Schedulability Analysis and Performance Evaluation of WSAN

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Abstract: The current trend in the development of Networked Control Systems (NCS) is the use of wireless networks to communicate the system nodes, which have been called Wireless Sensors and Actuators Networks (WSAN). This trend is principally to increase flexibility and reliability of these applications and to reduce the implementation cost. Several protocols have been used, however the latency and jitter presented in the transmission period produce that not always a similarity between experimental and simulation results can be obtained. This is because imprecise models for analyzing and designing these systems are used, and to make use of inadequate validation methods and platforms that do not support the models utilized. Therefore this paper presents a method to analyze end – to – end schedulability of WSAN, and evaluate the performance of case study using Medium Access Control (MAC) algorithms TDMA and CSMA – CA.

Keywords: Real-time systems, Wireless sensors and actuators networks, Embedded systems, Real time monitoring and control.

1. INTRODUCTION

As a consequence to the increasing complexity of control systems, most of activities have been distributed over different nodes, where control loops are closed through a communication network. These systems are called Networked Control Systems (NCS). The implementation of NCS also reduces the impact of failures in a system component and facilitates the diagnosis, maintenance and traceability processes.

The MAC algorithm utilized by the network characterize the latency and jitter presented in the transmission period, which produce that not always a similarity between experimental and simulation results can be obtained. This is because imprecise models for analyzing and designing these systems are used, and to make use of inadequate validation methods and platforms that do not support the models utilized. The use of wireless networks to communicate the system nodes enable the development of new applications on wireless sensors and actuators networks (WSAN) in order to increase the applications flexibility and reliability. At the same time its impact on the reduction of implementation cost is significant.

This paper presents a method to analyze end – to – end schedulability of WSAN, and evaluate the performance of a case study using Medium Access Control (MAC) algorithms TDMA and CSMA – CA, which are used by current wireless networks.

The paper is organized as follows. In section 2 the related work is presented. A method to analyze end – to – end schedulability of WSAN is presented in section 3. Section 4 presents the analysis and simulation results of a case study using MAC algorithms TDMA and CSMA – CA. Finally in section 5 conclusions and future work are presented.

2. RELATED WORK

This area integrates several disciplines; the following is an analysis of works presented at each one.

2.1 Networks protocols

An analysis of the performance of wired networks for control process is presented in (Lian, 2001). With regard to wireless networks, in (Hristu-Varsakelis, 2005) and (Lee, 2008) the use of Bluetooth and IEEE 802.11b like networks for control applications is analyzed, while giving a four layers architecture to achieve a predictable behaviour in IEEE 802.11b. (Pantazis, 2007) examines several methods for reducing the power consumption at different levels of the communication stack in wireless sensor networks, one of which is the TDMA MAC algorithm that contributes to ensure time transmission bounds, to minimize collisions, and power-aware.

The results presented in (Moraes, 2008) and (Cena, 2008) allow to conclude that IEEE 802.11e EDCA mode offers a
good alternative to fulfill the requirements in real-time industrial applications. A conclusion of scenarios presented is that using the EDCA default values can guarantee the requirements for submitting information in industrial applications, with a number of stations smaller than 10 and message stream periods above 10 ms.

At this time there are several commercial devices that use Zigbee (Zigbee Specification) and WirelessHART (WirelessHART), which have lower power consumption than developments supported by IEEE 802.11. Zigbee is supported by the IEEE 802.15.4-2003 protocol, which implements two basic types of media access, without synchronization and synchronization through beacons. The advantage of the MAC algorithm without synchronization is to facilitate the scalability and autoconfiguration of the network, but no warranty time transmission bounds.

In the IEEE 802.15.4 synchronization mode the maximum time to transmit information can be bounded using guaranteed time slots (GTS) within a superframe, which is a very important characteristic for the development of control applications (Martínez, 2008). It is possible to assign a maximum of seven slots, with a minimum frame period of 15.36 ms, which may be enough in some cases. In (Koubâa, 2006) a method for the allocation of GTS is presented. However, the use of GTS is restricted to networks with star topology, which limits the reliability and scalability of the application.

Although networks with star topology allow the use of GTS, the development of control applications in industrial environment requires a reliable and secure communication. This requirement is easier to provide by networks with mesh topology, which also benefits the applications scalability. In order to construct a mesh networking architectures, Zigbee uses a MAC algorithm without synchronization, nevertheless some proposals have been developed to construct cluster tree networks synchronized as presented in (Koubâa, 2007).

WirelessHART is based on the physical layer of IEEE 802.15.4-2006 protocol, but specifies new levels of Data link, Network, Transport and Application, (Lennvall, 2008). WirelessHART uses a MAC mode by TDMA, with 100 slots per second. Additionally WirelessHART allow developing mesh topologies networks providing redundant paths that permit routing messages through different routes to avoid broken links, interference, and physical obstacles.

2.2 Feasibility testing for real time tasks

By the effect of delays on the performance of NCS these applications have real time constraints. This time is calculated from the moment when the measurement is made until the actuator applies the control action on the system, and its magnitude depends on worst-case response time of control tasks and the time required sending the information by the network. A general architecture for these applications is presented in figure 1.

In its general formulation, the problem of scheduling in hard real-time distributed systems is NP-hard. With the aim of reducing the difficulty, heuristics and constraints should be used. A common approach is to allocate tasks statically to nodes and locally use a scheduling algorithm such as EDF or RM (Spuri, 1996).

Distributed applications are characterized by precedence relationship between their tasks. If the tasks are statically allocated to single processors, \( end – to – end \) timing constraints can be analyzed by a theory which assumes release jitter (Audsley, 1993). Several papers have been developed oriented to analyze \( end – to – end \) schedulability, which have used tasks scheduling algorithms like RM and EDF, and MAC protocols based on TDMA, Token and Priorities (Tindell, 1994), (Tindell, 1995), (Spuri, 1996). Additionally, these works consider the use of buffers to store messages in the network nodes, and therefore employ a scheduling method to get out the messages from buffers.

Fi. 1. General architecture of NCS

This work does not consider message storage in buffers, because the size of messages in industrial applications is small compared to the amount of data supported by each message in current standard protocols (maximum payload in physical layer PDU of 127 bytes for WirelessHART and ZigBee). Then it is assumed that each message is sent within the space reserved for a node in the TDMA network. This proposal differs from previous ones in that it is not necessary to make a scheduling of messages in buffers, therefore we assume that the delay introduced by the network is constant and equal to the maximum possible, which is the period to repeat the slots in the TDMA network.

About tasks schedulers, in the context of wireless sensor networks the most commonly used operating systems is TinyOS (TinyOS). It was designed to be used in systems with limited resources, such as 8-bit microcontrollers with small memory. It is supported by a programming model based on components and guided by events, with event handlers’ priority higher than tasks, which are executed based on scheduling policy FCFS. However, such schedulers are not appropriate for real-time systems. Zigbee products from
Chipcon and Texas Instruments use a scheduler based on static priorities.

Although fixed priority scheduling is the most popular online scheduling policy in real-time systems, usage of the EDF policy is starting to get more attention in industrial environments, due to its benefits in terms of increased resources usage. EDF is currently available in real-time languages such as Ada 2005 and RTSJ. It is also available in real-time operating systems like SHark and Erika.

2.3 Networked Control Systems

There are several authors who have analyzed the performance and stability of NCS for network protocols with constant and variable delays, by the same way some proposals to modify the control algorithms in order to compensate delay effects have been developed, (Gregory, 1999), (Walsh, 2002), (Yang, 2006), (Hespanha, 2007), (Tabbbara, 2007), (Hu, 2008), (Huang, 2008), (Zhang, 2009), (Xiong, 2009). However there is not a general method to analyze stability and performance to any NCS. Each method is limited to the network configuration, the communication protocol used and system and control algorithm assumptions. Furthermore, the design methodologies use different ways, by designing the control algorithm with traditional methods and transferring the problem to the design of the computer system, considering the characteristics of the computer system and designing a control algorithm to compensate its effect, or using an approach where the computer system and control algorithm are co-designed. In most cases only the closed loop system stability is analyzed.

3. METHOD TO ANALYZE END-TO-END SCHEDULABILITY

In order to fulfill with real-time constraints and facilitate the implementation of strategies to optimize the power consumption, in this proposal a local EDF policy and TDMA based network with guaranteed time slots for each node were chosen, and message storage in buffers was discarded.

3.1 System Model and Notation

Whereas a general framework where the tasks to perform the functions within the NCS, Sensor, Controller and Actuator, have precedence relationship between their and are executed in exclusion in different nodes. Following functions and concepts are defined:

- \( T_{SF} \), is the period to repeat the slots in the TDMA based network.
- \( D_{CCR} \), is the end – to – end deadline according to the control performance goals.
- \( T_S \), is the sampling period used by the task sensor, which is defined according to the dynamic system and comply with \( D_M + D_C + D_A \leq D_{CCR} \leq T_S \), with \( D_M \), \( D_C \) and \( D_A \) are the deadlines of Sensor, Control and Actuator tasks respectively.
- \( \tau = \{ Task_1, Task_2, ..., Task_n \} \), is a tasks set feasible by EDF policy with \( Task_i = (WCET_i, D_i, T_i) \); \( WCET_i \), \( D_i \) and \( T_i \) are the respective values on worst-case execution time, deadline and period of task.
- \( WCRT_i \), is the worst-case response time for task \( Task_i \).

3.2 Schedulability Analysis

According to schedulability analysis in EDF (Ripoll, 1996):

- \( H_z(t) = \sum_{i=1}^{n} C_i \left[ \frac{t + T_i - D_i}{T_i} \right] \), is the amount of computation time that has been attended by the processor until time \( t \) to fulfill with all deadlines in the system.
- Initial critical interval (ICI), is the time interval between time zero and the first time such that no outstanding computation exists, \( [0, R] \).

The schedulability test consists in to verify that

\[ H_z(t) < t \quad \forall \quad t \leq R \]  

(1)

Then to verify the end – to – end schedulability for Sensor, Controller and Actuator tasks, according to the previous assumptions, will consist in verifying if \( D_M, D_C \) and \( D_A \) fulfill with expressions presents in table 1.

### Table 1. Tasks Parameters to verify end – to – end schedulability

<table>
<thead>
<tr>
<th>Task Sensor</th>
<th>Task Controller</th>
<th>Task Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic, ( T_{Sen} = T_S )</td>
<td>Sporadic, ( T_{C_{Sen}} = T_S )</td>
<td>Sporadic, ( T_{A_{Sen}} = T_S )</td>
</tr>
<tr>
<td>( WCET_{Sen} \leq WCRT_{Sen} \leq D_{Sen} )</td>
<td>( WCET_C \leq WCRT_C \leq D_C )</td>
<td>( WCET_A \leq WCRT_A \leq D_A )</td>
</tr>
<tr>
<td>( D_{Sen} = D_{CCR} ) ( { WCRT_C + WCRT_A + T_{SF} } )</td>
<td>( D_{C_{Sen}} = D_{CCR} ) ( { WCRT_{Sen} + WCRT_A + T_{SF} } )</td>
<td>( D_{A_{Sen}} = D_{CCR} ) ( { WCRT_{Sen} + WCRT_C } )</td>
</tr>
<tr>
<td>( WCRT_{Sen} \leq WCRT_{Sen} + T_{SF} )</td>
<td>( WCRT_C \leq WCRT_C + T_{SF} )</td>
<td></td>
</tr>
</tbody>
</table>
In order to select \(D_0, D_c\) and \(D_t\) for implementation a value between \([D_{0\text{min}}, D_{0\text{max}}]\) can be used, where \(D_{0\text{min}}\) and \(D_{0\text{max}}\) are the minimum and maximum values of \(D_t\) to local and end – to – end schedulability, taking into consideration its effect on parameters such as power consumption at each node (using strategies of dynamic voltage scaling), latency and jitter in control system delays, between others. \(D_{0\text{max}}\) is obtained from Deadlinemin algorithm presented in (Balbastre, 2008).

Depending on the physical characteristics of the system, tasks Sensor and Actuator can be allocated to the same node, similarly task controller can be executed on any node with the purpose of balancing the utilization rate among them, which affect the primary limiting factor for the lifetime of a sensor network which is the energy supply. Therefore, three more architectures can be presented for the control system architecture and previous parameters must be modified as follows:

- Sensor and Controller in the same node: \(WCR_T^M = WCR_T^M\).
- Controller and Actuator in the same node: \(WCR_T^C = WCR_T^C\).
- Sensor and Actuator in the same node. In this case there are not changes because network is used to send information from Sensor to Controller and from Controller to Actuator.

4. CASE STUDY

As a case study three different control loops with same parameters were considered, each one regulates the output signal in a first order system.

In many practical cases the desired performance is specified in terms of the transient response in control systems; for this reason, in this paper a linear model to analyze the transient response of close loop system for constants delay is presented.

Assumptions about the system are:

- Single Input Single Output.
- Sensor task is time-driven, with a sampling period \(T_S\), but Controller and Actuator are event-driven, then the system is synchronized.
- The delay from task Sensor start until task Actuator is finalized is less than or equal to \(T_S\).
- There are not network messages lost and the throughput is enough to ignore the transmission time.
- The context switches time is part of the task execution time.

- The communication delays only depend of collisions between frames.

If the system is synchronized, it is possible to consider a single delay located in the forward loop, figure 2.

![Figure 2. Representation of synchronized system](image)

The network delay can be modelled as \(e^{-\tau_x s}\), with \(\tau_x = (1 - m) T_S\), \(0 \leq m \leq 1\), and \(\tau_x\) represents the latency from task Sensor start until task Actuator is finalized.

Then, using the modified Z transform is possible to find a transfer function to analyze the system performance for a specific delay as follow:

\[
H_{(Z,m)} = \frac{G_c(Z) G_p^r(Z,m)}{1 + G_c(Z) G_p(Z,m)}
\]

Where:

\[
G_p^r(Z,m) = (1 - z^{-1}) \left[ \frac{G_p(S)}{S} \right]
\]

\(G_p^r(Z,m)\) is the modified Z transform of \(G_p(S)\).

For a first order system \(G_p(S) = \frac{K}{\tau_p S + 1}\), then

\[
G_p^r(Z,m) = K \left[ \frac{1 - e^{-m\tau_s / \tau_p}}{z - e^{-m\tau_s / \tau_p}} \right]
\]

For the case study \(G_p(S) = \frac{0.3}{0.86 s + 1}\), using (3)

\[
G_p^r(Z,m) = \frac{0.3}{Z} \left[ \frac{1 - e^{-0.3/0.86}}{z - e^{-0.3/0.86}} \right]
\]

In order to reduce the settling-time the following PI control algorithm was used:

\[
G_c(Z) = \frac{k_p z + (k_i T_S - k_p)}{z - 1}, k_p = 30.2778 \text{ and } k_i = 25.463.
\]

It is assumed that for each control loop the accepted performance is presented in figure 3, which is generated with \(T_S = 110\ ms\) and \(\tau_x = 80\ ms\), then \(D_{cGR} = 80\ ms\).

The approach is as follows. Each control loop requires three tasks, Sensor, Controller and Actuator, which are pre-as-
signed in different nodes. The tasks computation time are $C_M = 1.5\, ms$, $C_M = 5\, ms$, $C_A = 0.3\, ms$.

With the aim of increasing the processor and network utilization, following factors have been generated:

- Two periodic tasks for each node, called $L_1$ and $L_2$, whose parameters are: $C_{L,i} = 3\, ms$, $D_{L,i} = D_{L,i} = 10\, ms$.
- Three nodes generating traffic, called $GT_1$, $GT_2$ and $GT_3$, which sends a frame with 144 bits every 35 ms.

The network parameters are:

- Frame size = 144 bits.
- Data rate = 250 kbps.
- Guaranteed time slots of 1 ms in a TDMA based network.
- The time slots are repeated in the TDMA network every 35 ms.

The procedure to analyze the system is as follows:

- Local schedulability is analyzed by use the equation (1). Because only the end-to-end deadline is known for any control loop, but individual deadlines for Sensor, Controller and Actuator tasks are unknown, initially this test is realized with $D_M = D_C = D_A = 110\, ms$. Results are presented in Table 2.

Data presented in Table 2 show the fulfillment of local and end-to-end constraints in all control loops.

To analyze the behavior of every control loop the case was simulated using Truetime (Cervin, 2003). Figures 4, 5 and 6 show the network messages schedule, tasks schedule in the

<table>
<thead>
<tr>
<th>Task</th>
<th>Local Schedulability</th>
<th>$D_{Min}$</th>
<th>$D_{Max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor_1</td>
<td>Yes</td>
<td>1.5 ms</td>
<td>38.5 ms</td>
</tr>
<tr>
<td>Controller_1</td>
<td>Yes</td>
<td>11 ms</td>
<td>29 ms</td>
</tr>
<tr>
<td>Actuator_1</td>
<td>Yes</td>
<td>0.3 ms</td>
<td>39.7 ms</td>
</tr>
</tbody>
</table>

Fig. 3. System response for a square input, with $T_s = 110\, ms$ and $\tau_s = 80\, ms$.

Fig. 4. Messages schedule for TDMA based network. $T$, $W$, and $I$ represents Transmitting, Waiting and Idle states.
node which executes the task Actuator in control loop 1, and
the transient response in all control systems respectively.

In figure 4 it is possible to see that time to sending messages
by each nodes is not regular, and depends on the moment
when the task finalizes its execution and the node tries to ac-
cess to the network, and the synchronization of this time
with the time slot assigned to realize the transmission, gener-
ating cases in which a node must wait until the next slot in
order to transmit, anyway this value is bounded. This result
is very important because it indicates that the processor in
every node assigned to develop communications activities
does not need to be synchronized with those who execute the
application.

Furthermore, although the transmission time is not periodic,
the end – to – end deadlines can be fulfillments, it can be
seen in figure 5, where the task Actuator of control loop 1
ends before $D_{CCRT}$.

Figure 6 shows that the performance of three control loops
are very similar and fulfilled with desired performance.

To analyze the performance of control loops using a CSMA-
CA based network, the case was implemented in Truetime
with a ZigBee network and same parameters of data rate and
frame size used for the TDMA based network case. Results
are presented in figures 7 and 8.
CONCLUSIONS

The performance of the proposed method to analyze end-to-end schedulability of WSAN was analyzed by simulation of a case study, at the same time the effect of delays on these systems using TDMA and CSMA–CA protocols was observed, the conclusions obtained are:

- The method proposed allows to analyze end-to-end schedulability in WSAN, when task schedulers EDF and TDMA based network are used, in order to fulfill with the desired performance in control applications.
- To ensure compliance end-to-end deadlines, based on assumptions realized, it is not necessary to synchronize the processor in every node assigned to develop communications activities with that who execute the application.
- The use of CSMA-CA protocols, like used by ZigBee in networks with mesh topology, does not guarantee a maximum latency in NCS, then the performance of these systems can be significantly degraded.

Future work will focus on to considerate nodes with Dynamic Voltage Scaling capabilities, and to propose a design method of WSAN with real time constraints that optimize the power consumption and the transient response in control applications.
REFERENCES


TinyOS: http://www.tinyos.net/


WirelessHART:


