A Spectrum Reuse/Token Passing (SRTP) Protocol for Communications in the Factory Environment over the Power Grid

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Abstract — This paper presents a Spectrum Reuse/Token Passing (SRTP) protocol for communications over power lines for monitoring and control in a factory environment. The paper presents a new method for organising a sensorial token passing network in multiple logical rings using a centralised scheduler. It also presents a technique for increasing the power grid bandwidth by splitting up the power grid, using power EMI filters. The SRTP protocol is analysed in terms of token cycle time and its performance is compared to the token bus passing protocol.

Keywords: *Power line communications, token passing protocols, sensorial monitoring and control.*

I. Introduction

The factory environment is characterised by the large number of data collecting and processing applications that have to be supported [1]. These applications have different, usually contradictory requirements, and the current trend is to have a unified communication system for supporting these requirements [2]. Although this methodology is generally the most appropriate, it is difficult to implement and results to high cost, when data collection of sensors at the factory environment is supported, since a large number of sensors is spread in different locations inside the factory.

There are some types of factories, like those for diary products, which have a huge amount of sensors spread all over the factory for collecting data. Sensors are used in storage areas, in incubation areas, in distribution vehicles etc. Depending on the factory production capabilities, the number of sensors that have to be monitored, varies from a few tens to a few hundred sensors. Data are generated either in constant time intervals for data collection purposes or asynchronously, during alarm conditions, when a local measurement exceeds a predefined value. There are various medium access protocols proposed for the sensorial environment, and different transmission media has been considered.

The next section presents a concise description of available technologies for sensorial data communications and highlights their applicability in the factory sensorial environment. Section III describes the proposed Spectrum Reuse Token Passing (SRTP) protocol, while its performance analysis is presented in Section IV and comparison with the basic Token Passing protocol is performed in Section V.

II. Communication Technologies For The Sensorial Environment

The first topic that has to be addressed is the communication medium type. There are various options for using a dedicated communication medium with low cost interfacing hardware, like dedicated cable, RF frequencies, power lines etc. The usage of the power cabling as the communication channel is considered more appropriate than other solutions, due to low cost of installation, no interference with regulatory bodies and due to enhanced reliability, since external interference is not possible. The main advantage of the power lines solution is that the connection to the communication medium already exists, since the circuit of each sensor is connected to the power grid for power dissipation purposes.

Although the power line, especially in the factory environment, is an inhospitable environment for data communications due to substantial noise and frequency-dependent signal attenuation [3], [4], various transmission techniques have been developed, like power line carrier using frequency shift keying (PLC-FSK) and spread spectrum and they have been used successively in the factory environment [5].

From the medium access protocol point of view, the Manufacturing Automation Protocol (MAP) is the most successive protocol for real time applications, especially

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in the factory environment. It is usually applied using a reduced communication architecture, based only on three layers and its usage, without the immediate response option, is recommended for time critical applications [6]. The MAP has better performance when a small number of nodes is used with large generated messages. In a sensorial environment, which is characterised from the large number of nodes and the low offered load per node, the MAP performance decreases significantly due to waste of time for passing the token from one node to another. Other problems encountered is the installation cost of a MAP based network and its inflexibility on changing the network topology.

Various medium access protocols have been proposed for sensorial applications over power lines, although they have been developed mainly for residential applications. They follow either random access methods or deterministic approaches. Random access methods include the CSMA/PA protocol [7] and the LONTALK protocol [8]. The CSMA/PA protocol can not support real-time applications since there is no guaranteed maximum delay, while the LONTALK protocol uses a priority mechanism for supporting time-critical transmissions, but its effectiveness depends on the number of nodes that have to transmit priority messages, and a large number of nodes make the protocol unreliable.

The most promising deterministic approach is the Hybrid Token Passing protocol proposed in [4]. This protocol switches between dynamic and static token passing schemes depending on traffic loading. Under light traffic conditions, the protocol forces any idle node to be disconnected from the logical ring when it has no data to transmit, in order to decrease the token rotation time. In heavy traffic conditions, the protocol uses the static token passing mechanism of MAP. Its performance depends on the time required for completing the solicit successor procedure, the frequency this procedure is performed and the number of nodes.

III. THE SRTP PROTOCOL

The data link protocol in a communication network is used to enhance the transmission service by satisfying the requirements imposed by the physical layer. When a limited protocol stack is used, the data link layer implements all communication functions, including management. In a sensorial network, two types of messages are exchanged between the nodes and the central unit:

- Application messages, and
- Network maintenance messages.

The application messages relate to sensory data and supporting functions (communication protocols) for reliable data transmissions. They are subdivided in two types:

- data collecting messages, and
- alarm condition indicators.

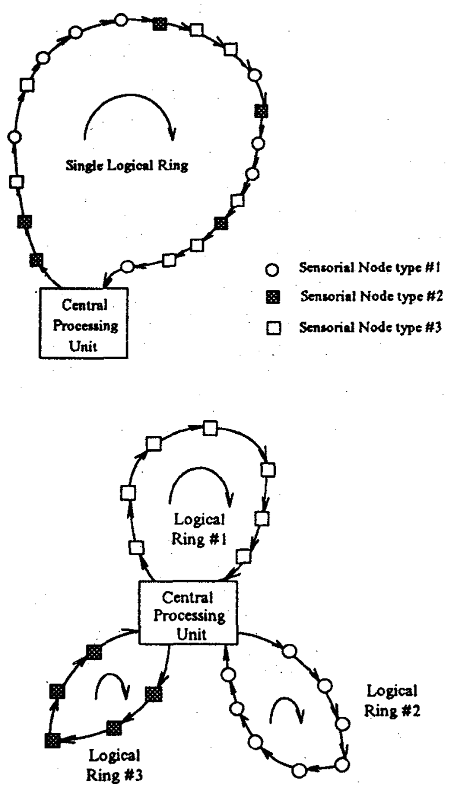
The data collecting messages are used for concentrating sensorial data to a central processing unit for display, storage and off-line processing purposes, while the alarm condition indicators are used for immediate reporting of detected failed equipment. The network maintenance messages are used for determining the network configuration and for routing purposes.

In token passing protocols, when a station finishes the transmission of its message, it sends a token to the next node in the logical ring for passing the permission to use the physical medium. In sensorial acquisition, data are generated periodically and the maximum achievable acquisition rate is determined by the token cycle time. Usually, the sensors are of different types and different acquisition rates are required.

The use of a single logical ring is not the best solution for sensorial networks, since the nodes that have low acquisition rate, add more overhead to the token cycle time, than the nodes with higher acquisition rates. To overcome this problem, the SRTP protocol is proposed.

The SRTP protocol uses the token passing mechanism, but differs from the basic token protocol in two functions: it uses multiple logical rings for supporting different acquisition rates and it can exploit the physical topology of the power grid for achieving concurrent transmissions by reusing the available bandwidth. These functions can be implemented only by using a central unit for network management. In the sensorial environment, there is a central unit for collecting the data and this unit can be used for network maintenance.

In SRTP, the sensorial nodes are grouped in different classes, based on their acquisition rate. Each class is organised in a logical ring, while the central processing unit participates in all rings and determines the procedure for generating the token into different rings. The token generation process is controlled by the central processing unit. Only nodes that participate in a logical ring contribute to the token cycle time of each ring. The total token cycle time is different for each ring, since it depends on the token cycle times of each ring and on the scheduling procedure that is implemented by the central processing unit. Figure 1 shows an example of a token passing protocol which is organised in three logical sub-rings, based on the type of sensorial nodes that the network supports.



(a)

(b)

Fig. 1. The token passing protocols organisation.
(a) The basic token passing approach.
(b) The SRTP approach.

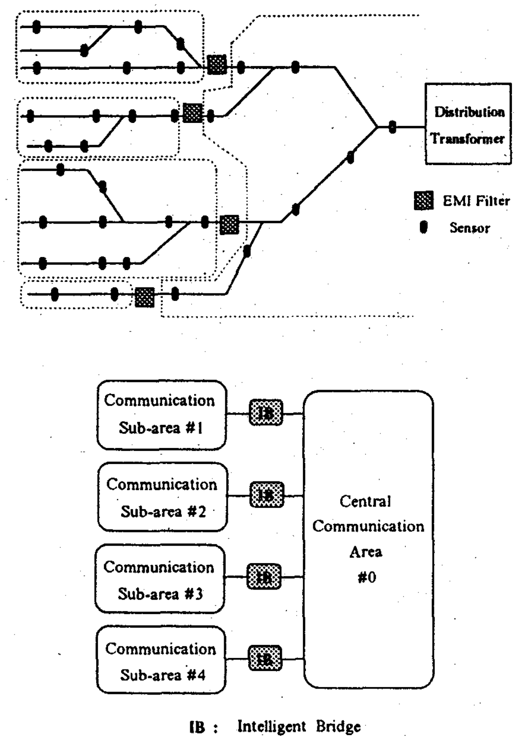


Fig. 2. The power grid structure using EMI filters and the respective communication areas.

Each node is informed only on its successor in the ring and on the address of the central processing unit. The three-way handshake is also used. Node addition to a logical ring is performed by the central processing unit, when it holds the token. In this case, a message is transmitted to the appropriate node for determining its next node in the logical ring.

The factory power grid is a unified communication network with three independent subnetworks (the three power phases) and its limitation is the power distribution transformer. The length of the cabling of each phase is usually long enough and in many cases, it is difficult to communicate between outlets belonging to different sections of the factory due to excessive attenuation. This problem can surpassed by using power line filters (EMI suppressors) in various positions inside the factory. These filters do not affect the power distribution process but allow the use of different segments of the power cabling for simultaneous transmissions, by isolating the frequency spectrum of each segment for frequencies higher than 50 kHz. The use of k EMI filters in a power segment increases the original segment transmission capacity from C bps to (k+1).C bps.

The communication between adjacent segments is achieved using intelligent bridges. The SRTP protocol uses this power line segmentation for achieving spectrum reuse. Since there is a central unit for collecting and processing the sensorial data, the EMI filters must be connected so that the power grid is subdivided into a central communication area and various sub-areas adjacent to the central one, as it is indicated in Figure 2. In this Figure, one phase of the power grid is divided into five (5) communication areas. The intelligent bridges are reconfigurable devices, which perform data collection functions in each communication sub-area under the supervision of the central processing unit. They store the collected data in a local memory and pass them to the central unit when they receive the token. The central processing unit is connected to the central communication area and uses multiple logical rings. One logical ring is formed by using the intelligent bridges, since they have large messages to transmit and require large token holding time.

The SRTP protocol requires central control for configuring the network and forming the logical rings. In order to simplify the hardware of each node, it does not use a solicit successor procedure, but the nodes implement the three-way handshake mechanism to detect a failed successor. In this case, the node sends the token back to the control unit, indicating the failed node, and then, the central unit bridges it out of the logical ring.

IV. Performance Analysis

For analysing the performance of the basic token passing protocol and of the SRTP protocol, the mean value analysis for polling systems, presented in [9], is used. In order to simplify the analysis, the following assumptions have been made:

- All sensors belong to the same line segment.
- There are N nodes in the network, which can be grouped in g-groups. There are k_i sensors in the i-group ($1 \le i \le g$), while the sensors of each group have the same offered load (acquisition rate). For the numbers of nodes in each group, the following equation holds:

$$N = \sum_{i=1}^{g} k_i \tag{1}$$

- There is a single message buffer in each node. If a new message arrives in a node, the previously stored message is discarded and the new message participates in the medium access process.
- Each node can be in one of two modes of operation, acquisition or alarm mode. In this analysis, only the acquisition mode is considered, and messages are generated in constant time intervals - t_{qi}.
- Each acquisition message is m_{qi} bits long, while the token length is the same for all rings and is equal to m_t.

Basic Token Passing Protocol

In the basic token passing protocol, the duration of a token cycle is denoted by T_c. The server spends m_{qi}/R seconds in a node for transmitting a message, while m_t/R seconds are required to pass the token from node i to node (i+1). If the queue of a node is empty, the token is passed to the next node immediately. So, the token cycle time is given by:

$$T_c = \frac{1}{R} \cdot \sum_{j=1}^{N} m_t + \sum_{i=1}^{g} \sum_{j=1}^{k_i} T_{k_i} \tag{2}$$

where R is the channel transmission rate and T_{k_i} is the time spend in a node of group k_i. Generally, the token cycle time T_c is less than the acquisition time intervals - t_{qi}, so the mean value of T_{k_i} depends on the cycle time. From equation (2), the cycle time depends also upon the T_{k_i} values, and that results to dependencies among the random variables $T_{k_1}, \ldots, T_{k_g}$.

Since the mean value of a sum of random variables is equal to the sum of their mean values, irrespective of any dependencies, the mean cycle time can be derived from equation (2):

$$\overline{T_c} = \frac{N m_t}{R} + \sum_{i=1}^{g} k_i \overline{T_{k_i}} \tag{3}$$

where $$\overline{T_{k_i}} = \frac{m_{qi} \cdot \overline{T_c}}{R \cdot t_{qi}} \tag{4}$$

Substituting equation (4) into (3), the $\overline{T_c}$ is equal to:

$$\overline{T_c} = \frac{N m_t}{R\left[1 - \sum_{i=1}^{g} \frac{k_i \cdot m_{qi}}{R \cdot t_{qi}}\right]} \tag{5}$$

The SRTP Protocol

In the SRTP protocol, there are multiple logical rings, which are specified by the network scheduler using their acquisition times - t_{qi}. It is obvious that the cycle time of each logical ring depends on the scheduling algorithm. So, before starting the analysis of the protocol performance, the algorithm used by the network scheduler for passing the token to various logical rings has to be determined. The t_{qi} values are put in increasing order. If $t_{qmax} = \max(t_{q1}, t_{q2}, \ldots, t_{qg})$, then, the scheduler uses the weights

$$w_i = \left\lceil \frac{t_{q\max}}{t_{qi}} \right\rceil \tag{6}$$

for specifying the token passing priorities of the various logical rings. The scheduler scans all rings initially, and then decreases their weights by 1. The second scanning is performed using only the rings that have weight greater than zero and the procedure finishes when no other logical ring can be used. When all weights become equal to zero, the scanning round restarts. Figure 3 presents an example of this procedure. Although this process can not be considered as the optimum one, it can be used for demonstrating the SRTP performance. Three new variables are defined:

T_{total} is the time required to complete the full scanning process,

T_{si} is the time elapsed from the time the scanning process in a logical ring starts, up to the time the process is finished, and

T_{ci} is the token cycle time for the i-logical ring

By using the previously mentioned mean value property, $\overline{T}_{total}$ is given by:

$$\overline{T}_{total} = \sum_{i=1}^{g} w_i \overline{T}_{si} \tag{7}$$

$\overline{T}_{ci}$ is equal to:

$$\overline{T}_{ci} = \frac{\overline{T}_{total}}{w_i} \tag{8}$$

and, following the methodology for deriving equations (3) and (4), the $\overline{T}_{si}$ is calculated as:

$$\overline{T}_{si} = \frac{k_i m_i}{R} + k_i \frac{m_{qi}}{R} \frac{\overline{T}_{ci}}{t_{qi}} \tag{9}$$

By combining equations (7), (8) and (9), the analytic expression of $\overline{T}_{cn}$ is derived:

$$\overline{T}_{cn} = \frac{m_i \cdot \sum_{i=1}^{g} (w_i \cdot k_i)}{w_n \cdot R \left[1 - \sum_{i=1}^{g} \frac{k_i \cdot m_{qi}}{R \cdot t_{qi}} \right]} \qquad \forall n = 1, 2, \ldots, g \tag{10}$$

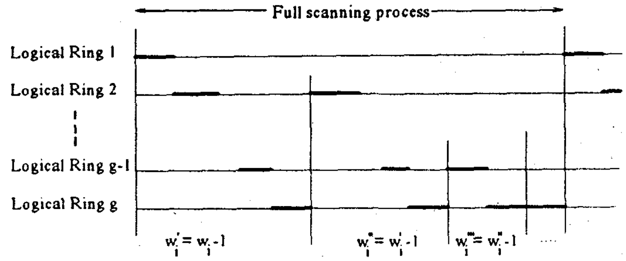


Fig. 3. The scheduler scanning process.

For any n_1 and n_2 logical rings, the cycle times are proportional to their acquisition time intervals, since

$$\frac{\overline{T}_{cn_1}}{\overline{T}_{cn_2}} = \frac{w_{n_2}}{w_{n_1}} \cong \frac{t_{qn_1}}{t_{qn_2}} \tag{11}$$

The main performance difference between the basic token passing and the SRTP protocols is that, while in the former the protocol overhead is the same for all types of nodes, in the latter, the token passing overhead is adapted to the acquisition rate of each logical ring, thus allowing service time dependable on the type of each sensorial node.

V. Comparative Results

Based on the previous analysis, various experimental results have been derived and the performance of both protocols for sensorial monitoring applications is highlighted. In these results the two different cases depicted in Table 1, have been considered. Figures 4 and 5 show how the token cycle time is affected by the number of nodes in the network and how it is related to the respective acquisition times. In case 1, all nodes generate messages of equal length, irrespective of their acquisition time, while in case 2, the nodes contribute the same offered load. As the results show for case 1, by using a network based on the basic token passing protocol, a maximum of 280 nodes can be supported, while using the SRTP protocol, the number increases to 350. In these values, the token cycle time exceeds the acquisition rate of at least one group. For case 2, the values are 218 and 252 respectively.

Based on these results, it can be concluded that the SRTP protocol has better performance over the basic token passing protocol. The appropriate organisation of

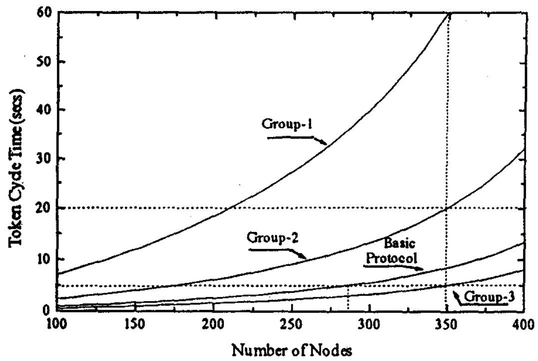


Fig. 4. Protocol performance on case 1.

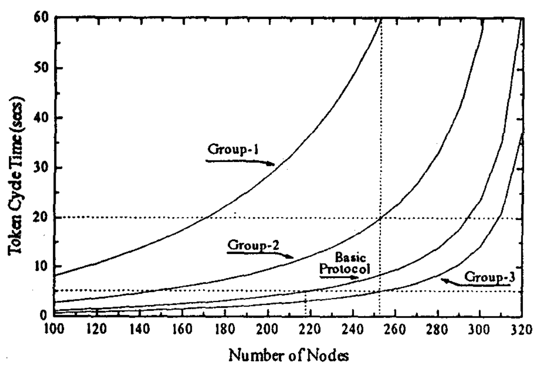


Fig. 5. Protocol performance on case 2.

the logical rings and the proper selection of the scheduling algorithm will achieve even better results.

VI. Conclusions

The paper presented the Spectrum Reuse/Token Passing (SRTP) protocol. This protocol was developed for monitoring and control of sensors in a factory environment over the power grid. The SRTP organises a sensorial token passing network in multiple logical rings using a centralised scheduler. It also uses a technique for increasing the power grid bandwidth by splitting it up, using power EMI filters.

The main advantages of the proposed protocol are the simplified hardware and the higher achievable acquisition rate. This is due to the fact that each node performs mainly the functions related to message transmission, while most of the network maintenance procedures are implemented by a central processing unit.

Table 1: Parameters of experimental results

Case 1:	$R = 10$ kbps, $m_t = 80$ bits
	$g = 3$, $k_1{:}k_2 = 1{:}2$, $k_1{:}k_3 = 1{:}3$
	$m_{q1} = m_{q2} = m_{q3} = 160$ bits
	$t_{q1} = 60$ secs, $t_{q2} = 20$ secs $t_{q3} = 5$ secs
Case 2:	$R = 10$ kbps, $m_t = 80$ bits
	$g = 3$, $k_1{:}k_2 = 1{:}2$, $k_1{:}k_3 = 1{:}3$
	$m_{q1} = 1800$, $m_{q2} = 600$, $m_{q3} = 150$ bits
	$t_{q1} = 60$ secs, $t_{q2} = 20$ secs $t_{q3} = 5$ secs

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