

## **EDF-based Real-time Message Scheduling of Periodic Messages on a Master-Slave-Based Synchronized Switched Ethernet**

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### **Abstract**

*Switched Ethernet is one of the most widely used networks and has many features for real-time communications such as providing traffic isolation, large bandwidth, and full-duplex links, and so on. The switched Ethernet, however, cannot guarantee the timely delivery of a real-time message due to possible collisions on the output ports. This paper first suggests a feasible condition for real-time communication of periodic messages on a master-slave-based synchronized switched Ethernet. Then an EDF (Earliest Deadline First)-based scheduling algorithm that satisfies the proposed scheduling condition is proposed. The master node checks the feasible condition for messages and makes a message transmission schedule for feasible messages. The proposed scheduling algorithm can handle dynamic message requests and performs the real-time communication without any modification in the switch. The performance of the proposed scheduling algorithm has been evaluated by simulation to show the timely delivery of real-time messages and the real-time communication capacity of the switched Ethernet.*

**Keywords:** *Real-time communications; switched Ethernet; scheduling algorithm; EDF-based message scheduling.*

### **1. Introduction**

Ethernet has become the most widely used network technology for data communication in office environments. Ethernet is very easy to install and shows good performance when the number of nodes on the network is small. However, due to sharing of a communication bus among all nodes, the performance decreases rapidly if the number of nodes on the network increases. On the other hand, switched Ethernet eliminates messages collision on the network by traffic isolation of messages to each port, which greatly enhances the performance of the switched Ethernet. Switched Ethernet has many attractive features for real-time communications, but cannot guarantee message transmission within the deadline mainly due to the collision on the output port.

Many research efforts have been done in order to use the switched Ethernet as a real-time communication network in the industrial environment. George et al. [3] analyzed the architectures of switched Ethernet networks and presented a method to minimize end-to-end delays by using network calculus theory. Lee et. al. [5] analyzed the real-time performance of the switched Ethernet and showed that can be used as an industrial communication network. Varadarajan and Chiueh [8] have proposed a real-time communication protocol called EtheReal. Their approach, however, has no support for hard real-time communication and no explicit support for periodic messages which is required for industrial applications. Another work by Loser and Hartig [6] and Mifdaoui et. al. [1] used a traffic shaper to regulate the

message traffic entering the switched Ethernet and to bound end-to-end delay. Their method, however, cannot guarantee the timely delivery of the messages per message basis. Hoang et. al. [4] attempted to support real-time communication of switched Ethernet by adding the real-time layer in both end nodes and the switches. Instead of using FIFO queuing, packets are queued in the order of deadline in the switch. A source node, before sending a real-time periodic message to the destination node, has to establish a real-time channel that is controlled by the switch for guaranteeing the deadline. Almeida et al. [2] have proposed FTT-CAN protocol which adds flexibility to the real-time system based on CAN and have extended the FTT paradigm to the Ethernet to support real-time communication on the synchronized Ethernet [7].

This paper first analyzes the feasible condition for real-time communication on a switched Ethernet. The feasibility of real-time messages on the Ethernet was analyzed by Pedreiras et al. [7], but, to the best of our knowledge, there has been no research result on the feasibility of real-time messages on a switched Ethernet until now. A message scheduling algorithm that satisfies the suggested feasibility condition is also proposed in this paper. We implemented the proposed scheduling algorithm and evaluated the performance of our algorithm by simulation to show the timely delivery of real-time messages and the real-time communication capacity of the switched Ethernet. The simulation results show that all of the messages which satisfy the feasible condition have been transmitted within their deadlines. The simulation result also shows that, in the case of Ethernet, the number of scheduled messages on the network is almost constant according to the number of nodes on the network. On the contrary, in the case of the switched Ethernet, the number of feasible messages was increased linearly according to the number of nodes on the network.

The rest of paper is organized as follow. The master-slave-based synchronized switched Ethernet model and message transmission model on the switched Ethernet are described in Section 2. In Section 3, the feasible condition of real-time messages and an EDF-based real-time message scheduling algorithm that satisfies the condition are described. Section 4 presents the performance evaluation of the proposed scheduling algorithm and Section 5 concludes the paper.

## 2. Message Transmission Model on the Synchronized Switched Ethernet

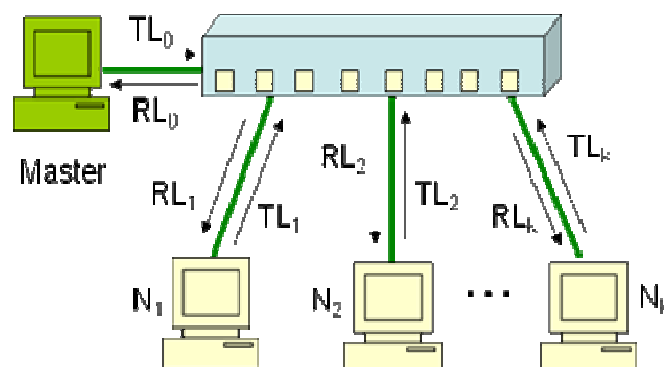


Figure 1. Maser-slave-based switched Ethernet

In this section, a message transmission model on the switched Ethernet for the proposed hard real-time communication is described. The switched Ethernet consists of one master node and many slave nodes as shown in Figure 1.

The switched Ethernet operates in full-duplex mode, where each node is connected to the switch through a pair of links which operate independently: a transmission link and a reception link. The master node handles the real-time communication of periodic messages. When a slave node has a new periodic message to send, it transmits the real-time specification of the periodic message to the master node, and the master checks the scheduling condition for the periodic message and makes a feasible schedule for the transmission of the message if it is schedulable.

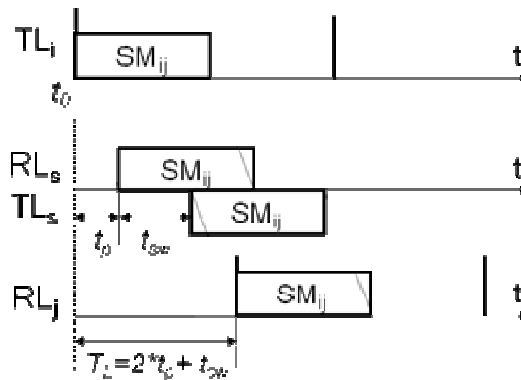


Figure 2. Message switching on switched Ethernet

In the cut-through switching, which is used for fast delivery of frames, the switch decides the output port right after receiving the header of a frame and forwards the frame to the output port. When a switch uses the cut-through switching mode, if a message from node  $i$  to node  $j$  begins to be transmitted at time  $t_0$ , the first bit of the message arrives at node  $j$  after  $T_L = 2*t_p + t_{sw}$  amount of delay from  $t_0$  if there is no collision at the output port and the output queue is empty. This is shown in Figure 2. Here,  $t_p$  is a propagation delay on a link between a node and the switch and  $t_{sw}$  is the switching latency (destination port look-up and switch fabric set-up time).

As shown in Figure 3, in our synchronized switched Ethernet, all of the links consist of a set of consecutive Macro Cycles (MCs), and each MC consists of *Sync* field and a set of consecutive Elementary Cycles (ECs) which is similar to that of FTT-CAN [2]. Each MC has  $L = \text{LCM}(P_{ij})$  ECs, where  $P_{ij}$  denotes the period of a synchronous message  $SM_{ij}$  and  $\text{LCM}(P_{ij})$  denotes the least common multiple of the periods of all of the synchronous messages. *Sync* field is used to synchronize all of the slave nodes, and includes information about the message transmission model. Message transmission on the switched Ethernet is triggered by a master node which sends a *TM* (Trigger Message) at the beginning of every EC. An EC consists of a *TM*, a *SMP* (Synchronous Message Period) for transmitting periodic messages and an *AMP* (Asynchronous Message Period) for transmitting aperiodic messages. In this paper, we only consider the scheduling of periodic messages. The *TM* contains a message schedule for the periodic messages that are transmitted on the respective EC.

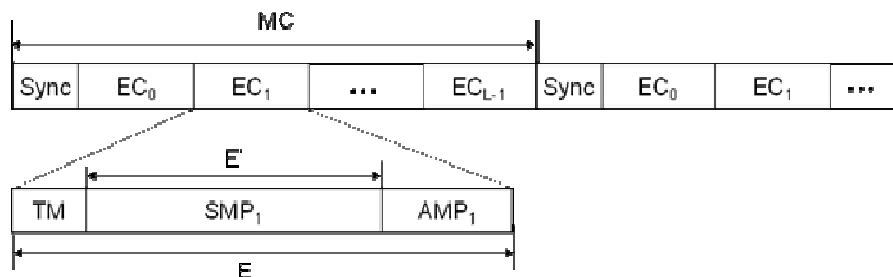


Figure 3. Message transmission model on the synchronized switched Ethernet

Each periodic (or synchronous) message from node  $i$  to node  $j$ ,  $SM_{ij}$ , has a real-time requirement that are characterized by  $(D_{ij}, P_{ij}, C_{ij})$  where  $D_{ij}$ ,  $P_{ij}$ ,  $C_{ij}$  are the deadline, period, and length of  $SM_{ij}$ , respectively. We assume that all the  $D_{ij}$  and  $P_{ij}$  are the multiple of  $E$  and  $P_{ij} = D_{ij}$ . Thus, the real-time requirement of a periodic message  $SM_{ij}$  can be represented by  $RT_{ij} = (P_{ij}, C_{ij})$ .

### 3. EDF-based Real-time Message Scheduling of Periodic Messages on the Synchronized Switched Ethernet

In this section, a feasible condition for real-time scheduling of periodic messages on the switched Ethernet and an EDF-based real-time message scheduling algorithm which satisfies the condition are described.

When a message is transmitted on a transmission link, it can appear on the reception link after  $T_L$  amount of time (Figure 2). We define the following notations for the description of the feasible condition and scheduling algorithm.

- $UT_i$  and  $UR_j$  are the utilization of  $TL_i$  and  $RL_j$  such that

$$UT_i = \sum_{j \in ST_i} \frac{C_{ij}}{P_{ij}} \quad UR_j = \sum_{i \in SR_j} \frac{C_{ij}}{P_{ij}} \quad (1)$$

where  $ST_i$  is a set of nodes to which node  $i$  sends its messages and  $SR_j$  is a set of nodes from which node  $j$  receives the messages.

- $UT_{max,j}$  is the maximum utilization of a set of transmission links that transmit messages to node  $j$ , such that

$$UT_{max,j} = \max_{i \in SR_j} \{UT_i\} \quad (2)$$

- $T_{i,n}$  is the total time of messages which are transmitted on  $TL_i$  in  $n^{th}$  EC.

#### 3.1 Feasible Condition of Periodic Messages on the Switched Ethernet

The feasible condition for real-time scheduling of periodic messages on the switched Ethernet is in **Theorem 1**.

**Theorem 1.** Let  $C$  be a set of periodic messages such that  $C = \{SM_{ij}\}$  with  $RT_{ij} = (P_{ij}, C_{ij})$ .  $C$  is feasible on the switched Ethernet if it satisfies the following condition for every message  $SM_{ij}$  in  $C$ ,

$$UT_i + UR_j \leq \frac{E' - 2 * \max\{C_{ij}\} + \min\{C_{ij}\}}{E} \quad (3)$$

*Proof.* See [9].

An algorithm to check the scheduling condition of **Theorem 1** in the master node is described in [9].

### 3.2 EDF-based Real-time Message Scheduling Algorithm on the Switched Ethernet

The master node receives the dynamic changes of the real-time applications from the slaves in AMP and checks the scheduling condition and makes a message transmission schedule for the next MC on the switched Ethernet. The master node transmits a list of messages to be transmitted on each EC of the MC in the *TM* message which is transmitted at the beginning of each EC. When a slave node receives a *TM* message, it interprets the message and transmits the messages specified in the *TM* message. The following *edfScheduling* algorithm is an EDF-based scheduling algorithm which makes a transmission schedule for a set of periodic messages which satisfies the feasibility condition of **Theorem 1**.

```

Algorithm edfScheduling (schedBuf, MS)
// schedBuf: sorted message buffer to check feasibility
// MS(n): message transmission schedule for n-th EC
// Cmin, Cmax: minimum and maximum length of messages
// r(k): variable to check the readiness of k-th message
// r(k) = 1 if k-th message is ready
// T_max(i): the latest finishing time of messages on TL_i
// R_max(j): available time to send messages on RL_j in the worst case
1. for (i = 0; i < N; i++) {
2.     T_max(i) = UT_i * E + C_max;
3.     maxTL = max{UT_j} for all j where TL_j sends messages to RL_i;
4.     R_max(i) = E' - maxTL * E - C_max + C_min;
5. }
6. for (k = 0; k < M; k++) r(k) = 1;
7. for (n = 0; n < L; n++) { // L: LCM(P_ij)
8.     MS(n) = NULL;
9.     for (i = 0; i < N; i++) { TL_i = RL_i = 0; }
10.    for (k = 0; k < M; k++) {
11.        if (r(k) == 1) {
12.            SM_ij = k-th message in schedBuf;
13.            if ((TL_i + C_ij) <= T_max(i) && (RL_j + C_ij) <= R_max(i)) {
14.                Add SM_ij to MS(n);
15.                TL_i = TL_i + C_ij;
16.                RL_j = RL_j + C_ij;
17.                r(k) = 0;
18.            }
19.        }
20.        if ((n+1) mod P_ij == 0) r(k) = 1;
21.    } // end of inner for
22.} // end of outer for

```

In *edfScheduling* algorithm,  $T_{max}(i)$  denotes the latest finishing time of messages transmitted on  $TL_i$  which denotes the latest time that can be transmitted without violating the boundary of the corresponding EC on RLs.  $R_{max}(i)$  denotes the latest finishing time of messages transmitted on  $RL_i$  which denotes the latest time within which all of the messages arrived at  $RL_i$  have to be transmitted completely (see [9] for more details). The following theorem proves that all of the messages in a feasible message set satisfying the condition of **Theorem 1** can be delivered within their deadlines if we schedule those messages according to the proposed *edfScheduling* algorithm.

**Theorem 2.** The EDF-based scheduling algorithm, *edfScheduling*, guarantees the timely delivery of messages for a message set satisfying the scheduling condition of **Theorem 1**.

*Proof.* See [9].

#### 4. Performance Evaluation

This section describes the performance evaluation of the proposed real-time protocol on the switched Ethernet. Firstly, we have evaluated whether all of the messages that passed the feasibility condition of Theorem 1 are actually transmitted within their deadlines. The simulation parameters are shown in Table 1. The switched Ethernet has 10Mbps data rate and 1 master node and 10 slave nodes on the network. We have generated messages with random source and destinations. Message length was chosen randomly from 100 to 200Bytes. The period of each message was chosen randomly from 1, 2, 3, 4, 6, and 12, so the MC size is 12.

Table 1. Simulation condition

Bandwidth	10Mbps
Minimum size of a control message	100Bytes
Maximum size of a control message	200Bytes
EC length	1,000us
SP length	900us
MC size	12 ECs

Our message scheduling algorithm is dynamic, which can add new periodic messages while transmitting real-time messages scheduled already. At each MC, the master node collects the message specifications of the messages newly added and checks the feasibility of those messages without affecting the real-time transmission of the messages that had been scheduled already. To show the dynamic feature of the proposed algorithm, we generated 40 messages initially (at MC 0), and checked the feasibility of the messages. All of the initial 40 messages were feasible. After that, we continue to add 10 new messages at each MC while transmitting the messages that were scheduled already until the minimum drop ratio becomes lower than 20%. The simulation result showed that the number of feasible messages increased from 40 (at MC 0), 49 (at MC 1), 55 (at MC 2), 61 (at MC 3), 67 (at MC 4), 71 (at MC 5), 73 (at MC 6), 75 (at MC 7). The number of feasible messages increases as the MC goes by, but the number of newly admitted messages decreases because the link utilization of the switched Ethernet becomes high as more messages are added newly.

To show whether all of the feasible messages are transmitted within their deadline, we have calculated the response time of each message instance of feasible messages. The response time of a message instance is the elapsed time from when the message was generated to the time when the message arrived at the destination. Figure 4 shows the response time for the messages that were feasible at MC 7. As shown in Figure 4, all of the message instances were transmitted within their deadline

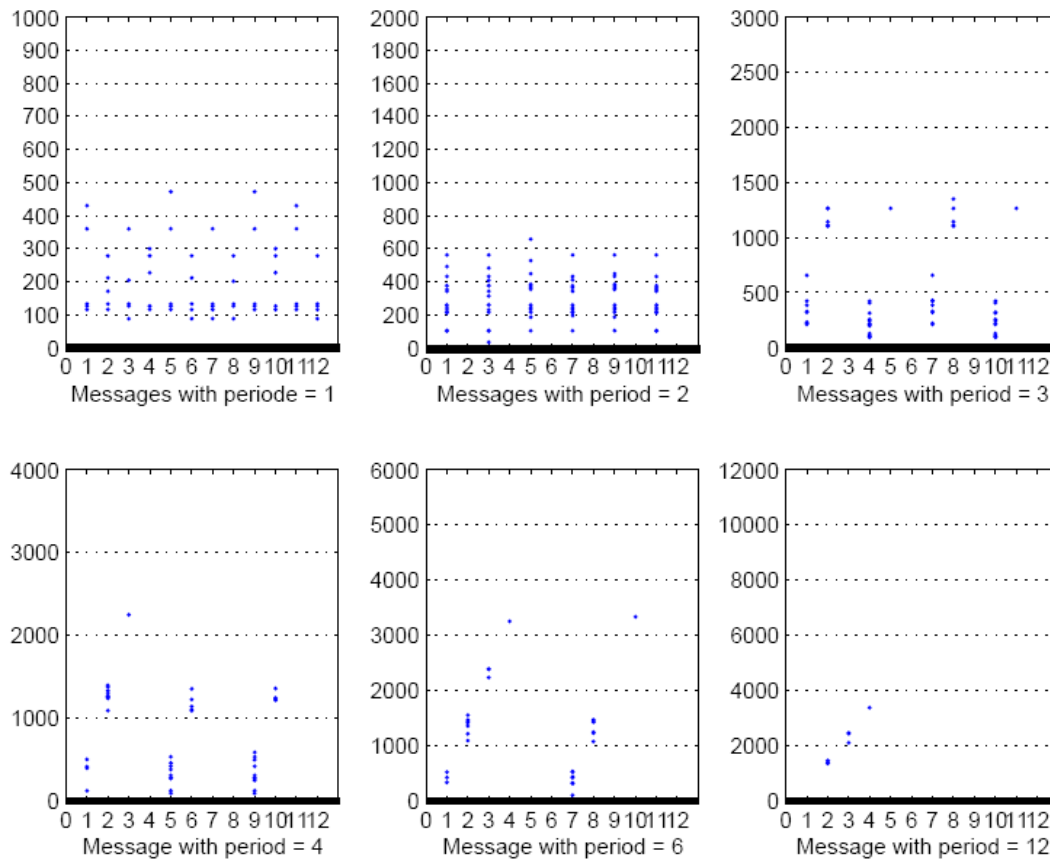


Figure 4. Response times for the messages that were feasible at MC 7

Secondly, we have compared the real-time capacity between the switched Ethernet and the original Ethernet. The switched Ethernet with  $N$  nodes consists of  $N$  transmission links and  $N$  reception links. Thus, the message transmission capability of the switched Ethernet will be higher than that of Ethernet. However, how much is the communication capability of the switched Ethernet depends on the traffic pattern of the messages in the head of the queue of each node. If all of the messages in the head of the queue are destined to the same node (as shown in Figure 5-(a)), then the communication capability of the switched Ethernet will almost be the same as that of Ethernet due to the collision at the reception link. On the contrary, if all of the messages in the head of the queue are destined to the different nodes (as shown in Figure 5-(b)), then all of the messages can be transmitted at the same time, thus the message transmission capability of the switched Ethernet will be  $N$  times higher than that of Ethernet.

To compute the message transmission capability of the switched Ethernet, we generated 500 messages randomly, and checked the feasibility condition of Theorem 1 from the first message increasing the number of messages one by one until a certain percentage of message drop occurs and calculated the number of feasible messages. In the case of the Ethernet, we checked the feasibility condition in [7] in the same way.

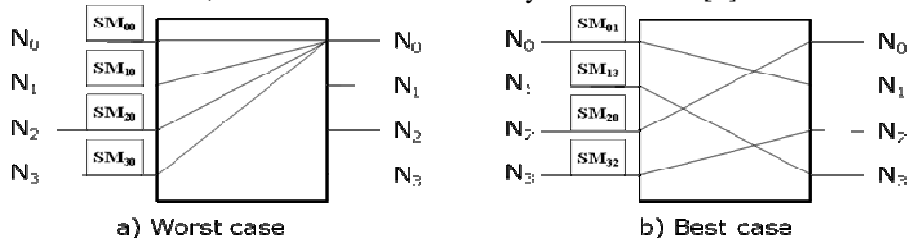


Figure 5. Message transmission capability of a switched Ethernet depending on the traffic pattern

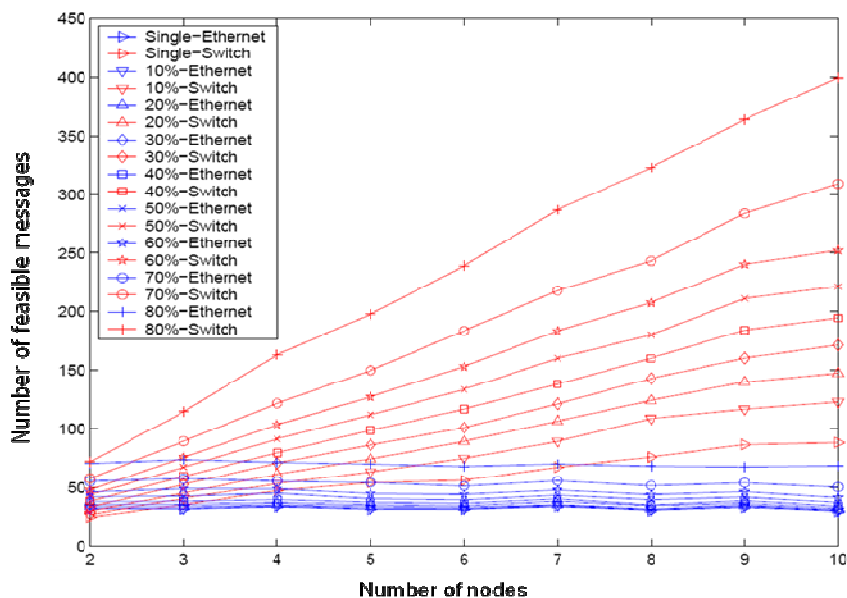


Figure 6. Comparison of the message transmission capability

We have done the same kind of simulation 10 times and calculated the averages number of feasible messages. Figure 6 denotes the message transmission capability of the switched Ethernet and Ethernet. *Single-Ethernet* and *Single-Switch* denotes when we have increased the number of messages until the first message drop occurred in the Ethernet and the switched Ethernet, respectively, and *10%-Ethernet* and *10%-Switch* denotes when we have increased the number of messages until 10% message drop occurred. In the case of the Ethernet, the number of feasible messages has increased just a little when we increased the percentage of message drop, but was almost the same when the number of nodes on the network was increased. On the contrary, in the case of the switched Ethernet, the number of feasible messages has increased as the percentage of message drop was increased. Also the number of feasible messages has increased linearly as the number of nodes on the network was increased.



## 5. Conclusions

Real-time distributed control systems have been widely used in many industrial applications, such as process control, factory automation, vehicles and so on. In these applications, each task must be executed within a specified deadline, thus, the communications between the tasks have to be completed within their deadlines to satisfy the real-time requirements. Switched Ethernet which is the most widely used in the office has certain good operational features for real-time communications. However, it needs some mechanisms to regulate the traffic on the network in order to satisfy the hard real-time communication requirements of the industrial applications.

In this paper, an EDF-based scheduling algorithm for hard real-time communication over switched Ethernet was proposed. With this scheduling algorithm, there is no need to modify the original principles of switches to support hard real-time communication in industrial environment. This paper also analyzed the scheduling condition for real-time periodic messages and showed that the proposed scheduling algorithm reflects correctly the feasibility condition of the periodic messages on the switched Ethernet. The proposed scheduling algorithm can handle dynamic real-time messages. When some messages need to be added or be deleted, the master node checks the scheduling condition for the updated message set and makes a transmission schedule for the newly updated message set.

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