period for each control loop with the constraint of $n_i<k_i$. Proper choice of the sampling period and the permitted jitter range satisfy the requirement of good control performance; affect the network traffic load and the requirement for the bandwidth as well. The constraints of $n_i<k_i$ and $\beta\leq r$ give the necessary and sufficient conditions of the NCSs' schedulability.

The optimal sampling scheduling problem can be described given the NCSs with the maximum allowable loop delay ϕ_i, i=1, 2, …, M satisfying $\phi_{i-1}\leq\phi_i$ and the token-type network condition. Non-jitter scheduling is obtained by finding the optimal sampling periods (T_i, $\forall i$) and the optimal initial phase (φ_i, $\forall i$) for each control loop, which are searched under both constraints of the control performance and the bandwidth, which is formulated as follows

$$\min OSJ = \min\left(\frac{2}{T}\right)\sum_{i=1}^{M}\sum_{k=1}^{(T/T_i)}\frac{ts_{i,k}-T_i-\varphi_i}{T_i} \tag{13}$$

$$\text{s.t.:}\quad \beta\leq r,\quad \max\tau_{im}\leq(n_i+1)T_1\leq T_i,$$

$$T_i\leq\left\lfloor\frac{\phi_i-(n_i+1)T_1+L}{2T_1}\right\rfloor T_1$$

$$T_{i-1}\leq T_i,\ \forall i=1,2,...,M,\ \forall im=1,2,...,N$$

The performance measure is the overall system jitter (OSJ) obtained by integrating the individual jitter for each instance of data for each node over the system's macro-cycle T. $jitter(i,k)=ts_{i,k}-T_i-\varphi_i$ is the jitter for the kth instance of data for the control node i where $ts_{i,k}$ is the actual transmission time of this instance. Constraint 1 is the bandwidth limitation, constraint 2 is conditions C1 and C3, constraint 3 is condition C2 and constraint 4 limits the control loop with the larger ϕ_i not occupying too much bandwidth.

Jitter-dependent optimal sampling periods scheduling

In order to solve this optimization problem Eq.(13), branch and bound+genetic algorithm (GA) is proposed and presented as follows:

Step 1: Determine the feasible sampling periods for each control loop and the corresponding maximum allowable network-induced delay, $(n_i+1)T_1$.

Step 2: Choose the possible sampling periods branches that satisfy the bandwidth resource constraints.

Step 3: Search for the optimal initial phases of the given sampling periods branches with minimum jitter using GA and find the feasible sampling periods and the feasible initial phases.

Step 4: Compare all feasible branches of the optimal performance measure and obtain the preferable solution.

The feasible sampling periods of one control loop are determined independent of those of the other control loops, but the selected sampling periods composition (some branch) for all control loops are limited by the bandwidth constraint. What is more, their mutual relationships may affect the minimal possible jitter range that may exceed the maximum allowable network-induced delay, $(n_i+1)T_1$.

Jitter minimization can be achieved by using GA, where the genome is a simple vector with values of $(\varphi_i, \forall i=1,2,\cdots,N)$ for all control loops. The allele is a value of multiples of T_1 within the range [0, T_i] that represents the initial phase of the ith control loop. The best solutions are those that generate smaller OSJ, so the fitness of each individual is computed as 100/(OSJ+1). If $jitter(i,k)>(n_i+1)T_1$, that is jitter exceeds the maximum allowable network-induced delay, it is set that $jitter(i,k)$=99. Therefore fitness of 100 means that the properly selected initial phases for a given sampling periods branch is non-jitter scheduling while fitness less than or equal to 1 means that the given sampling periods branch does not satisfy condition C3 and also the real-time requirement of the control loops. Fitness between 1 and 100 means that the real-time requirement of the control loops is guaranteed with jitter scheduling.

SIMULATION TESTS

The jitter-dependent optimal sampling periods scheduling algorithm is realized by MATLAB. A developed software package was used to complete the simulation tests for the designed NCSs. The NCS is assumed to have 5 control loops with 10 data transmission nodes. Nodes (1, 2), (3, 4), (5, 6), (7, 8) and (9, 10) are included in the control loops 1, 2, 3, 4, 5 respectively. The maximum allowable loop delays are $[\phi_1, \phi_2, \phi_3, \phi_4, \phi_5]$=[25, 75, 100, 135, 160] ms. It is assumed that the period data transmission time of the candidate network is L=2 ms, and the overhead of the token is σ=0.1 ms. Eqs.(9) and (12) are used to determine that T_1=9 ms and r=4. Based on Eq.(11), the range of k_i is determined by different n_i and as shown in Table 1 where the shaded parts are the allowable value of k_i with the constraints of $n_i < k_i$ and C2. Hence, the feasible sampling periods for each control loop and the corresponding maximum allowable network-induced delay, $(n_i+1)T_1$ are listed as shown in Table 2.

Using the branch and bound+genetic algorithm (GA), the feasible sampling periods and their initial phases are searched and listed as shown in Table 3, which satisfy the constraints of the control performance requirement and of the bandwidth limitation. This shows that there exists a non-jitter solution with the sampling periods of the control loops being $[T_1, T_2, T_3, T_4, T_5]$=[9, 27, 27, 54, 54] ms and corresponding initial phases of $[\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5]$ = [0, 0, 9, 18, 45] ms. Note that the initial phases are not unique for the minimal *OSJ*. The preferable sampling periods and the corresponding optimal initial phases are dependent on the choice in practice and the tradeoff between bandwidth occupancy and acceptable control performance. For the non-jitter solution of the NCS, the maximum network-induced delays are all 9 ms and the maximum loop delays for the control loops are 18 ms, 36 ms, 36 ms, 63 ms, 63 ms respectively, which are less than the maximum allowable loop delays. For the minimum bandwidth occupancy solution of 83.33%, the maximum network-induced delays are 9 ms, 9 ms, 18 ms, 9 ms, 18 ms and the maximum loop delays for the control loops are 18 ms, 36 ms, 54 ms, 63 ms, 72 ms respectively, which are less than the maximum allowable loop delays, but larger than those of the non-jitter solution. Therefore the control performance of the non-jitter solution is better than that of the minimum bandwidth occupancy solution.

CONCLUSION

Network-induced delay and jitter are the key affecting factors of the performance degradation and instability of the NCSs and are related to the network topology, the MAC protocol used, bandwidth alloca-

Table 1 The range of k_i (i=2 to M) for control loops of the NCSs

n_i	k_i			
	Φ_i=75 ms	100 ms	135 ms	160 ms
0	1~3	1~5	1~7	1~8
1	2~3	2~4	2~6	2~8
2	2	3	3~6	3~7
3		3	4~5	4~7
4			5	5~6
5			4	6
6				5

Table 2 The feasible T_i and the corresponding maximum allowable network-induced delay $(n_i+1)T_1$

Φ_2=75 ms		Φ_3=100 ms		Φ_4=135 ms		Φ_5=160 ms	
T_2	$(n_2+1)T_1$	T_3	$(n_3+1)T_1$	T_4	$(n_4+1)T_1$	T_5	$(n_5+1)T_1$
9	9	9	9	9	9	9	9
18	18	18	18	18	18	18	18
27	18	27	27	27	27	27	27
		36	27	36	36	36	36
		45	9	45	45	45	45
				54	27	54	54
				63	9	63	36
						72	18

Table 3 Optimal sampling periods and optimal initial phases (Time unit: ms)

T_1	T_2	T_3	T_4	T_5	Optimal initial phase	Fitness	Bandwidth occupancy
9	27	27	54	54	0,0,9,18,45	100	88.89%
9	27	36	36	54	0,9,0,18,27	66.67	88.89%
9	27	36	45	54	0,9,0,0,27	17.39	85.67%
9	27	36	54	54	0,9,9,0,18	70.59	85.19%
9	27	36	54	72	0,18,0,9,18	61.54	83.33%

tion schemes, as well as the network traffic load that is directly related to the selective sampling periods of the control loops. Aimed at the token-type networks, this paper studies the relationships of the sampling periods of the control loops, network-induced delay and jitter, and proposes an algorithm of jitter-dependent optimal bandwidth scheduling based on the idea of multi-cycles scheduling. Through the repetitive searching process, a tradeoff, which is based on the practical requirements, between the control performance of the NCSs and the bandwidth occupancy was obtained with the constraint of jitter. Simulation tests were used to prove the effectiveness of this optimal scheduling algorithm.

References

Chan, H., Özgüner, Ü., 1995. Optimal Control of Systems over A Communication Network with Queues Via A Jump System Approach. Proceedings of the 4th IEEE Conference on Control Applications, p.1148-1153.

Chow, M.Y., Tipsuwan, Y., 2001. Network-based Control Systems: A Tutorial. The 27th Annual Conference of IEEE Industrial Electronics Society, p.257-261

Coutinho, F., Fonseca, J., Barreiros, J., Costa, E., 2003. Using Genetic Algorithms to Reduce Jitter in Control Variables Transmitted over CAN. http://www.ieeta.pt/~jaf/papers/Ano2000/icc_coutin.pdf.

David, L., Cottet, F., Nissanke, N., 2001. Jitter Control in On-line Scheduling of Dependent Real-time Tasks. 22nd IEEE Proceedings on Real-Time Systems Symposium, p.49-58.

Hong, S.H., 1995. Scheduling algorithm of data sampling times in the integrated communication and control systems. *IEEE Transactions on Control System Technology*, **3**(2):225-231.

Hong, S.H., Kim, Y.C., 2002. Implementation of a bandwidth allocation scheme in a token-passing fieldbus network. *IEEE Transactions on Instrumentation and Measurement*, **51**(2):246-251.

Lian, F.L., Moyne, J.R., Tilbury, D.M., 2002. Network design consideration for distributed control systems. *IEEE Transactions on Control System Technology*, **10**(2):297-307.

Nilsson, J., Bernhardsson, B., 1997. LQG Control over A Markov Communication Network. Proceedings of the 36th Conference on Decision and Control, p.4586-4591.

Raja, P., Ulloa, G., 1993. Priority Polling and Dynamic Time-window Mechanisms in A Multi-cycle Fieldbus. CompEuro'93. Computers in Design, Manufacturing, and Production Proceedings, p.452-460.

Ray, A., Halevi, Y., 1988. Integrated communication and control systems: part I–analysis and part II–design consideration. *ASME Journal of Dynamic System Measurement& Control*, **110**:367-381.

Stothert, A., Macleod, I.M., 1998. Effect of Timing Jitter on Distributed Computer Control System Performance. Proceedings 15 IFAC Workshop DCCS'98–Distributed Computer Control Systems.

Tou, J.T., 1959. Digital and Sampled-Data Control Systems. McGraw-Hill, New York.

Walsh, G.C., Beldiman, O., Bushnell, L.G., 1999. Stability Analysis of Networked Control System. Proceeding of the American Control system Conference, p.2876-2880.

Walsh, G.C., Beldiman, O., Bushnell, L.G., 2001. Asymptotic behavior of nonlinear networked control systems. *IEEE Transactions on Automatic Control*, **46**(7):1093-1097.

Zhang, W., 2001. Stability Analysis of Networked Control Systems. http://dora.cwru.edu/msb/pubs/wxzPHD.pdf.