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Derivation of Response-time Model for Share-driven Scheduled TDMA Network

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ABSTRACT

TDMA (Time Division Multiple Access) networks are known for their predictable response. This is achieved because each node is allotted a time slot for data transfer. This mechanism results in low throughput as data is transmitted in its time slot irrespective of whether it is changed or not.

A share-driven scheduled TDMA scheme has been recently proposed. This scheme promises to increase throughput of the network under certain scenarios. This paper extends this work to drive an empirical model for response-time. The model gives response-time for a given network parameters (event rate, Frame size, Number of devices on network). The model will be useful tool for network/system designer for making design related decisions.

General Terms

TDMA networks, Response-time model

Keywords

Time Division Multiple Access (TDMA); Time-Triggered Protocol (TTP/C); throughput; event rate; discrete-event simulation

1. INTRODUCTION

Computer-based systems – networked control systems (NCS), supervisory control & data acquisition (SCADA), etc. – use communication network for data transmission between the various interconnecting devices. For these systems the candidate communication network must meet two main criteria: bounded response-time and guaranteed delivery. Means, a message must be transmitted successfully within a bounded time delay. Unsuccessfully transmitted or large time-delay messages in a system, may deteriorate system performance, make systems unstable or lead to failure. Several communication networks are available which meet these criteria, e.g. Token bus (IEEE 802.4) [6], Token ring (IEEE 802.5) [12], CAN (CSMA/AMP) [11], Time-Triggered Architecture (TTP/C) [2], MIL-STD-1553B [1] etc.

TDMA (Time Division Multiple Access) networks –TTP/C, MIL-STD-1553B – are preferred for predictable response. Predictable response of TDMA networks comes at the cost of low throughput. MIL-STD-1553B is widely used in critical applications, such as avionics, military systems and nuclear plants. In addition to low throughput, this network has another two limitations, i) 32 number of nodes, ii) 1 Mbps data rate.

A scheme called share-driven scheduled MIL (MIL-STD-1553B) has been proposed [23]. This scheme tries to increase the throughput of MIL by avoiding redundant transmission of data (messages). Redundant transmission means exchange of data whose value has not changed. The scheme requires detection of change, querying & scheduling. The advantage of this scheme is it uses same proven hardware components.

In [23] response-time of MIL networks for specific configurations was only given. This poses a difficulty as one has to make experimental setup or simulate for any other configuration. This paper derives an empirical model of response-time for share-driven scheduled MIL. This enables estimation of response-time for any network configuration.

Section 2 outlines the background material necessary for the context. Overview of share-driven scheduled MIL and simulation model along with performance data is presented in section 3. Derivation of empirical models is given in section 4. Finally conclusion follows in section 5.

2. BACKGROUND

2.1 MIL-STD-1553B

MIL-STD-1553B is a military standard that defines the electrical and protocol characteristics for a data bus. The data bus is used to provide a medium for exchange of data and information between various nodes of a system. This standard defines requirement for digital, command/ response, time division multiplexing techniques for a 1 MHz serial data bus and specifies the data bus and its interface electronics [8]. Originally this standard was intended for Air Force applications. But with its wide acceptance and usage, it is being used in a large number of critical applications, such as, space shuttles, space stations, surface ships, submarines, helicopters, tanks, subways and manufacturing production lines.

The standard defines four hardware elements. These are:

1. Transmission media
2. Remote terminals
3. Bus controllers
4. Bus monitors

A typical network consisting of a Bus controller and a remote terminal with dual redundant bus is shown in Fig 1.

The bus has been used in mission critical and time critical applications. MIL-STD-1553B bus has following features:

1) MIL-STD-1553's multi-drop bus topology enables nodes to be interconnected with ease.
2) Command/response protocol provides deterministic response-time in the system.
3) Electrical isolation with transformer coupling enables containment of electrical faults.

4) MIL-STD-1553B silicon is widely implemented in extended temperature and military specification as a commercial off-the-shelf (COTS) packages for deployment in harsh environments.

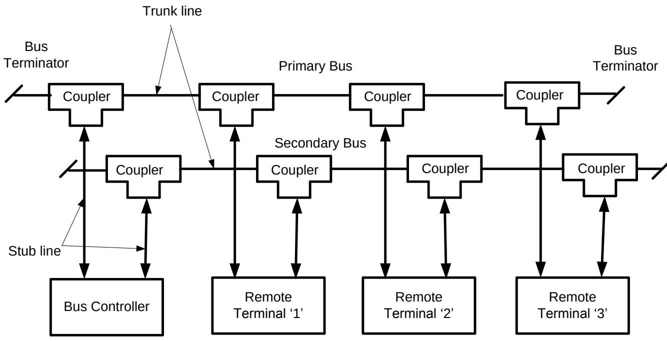

Fig 1: MIL-STD-1553B Network

Despite these positive features, future adoption of MIL bus in real-time applications is challenging because of limited bandwidth of 1 Mbps. According to MIL bus standard maximum number of nodes on MIL bus is 31. This is because of 5 bit address field in its command word frame. Addition of nodes on the MIL bus or increase in data (message) size leads to an increase in overall system response-time.

Hegarly [14] has proposed Enhance Bit Rate (EBR)-1553. The EBR-1553 defined within the Miniature Munition/Store Interface standard uses the same familiar protocol as MIL-STD-1553 and increases the data rate from 1 Mbps to 10 Mbps. Several topologies and physical layer interface options are being considered. The initial topology is a star configuration with RS-485 as the physical layer. EBR-1553 extends the number of addressable terminals form 31 to 248 by using a segmented address. The message structure is identical to MIL-STD-1553B including the command word field. This limits the number of Remote Terminals (RTs) to 31 on a single bus. EBR-1553 defines "logical buses" through an active hub. Multiple hubs can be used to form a network with more than 31 remote terminals. EBR-1553 defines a three-bit segment field that extends the logical remote terminal address to 8-bits. Each logical bus segment has 31 addresses plus a broadcast address. EBR-1553 maintains several major benefits of MIL-STD- 1553B, including deterministic communication, fast error detection and error handling and a lightweight protocol optimized for command and control systems. This approach requires a complete set of new hardware components.

Another approach to use a scheduling over MIL to increase throughput has advantage of using the same infrastructure or MIL bus components. Scheduling policy is one of the prime factor which affects real-time performance of the communication network. In literature, various communication schemes are available for the real-time networks to meet the real-time requirements [7]. The goal of the real-time scheduler is to ensure that the timing constraints of the tasks are satisfied. The scheduler makes decision based on the task timing constraints or priority and allows one task to execute or to use the resource at any given time. Due to dynamic nature of scheduling, it is not appropriate to specify worst-case response-time of tasks (or jobs).

2.2 Evaluation of Event Rate

Ref. [23] discussed an aperture technique to detect change in data. In aperture technique, a threshold or window around the present process value is used for detection of significant change in process value. Excursion beyond aperture by a process parameter leads to generation of transmission event. To model these transmission events of process parameters, node event rate and system event rate is defined. These are explained in following sections.

Fig 2 illustrates the concept of aperture and event generation for a process parameter. Parameter has a window around its present value. This kind of window can be dynamic or static with respect to the process parameter. If the process parameter crosses this window an event is generated with data corresponding to process value.

Let event at time t_1 is generated at process value i_1. A window of size Δ1 is set to detect the significant change in the process value in the subsequent time. At time t_2, process parameter crosses the window Δ1 and event is generated with data corresponding to process value i_2. A new window Δ2 with respect to process value i_2 at time t_2 is set for the subsequent event detection. Another event at time t_3 is generated as process crosses window Δ2.

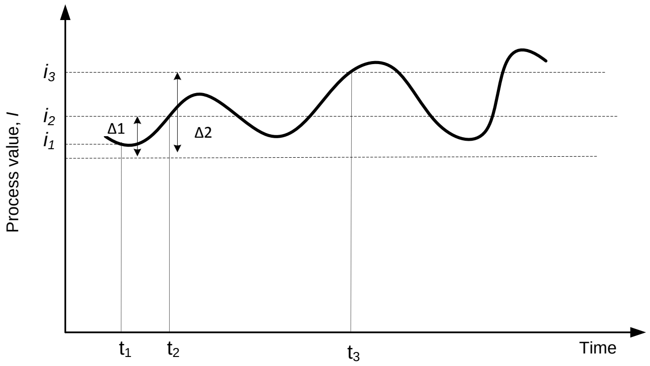

Fig 2: Event generation from plant process

Consider a node *i* with five sensors (A to E) connected to it as shown in Fig 3. Event arrival rate on the particular node has contribution from its attached sensors. Number of events on the node i.e. events/sec is sum of event arrival from each sensor with respect to time. Generally sensor has window corresponding to its process parameter and change in the process parameter outside this window generate an event. For evaluation of event arrival rate following assumptions are made.

- Plant is in stabilized condition.
- Events generated within plant are memory less i.e. the time to wait for an event to occur has the memory less property. Memory less means probability that one has to wait an additional time *t* is the same no matter how much time has already been spent.
- Events generated from the plant independent from each other.
- All sensors are identical and affect fixed number of data words to corresponding node, irrespective of magnitude of change.

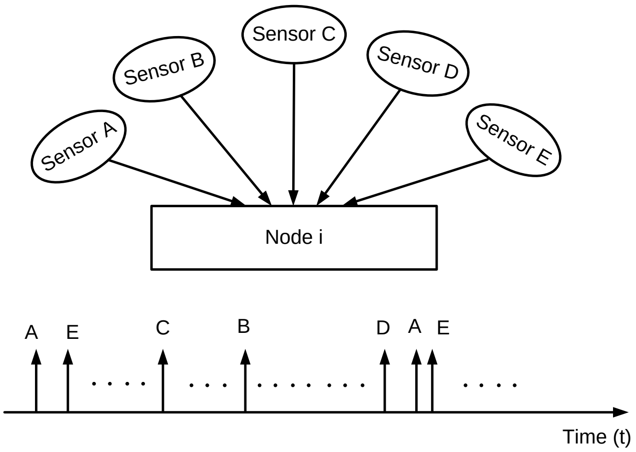

Fig 3: Event arrival rate at node with respect to time

With the above assumptions of memory less events, time between successive significant changes in the sensor value i.e. inter-arrival time between the events can be model by exponential distribution with parameter λ [18]. So, if n sensors are connected to a node with parameters, λ_1, λ_2... λ_n, then "number of events arrival to a node per unit of time" is given by the term λ_{node}.

$$\lambda_{node} = \sum_{i=1}^{n} \lambda_i \tag{1}$$

The inverse of λ_{node} node is the mean time between any sensor values changes on the node i.e. mean inter-arrival time between the successive events on the node. Exponential distribution of time between two events corresponds to Poisson arrivals for a given time, Δt with parameter $\lambda * \Delta t$ [21], [16].

With previous assumption, numbers of events per unit of time for a system can be evaluated for communication network as shown in Fig 4.

Each node on the network has event arrival rate constituted by the individual sensors. Node i, j and k connected to a network has event arrival rates λ_i, λ_j and λ_k respectively. System event rate i.e. number of event arrival due to all the nodes on communication network is given by λ_{system},

$$\lambda_{system} = \sum_{\forall n \in \{i,j,k\}} \lambda_n \tag{2}$$

System event rate of system as shown in Fig 4 expressed in terms of number of events per second because of all the nodes on the network. This system event rate act as an input parameter during the simulation of share-driven scheduling for MIL-1553 network.

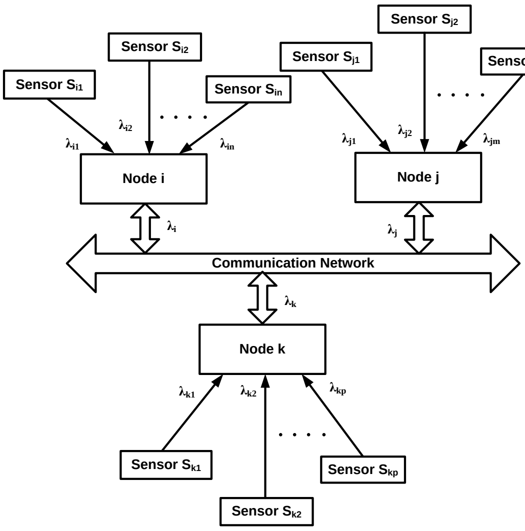

Fig 4: System event rate evaluation

3. OVERVEIW OF SHARE-DRIVEN SCHEDULED MIL-STD-1553B NETWORK

3.1 Share-driven Scheduled MIL-STD-1553B Network

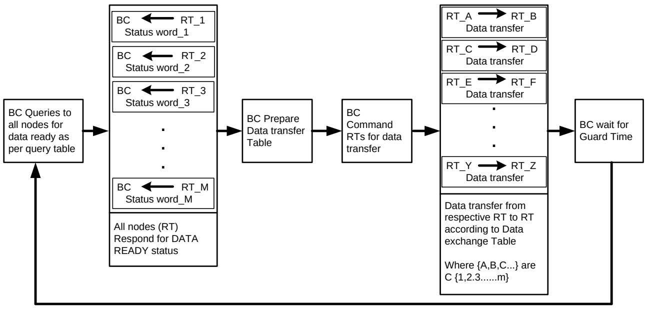

Fig 5: System model for simulation of Share-driven scheduled MIL-STD-1553B network

In share-driven scheduled MIL bus, Bus controller (BC) scans each Remote Terminal (RT) for its DATA READY status. The numbers of nodes with DATA READY status are modeled as Poisson distribution (normalized to maximum number of available nodes) with parameter system event rate (λ).

BC has two tables in its memory (RAM) - query table and data transfer table. The query table is static table, using this BC probes each RT for its DATA READY. In response to query table, it prepares data transfer table. So, data transfer table is dynamic. BC first load query table into its memory and queries to all nodes for DATA READY status. BC prepares data exchange table according to number of nodes are ready with fresh data found during the query phase.

3.2 Simulation Model

Fig 5 shows the system model for discrete-event simulation of share-driven scheduled MIL-STD-1553 network. Discrete-event simulation is a simulation that experiment on the system in which the state alters instantaneously and driven by lots of random event. In such system the state variable remains the same between two events, and so it is a discrete change. In general, the incident is random and events are uncertain.

Algorithms start with initialization various network and node related parameter such as number of nodes connected on network, data rate, event rate, number of data word for transmission etc. The number of nodes ready with fresh data is simulated by generating the Poisson distributed random variates. This can be archived by converting uniform distribution random variates into the Poisson distributed random variates using inverse transformation method [16]. This number of node(s) ready simulates the number of node(s) ready found during the probing phase by BC. A data transfer table is prepared with ready nodes. The BC executes the data transfer as per the data transfer table. This sequence is repeated for length of simulation run.

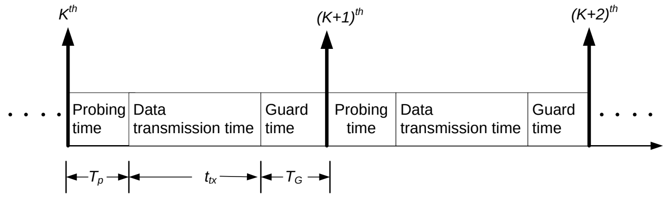

Fig 6: A typical time trace Share-driven scheduler

Fig 6 shows the time trace of a typical cycle on share-driven scheduled MIL-STD-1553B network. At the beginning of the (k + 1)th cycle, it generates a Poisson number, α with parameters $\lambda_{sys} * T_k$, where T_k is previous cycle time. This Poisson number is normalized to available number of nodes. This Poisson number simulates the number of node ready found ready during the query or probing phase. Here for MIL-STD-1553B, probing time interval i.e. T_p is determined by the number of nodes available on the network. As the number of nodes on the network remains constant, T_p also remains constant. Data transmission time i.e. t_{tx} is total data transmission time for those nodes which was found ready during the probing time, T_p. The guard time after the data transmission is introduces to incorporate the future expansion. Number of node ready with the data i.e. α is function of previous cycle time, T_k. Parameter λ_{sys} is a system event rate as discussed in previously. This generated Poisson number, α indicates the number of nodes with DATA READY. The next probing time T_{k+1} estimated as:

$$T_{k+1} = \begin{cases} T_k + \alpha t_{Tx} + T_G, & \text{if } \alpha > 0 \\ T_k + t_W + T_G, & \text{if } \alpha = 0 \end{cases} \quad (3)$$

Where,

t_{tx}: Transmission time of one RT-RT transfer

t_W: wait time

T_G: Guard time

Here wait time; t_W is introduced to avoid the immediate probing of nodes on the network if there is no node ready with data during the current probing phase.

The operation of system model of MIL-STD-1553B is as follow. System loads a query table for inquiring the DATA READY status. This query table remains same for a given set of nodes. This table is loaded to memory of BC, which executes the status gathering as per the MIL protocol. Based on the status from nodes, system prepares a data transfer table for those nodes which was found ready with fresh data during probing. The table is made in ascending order with RT address. This table is loaded in BC for data transfers. On completion of these data transfer system wait for a time called Guard time. Guard time is there to accommodate future expansions/retransmission and provide a minimum query time. System starts next cycle with loading of query table and other steps. Here query table remains the same as number of node needed to be scan i.e. number of node available on the network is same. Data exchange table is updated every cycle depending upon number of ready nodes.

A simulation that has any random aspects at all must involve sampling, or generating, random variates from the probability distribution. Inverse transform method can be used to convert a uniform distributed random number into given distribution [16] .

During initial period of simulation measured parameters have “transient” effects. These transients may affect the estimation of steady state values. The simulation length required to nullify the effect of transients is termed as warm-up period [16], [20].

3.3 Performance Data

The validated simulation model is used to measure response-time and utilization for various event rates under four different test cases for share-driven scheduled MIL network and compared with native MIL-STD-1553B network. These test cases are for comparison given Table 1.

Table 1. Test Cases

Case	No. of nodes on MIL network (*N*)	Data words In RT to RT Transmission (*DW*)
Case 1	10	20
Case 2	10	32
Case 3	20	20
Case 4	20	32

3.3.1 Basic MIL Bus

The basic MIL-STD-1553B bus follows static table-driven approach. As shown Fig 7 data exchange table for transmission is prepared during the system design phase and BC uses this during run time.

The BC is responsible for directing the flow of data on the data bus. The commands may be for the transfer of data between RTs or control & management of the bus (referred to as mode commands). When RT receives a valid command, it shall respond within a defined amount of time i.e. response-time. BC keeps on repeating the transmission according to data exchange table.

The serial bus standard is like many others, it works fine until it is overloaded. For basic MIL analysis of bus loading (or utilization) is a relatively simple matter.

The bus utilization, U, of a network is defined by the ratio of the total time used to transmit data, C_i, and the total run time, T_i:

$$U = \sum_{i=1}^{m} C_i / T_i \quad (4)$$

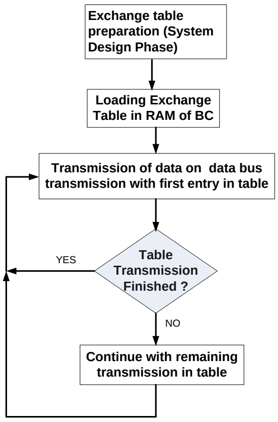

Fig 7: Basic MIL scheduling

A single RT-RT transmission with 20 data words on the network takes around 600 *μsec* i.e. data transmission time C_i = 600 *μsec*.

Maximum bus utilization during design phase is kept less than 100% to provide time for error recovery/automatic retry and to allow expansion during the system's life. Here, percentage bus utilization of MIL-STD-1553 data bus is limited to 60% i.e. U = 0.6. Total running time for m =10 nodes and data words = 32 is given by T = 13.5 *msec* ($T = \sum T_i$). Cycle time for MIL bus is time interval after which the transmission from the nodes starts repeating. In this case, node transmission repeat after 14 *msec*. Cycle time for basic MIL protocol is same as worst-case response-time of node. Entire messages as per data transfer table are transmitted in every cycle. So, response-time in basic MIL bus is independent of event rate.

Table 2. Response-time with basic scheduling for MIL network

Case	WC Response -time (U = 0.6)
Case 1	10.0 msec
Case 2	13.5 msec
Case 3	20.0 msec
Case 4	27.0 msec

From above analysis, it is clear that response-time is function of bus utilization (U), number of data words and number of nodes. Table 2 gives the response-time with basic MIL bus for all test cases.

3.3.2 Share-driven Scheduled MIL Network

Discrete-event simulation model of share-driven scheduled MIL bus is used to estimate response-time distribution and utilization of bus. The analysis is performed for all the test cases for different event rates. For each case and event rate, 5 simulation runs each of 10000 transmission length are carried out. Response-time with 0.999 probability of meeting this time for all the test cases and event rate combination is tabulated in Table 3.Query phase of proposed share-driven approach utilizes the available bandwidth of the network; hence contribute to overhead of the network. Percentage overhead and bus utilization [6] of share-driven scheduling is calculated for different event rates and given in Table 4.

The results show a remarkable improvement in the response-time with share-driven scheduling. Table 2 gives the response-time with basic MIL. In this case, the entire messages as per data transfer table are transmitted in every cycle and hence it is independent of event rate. Fig 8 shows the variation of response-time (plotted on y-axis) in basic MIL with respect to bus utilization (plotted on x-axis). Here, response-time is same for all the messages and it is equal to cycle time. In case of share-driven scheduled MIL, response-time is a probabilistic estimate.

Table 3. Response-time (τ) with Share-driven scheduled MIIL Network (Probability of meeting given response-time is 0.999)

Event rate	Case 1	Case 2	Case 3	Case 4
100	3.62 *msec*	3.80 *msec*	5.80 *msec*	6.22 *msec*
200	3.62 *msec*	4.42 *msec*	6.35 *msec*	7.80 *msec*
300	4.25 *msec*	5.20 *msec*	7.53 *msec*	9.32 *msec*
400	4.85 *msec*	6.00 *msec*	8.20 *msec*	11.10 *msec*
500	5.40 *msec*	6.90 *msec*	9.40 *msec*	12.20 *msec*
600	6.00 *msec*	7.60 *msec*	10.56 *msec*	14.20 *msec*
700	6.80 *mesc*	8.70 *msec*	11.47 *msec*	16.45 *msec*
800	7.50 *msec*	9.10 *msec*	12.40 *msec*	18.10 *msec*
900	8.10 *msec*	9.10 *msec*	13.25 *msec*	18.10 *msec*

Table 4. % Utilization (% Overhead) with Share-driven

Event rate	Case1	Case 2	Case 3	Case 4
100	66.9 (36.49)	68.71 (36.08)	81.45 (44.94)	82.70 (44.42)
200	71.77 (35.70)	74.42 (34.73)	85.01 (43.50)	86.91 (41.95)
300	75.55 (34.40)	78.97 (32.67)	87.47 (41.22)	89.23 (38.59)
400	78.80 (32.92)	82.85 (29.85)	88.88 (38.50)	90.45 (34.66)
500	83.40 (28.69)	86.83 (23.41)	89.03 (32.04)	90.63 (25.61)
600	85.54 (23.34)	88.34 (17.67)	89.14 (25.18)	90.74 (16.82)
700	86.14 (18.65)	88.71 (13.18)	89.46 (18.58)	90.81 (12.21)
800	86.38 (15.90)	88.80 (11.59)	89.88 (15.13)	90.88 (10.94)
900	86.34 (13.70)	88.84 (10.30)	90.10 (13.15)	90.93 (9.40)

4. DEVIATION OF EMPHERICAL MODEL

4.1 Model

Ref [23] given the response-time distribution for 4 different cases corresponding to the different load scenario on network.

With statistical analysis, it is found that best fit for response-time (τ) has following relationship:

$$\tau = e^{\alpha * \lambda + \beta} \qquad \textbf{(5)}$$

Where,

λ is an event rate

α, β are network configuration dependent constants.

From (5) it is clear that the τ is function of event-rate, λ. and network configuration. Parameters α and β are the function of network configuration - N (number of nodes) and DW (number of data words).

With trial and error, α and β are fitted as given below:

$$\alpha = a * (N * DW) + b \qquad (6)$$

$$\beta = k * (N * DW) + l \qquad (7)$$

Where,

a = 0.6E-06, b = 0.92E-03, k = 1.24E-03, l =1.033

4.2 Discussion

Response-time as per (5) is plotted along with response-time values obtained from experimental in Fig 8. It can be observed that maximum error is ~10% between observed and estimated.

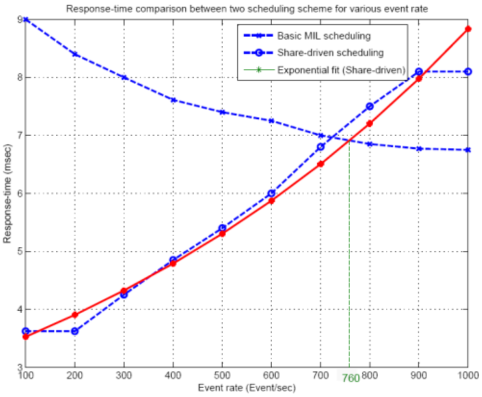

Fig 8: Response-time comparison between two scheduling scheme for various event rate for Case 1

5. CONCLUSIONS

MIL bus is in use for last four decades. It is facing problems mainly at two fronts, i) fixed data rate of 1 Mbps and ii) maximum of 32 nodes in the network. A lot of development is in progress to overcome these problems. Hegarly [14] has proposed Enhance Bit Rate (EBR)-1553 to overcome these two limitations. But EBR requires a whole new set of components.

Contemporary work on share-driven scheduled TDMA [23] promises better throughput under certain conditions. This was shown for specific case using measurement and simulation. The paper extends the works, by deriving empirical models for share-driven scheduled MIL. This model is in form of simplified equations. These equations take network parameters (λ, N, DW) as input and provide response-time. These models have been validated with exterminated data. These equations are convenient tool for system designers to compare design alternatives.

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