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Abstract: To implement and design an application of a real time fieldbus segment, engineers are obliged to estimate the communication load factor of the communication to secure the operation. According to the recent increase of the node number per segment, communication load management becomes a real issue. This paper gives the definition of the communication load and the procedure to estimate and measure the communication load of a real time fieldbus: FOUNDATION™ fieldbus and thus establish the theoretical and experimental base of the guidance to keep the periodical/stationary communication load less than 70%.

Key Words: FOUNDATION fieldbus, real-time, communication load.

1. Background

The importance of communication load planning on the FOUNDATION fieldbus project is increasing according to the progress of explosion protection technology to relax power limitation and accommodate user expectation for more devices connected to a segment.

Currently, a rule of thumb is provided in the System Engineering Guideline [1] “At least 30% of time must be left for acyclic communications at the engineering phase.”

The objective of this paper is to provide the definition of the communication load of the fieldbus and establish the procedure to estimate the periodical communication load at the engineering phase and the measurement procedure of the communication load during on line operation phase.

2. FOUNDATION Fieldbus

2.1 Communication Model of the FOUNDATION Fieldbus

The FOUNDATION fieldbus specification [2] provides three communication models, namely Publisher-Subscriber model, Client-Server model and Source-Sink model.

Publisher-Subscriber (P-S) model is the pre-scheduled periodic communications. The communications scheduled using this model never miss the deadline as they occur at the specified time in the macro cycle time.

Client-Server (C-S) model can be used for the periodical communications if the user application initiates certain data access periodically. But this model does not provide the pre-scheduled feature and then will miss the deadline when too many communications are requested. It is also used for aperiodic communications such as plant operators’ manual operations, configuration download to the field device, parameter upload from the field device for device management application and so on.

Source-Sink (S-S) model is initiated by the events occurred in a field device such as device diagnostics alarm (aperiodic) and trend data report (periodical). This model does not provide the pre-scheduled feature.

In summary, there are two types of periodic user data communication (scheduled and unscheduled) and aperiodic user data communication in the FOUNDATION fieldbus communication.

2.2 Real-Time Nature of the Periodical Communications on the FOUNDATION Fieldbus

To discuss real-time nature, the concept proposed in the Hartstone Benchmark project on real time task management is useful. Periodical communications have deadline and missing the deadline is the criteria of failure of real-time nature [3]. The periodical communications in the FOUNDATION fieldbus are defined as periodic communications, and usually scheduled in harmonic frequencies [3]. Periodic communications using Publisher-Subscriber model never miss the deadline as they are scheduled and correspond to “hard periodical” and periodic communications using Client-Server model or Source-Sink model sometimes miss the deadline as they are “soft periodical” in the Hartstone Benchmark definition. Here, deadline is defined as the next scheduled time.

2.3 Communication Load of the FOUNDATION Fieldbus

Currently, in the engineering phase, communication load is calculated as the ratio of the time scheduled for P-S model communication per control macro cycle time.

Time for a P-S model communication is calculated as the interval time between consecutive P-S model communications.

The scheduling of the P-S model communications is done using the maximum time of it assuming the data publish (DT frame) is done just before the time-out of the no response timer started after the data request (CD frame) as shown in the Fig. 1.

As the P-S model communication is executed as scheduled, it is naturally assumed that the estimated communication time and the measured time are the same. Thus, measurement of the communication load was not discussed today in the FOUNDATION fieldbus arena.

This paper introduces the new definition of the communica-
tion load according to the real time nature of the FOUNDATION fieldbus mentioned in Section 2.2. Current guideline considers only “hard periodical” communications and does not provide a measurement procedure. This paper proposes to include “soft periodical” communication as part of the real time communication to reflect the user needs not to miss any periodical communications. And the measurement procedure of the communication load is provided. The measurement procedure is useful to confirm the results of engineering work at the commissioning phase.

3. Communication Load Definition

In this paper, Communication Load is defined as the ratio of the sum of the User Data Transfer Time to Unit Time.

3.1 Communication Unit Time

In case of the “Token” based communication protocol such as FOUNDATION fieldbus H1, always one of the node residing on the segment is obliged to initiate the next transaction. This means the maximum duration of the silent time (no signal time) is defined by specification (time out) and the silent time is expected to be minimum regardless if there is a user data waiting to be transmitted in the designated node or not. For other communications using collision detection for example, the silent time may continue until one of the nodes wants to transmit a communication unit based on a request from an application process in it.

Figure 2 shows the definition of the Communication Unit Time, $T_{CU}$, as the sum of the signal time shown as black line, $T_{SG}$, and the consecutive silent time, $T_{SL}$.

$$T_{CU} = T_{SG} + T_{SL}.$$ (1)

3.2 Consideration of “Silent Time”

In the Token based protocol, $T_{SL}$ can be divided into two parts. In the FOUNDATION fieldbus, one is the part required by specification such as minimum silent time after a signal transmission to allow the nodes to become listening mode (Listen Time, $T_{LS}$), required time to accomplish the event of no response (No Response Time) and waiting time to the scheduled communication unit transmission (Waiting Time, $T_{WT}$).

Another is the part required by the next transmitting node for preparation to transmit. This part is depending on the node design by each manufacturer, so it may be called as “Device Time”, $T_{DV}$.

$$T_{SL} = T_{LS} + T_{WT} + T_{DV}.$$ (2)

3.3 Definition of “User Data Transfer Time”

Some Physical Data Units (PDU’s) contain User Data in them and some others do not. Figure 4 shows the two types of communication unit.

To transfer meaningful user data, several PDUs are used in combination. Combination of the PDUs depends on the protocol specification. To consider communication performance and communication load factor, a higher level concept named “User Data Transfer Time”, $T_{UT}$, is introduced. $T_{UT}$ is defined as the sum of the communication unit time in the combination of the PDUs required to transfer the User Data.

3.3.1 P-S model

The natural combination of PDUs consisting of a $T_{UT}$ in case of P-S model data publication in FOUNDATION fieldbus H1 protocol is defined as the data request and the data publish. As the P-S model communication is scheduled, there is some time to wait after the previous communication before the data request is issued to make it happen exactly on the scheduled time. Hence, in the real communication, an IDLE PDU is sent before the data request to avoid unintended detection of no communication for traffic management. Figure 5 shows the P-S model communication.

Here, after a required IDLE PDU, the data request: Compel Data (CD) PDU was issued by the Link Active Scheduler, a datalink layer function to arbitrate and schedule the traffic, and the data publish: Data Transfer (DT) PDU is transmitted by the requested field device. Therefore, $T_{UT}$ is the sum of the $T_{CU}$ for IDLE, CD, and DT.

The difference of the Fig. 1 for estimation and Fig. 5 for measurement of P-S model communication is noticeable. Fig-
Fig. 6 Interval time of P-S model communication.

Fig. 7 User Data Transfer Time for C-S model and S-S model using final bit feature.

Fig. 8 Sequence of the C-S model communication.

Fig. 9 Fieldbus configuration with Bus Monitor.

3.3.2 C-S model

Figure 7 shows the typical combination of PDUs consisting of a \( T_{UT} \) in case of C-S model data transfer in FOUNDATION fieldbus H1 protocol. Here, after the Pass Token (PT) PDU was issued by Link Active Scheduler, DT PDU is sent by the specified field device as either Request or Response of a C-S model. It requires Return Token (RT or RI) PDU after the last DT of the consecutive DTs for a given PT PDU. If the device uses Final Bit feature in DT PDU, RT PDU is not issued and thus shorten the \( T_{UT} \) as shown in Fig. 7.

As for the User Data transfer for the C-S model, the sequence of three PT-DT combinations for Request, Response and Acknowledge are required as shown in Fig. 8.

The DT for Acknowledge does not contain any User Data and can be included in the next Request as the acknowledge bit if appropriate. Hence, DT for Acknowledge is not counted as a part of the \( T_{UT} \). Therefore its \( T_{CU} \) is not counted as a part of communication load in this study. It is considered as a part of link management activities. Consequently, \( T_{UT} \) for a C-S model communication consist of two (2) sets of PT-DT combination.

3.3.3 S-S model

The S-S model communication consists of only one set of PT-DT sequence shown in Fig. 7. Trend data reporting is an unscheduled periodical communication.

3.4 Definition of “Unit Time”

To consider communication performance, certain length of time is assumed to calculate the averaged results. This duration of time is the “Unit Time” in this paper. In the process control industry, the concept of the control cycle time, typically one second, is widely used. Thus, the control cycle time of the targeted control system is used as the “Unit Time” for communication load calculation in this paper.

In case of FOUNDATION fieldbus H1, the control cycle time is called as the “Macro cycle time”.

4. Communication Performance

4.1 Estimation of the Periodical Load

Estimation of the periodic communications can be done based on the application and engineering using the following numbers:

\[
\begin{align*}
N_{P-S-P,E} : & \text{ Number of periodical P-S communication (all P-S communications are periodical) per Unit Time. } \\
N_{C-S-P,E} : & \text{ Number of periodical C-S communication per Unit-Time. } \\
N_{S-S-P,E} : & \text{ Number of periodical S-S communication per Unit-Time. } \\
T_{P-S,E} : & \text{ Estimated time required for a P-S model communication based on DL parameters } [2]. \\
T_{C-S,E} : & \text{ Estimated time required for a C-S model communication based on DL parameters. } \\
T_{S-S,E} : & \text{ Estimated time required for a S-S model communication based on DL parameters. } \\

\text{Estimated Periodical Load, } T_{PLE} & = N_{P-S-E} T_{P-S,E} + N_{C-S-P,E} T_{C-S,E} + N_{S-S-P,E} T_{S-S,E}. \\
\end{align*}
\]

(3)

4.2 Measurement of the Communication Load

For measurement work, the Bus Monitor record was taken capturing all PDUs for enough duration such as 100 control cycle time for averaging with the configuration shown in Fig. 9.

List of components:
- Host: CS3000 (Yokogawa Electric Corporation)
- Bus Monitor: NI-FMON V3.0 (National Instruments)
- Field Devices:
  - EJX-110 (Yokogawa),
  - YTA-320 (Yokogawa),
  - YVP-110 (Yokogawa),
  - YEWFLO (Yokogawa),
  - PR5350 (PR Electronics),
  - F809F (MTL Instruments).
Bus Monitor record is used to calculate following times:
\( T_{P-S,M} \): Measured time for P-S communication.
\( T_{C-S,M}, T_{S-S,M} \): Total Measured time for C-S and S-S communication for User Data respectively.

These values are calculated by extracting the PDUs used for each communication model from the Bus Monitor records and totaled of the \( T_{CU} \) of them.

The measured total load, \( T_{TLM} \) per Unit-Time is defined as follows.

\[
T_{TLM} = T_{P-S,M} + T_{C-S,M} + T_{S-S,M}.
\] (4)

4.3 Measurement of the Communication Performance

By measuring communication load with various applications and plotting both measured total load and measured periodical load against estimated periodical load, you will find the knee point [4] of the graph of \( T_{PLE} \) versus measured periodical load. The knee point value is the ultimate communication performance of the defined protocol and its implementation.

5. Estimation and Measurement Results

5.1 Periodical Load Estimation

\( T_{PLE} \) per Unit-Time can be calculated by eq. (3). \( T_{P-S,E} \) is calculated in eq. (5) as the sum of the signal time of CD, no response time, the signal time of DT for publication (\( DT_{pub} \)) and the silent time as depicted in Fig. 1.

\[
T_{P-S,E} = \{\text{lenb}(CD) + (MRD \times ST + 1) + \text{lenb}(DT_{pub}) + MID\}T_B.
\] (5)

Here, the function \( \text{lenb} \) is used to obtain byte count of the PDU, byte time is represented by \( T_B \) and DL parameters and its unit of \textit{FOUNDATION} fieldbus are used as follows:

- \( ST \): Slot time (byte time).
- \( MID \): Minimum Inter PDU Delay (byte time).
- \( MRD \): Maximum Response Delay (\( ST \)).

\( T_{C-S,E} \) is calculated in eq. (6) as the sum of the signal time of PT, silent time, signal time of DT for request (\( DT_{req} \)), silent time, signal time of PT, silent time, signal time of DT for response (\( DT_{resp} \)) and silent time, as two sets of user data transfer time in Fig. 7 as request and response in Fig. 8.

\[
T_{C-S,E} = \{\text{lenb}(PT) + MID\}T_B + T_{DV}
+ \{\text{lenb}(DT_{req}) + MID\}T_B + T_{DV}
+ \{\text{lenb}(PT) + MID\}T_B + T_{DV}
+ \{\text{lenb}(DT_{resp}) + MID\}T_B + T_{DV}.
\] (6)

\( T_{S-S,E} \) is calculated in eq. (7) as the sum of the signal time of PT, silent time, signal time of DT for report (\( DT_{report} \)) and silent time, as depicted in Fig. 7.

\[
T_{S-S,E} = \{\text{lenb}(PT) + MID\}T_B + T_{DV}
+ \{\text{lenb}(DT_{report}) + MID\}T_B + T_{DV}.
\] (7)

The byte time \( T_B \) is 0.256ms as the \textit{FOUNDATION} fieldbus H1 physical layer specifies 31.25kbps bit rate and byte count for each PDU is defined as follows according to the \textit{FOUNDATION} specification:

- \( \text{lenb}(CD) = 9 \)
- \( \text{lenb}(DT_{pub}) = 21 \)
- \( \text{lenb}(DT_{req}) = 20 \)

5.2 Measurement Results

In the Fig. 10, the periodical markers show the measured communication load without aperiodic communications and the Upload markers show the measured communication load including aperiodic communications.

Figure 11 shows a function block configuration of the H1 segment. In this figure, rectangles represent the function blocks with its block tag name in the upper part and the function block type in the lower part, lines represent the interconnections between function blocks with the corresponding parameter names on each end. The block tag name is the unique identifier given to each block. The function block type in this example includes FF-AI: Analog input block, FF-AO: Analog output block and FF-DI: Digital input block. The prefix FF- indicates that the block type is defined by the \textit{FOUNDATION} specification and reside in a field device. Other block types such as PID: PID control block, PVI: Process Value Indicator block and SI-1E: Status input block are reside in the control system used for the measurement and are defined by the manufacturer of them. The interconnections between function blocks represent the parameter value transfer from a function block to another function block. The parameter value transfers between function blocks residing different field devices or control system are realized by the fieldbus communication using the P-S model.

Each data point in the Fig. 10 is depicted based on the esti-
mation and measurement of communication load of respective configuration with a certain number of P-S communications and periodic C-S communications per unit time. To obtain various configurations, the number of function blocks and interval of periodic parameter read operation are modified by configuration to configuration. Each measurement value is obtained as the average over more than 100 unit time measurements.

In Fig. 10, the knee point can be said as 80 to 85%. Consequently, some or all of the periodic accesses begin delaying after this point and the delay will not be recovered so that eventually accumulated to full one cycle delay to violate the real time requirement even as “soft periodical”.

To put it another way, the link management load, which corresponds to the upper side of the measurement point in the Fig. 10, can be shrinkable down to 15% from the measurement results. Slight increase of measured load after the knee point indicates that even after the violation of soft real time criteria started, the H1 communication system still has further allowance of communication load.

5.3 Aperiodic Communication

Figure 10 with “Upload” marker shows $T_{PLM}$ with aperiodic communications for “uploading parameters from a device”. It shows maximum of 10% load added to the periodic communications because of the aperiodic communications. This shows that additional load caused by the successive access to a single device is limited by the response time of the device. In this case, 10% load is about three C-S model communications per 1 second as Unit-Time. With heavier periodical C-S model access, increase caused by aperiodic communication is getting smaller to almost zero because the device cannot respond in addition to the periodic access in a unit time.

Aperiodic accesses are caused by several operations such as “parameter setting by operator”, “parameter download by engineer”, “parameter upload by maintenance purpose” and “event notification from device”. “Parameter setting by operator” and “event notification from device” are normally single communications to/from a single device. “Parameter download by engineer” and “parameter upload by maintenance purpose” are also focused on a single device at a time although they are series of access. Thus some 10% increase of the load may be quite reasonable to be considered as required margin for additional load for aperiodic communication.

5.4 Engineering Guide

Currently, as the design guideline, “70% communication load limit” is widely used in the FOUNDATION Fieldbus arena [1]. But it considers only P-S model communications.

Figure 12 shows the same measurement results used for Fig. 10 by replacing the $T_{P,S}$ with the estimated $T_{P,S}$ load considering only P-S model communications according to the current guideline. Measured data marked Periodical are jumps up about 30% in this figure because of the deduction of $NC_{S-P,E}$ $TC_{S,E}$ from the $T_{PL,E}$.

It shows an overloading case happens with under 70% estimated load under the current guideline. The $T_{P,S}$ graph shows measured communication load of P-S model communication. It is well matched with the estimated $T_{P,S}$ communication load.

Instead, we propose to count all periodic communications. The concluded engineering guide is “Limit estimated periodical communication load less than 70%”. As far as the definition proposed in this article is followed, this guideline is quite reasonable. Remaining 10% ($\approx 80 - 70$) will be sufficient for aperiodic communication on to a single field device.

5.5 Evaluation of the Engineering Guide

If you use the $T_{UT}$ calculated without including Device Time, it will be the theoretical performance of the protocol and if you use the $T_{UT}$ including the Device Time or the $T_{UT}$ extracted from a monitored real communication, it will show the performance of the segment with assumed or connected nodes with real implementation. We define the communication load factor as the Ratio of “the measured (or calculated) User Data Communication Time per Unit Time”.

Alternately, the communication load factor may be defined as the ratio of “the measured (or calculated) User Data Communication Time per Unit Time” against “the maximum User Data Communication Time per Unit Time”. Here, “maximum User Data Communication Time per Unit Time” can be known from the knee point of the graph such as Fig. 10. It is difficult to obtain the knee point of a protocol or an implementation without measuring it. So, we do not use this definition as it is not practical because of the difficulty.

6. Conclusion

To explain the effectiveness of the proposal, FOUNDATION fieldbus H1 is used. Using the definitions, theoretical base of estimation and measurement of the communication load factor becomes clear and open to every player in the area.
The current engineering guide handles only scheduled communication. It is not enough to prevent communication overload from happening in the operation phase. Proposed estimation procedures encompass full scope of periodic communications including “soft real-time” ones and provide safe engineering guidance. Also, a principle measurement procedure is given for engineers to confirm communication load of operating segment. Please contact authors for detailed measurement procedure if needed.

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Nomenclature

Definition of terminology
Communication Load: Sum of “User Data Transfer Time” per “Communication Unit Time”
Communication Unit Time (Unit time): Sum of Signal Time and consecutive Silent Time of a Physical Data Unit
User Data Transfer Time: Sum of “Communication Unit Time” of required combination of Physical Data Units for each communication model

Abbreviations
CD: Compel Data
DL: Data Link
DT: Data Transfer
IDLE: Idle time
MID: Minimum Inter PDU Delay
MRD: Maximum Response Delay
PDU: Physical Data Unit
PT: Pass Token
RT (or RI): Return Token
ST: Slot time

Symbols
N: Number of communications per Unit Time [-]
T: Time [s]

Subscripts
B: Bit time
CU: Communication Unit
DV: Device time
LS: Listen time
PL: Periodical Load time per Unit Time
P-S: Sum of User Data Transfer time for P-S model
S-C: Sum of User Data Transfer time for S-C model
SG: Signal time
SL: Silent time
S-S: Sum of User Data Transfer time for S-S model
TL: Total Load time per Unit Time
UT: User Data Transfer time
WT: Wait time

Sub-subscript
E: Estimated value
M: Measured value

References

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