Hard Real-Time Wireless Medium Access in Action: Stop the Guillotine Within a Millisecond!

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***Abstract*—The demonstration deals with medium access schemes that can be used to realize hard real-time constrained transmissions over wireless links. We show that properly choosing a medium access scheme allows for fulfilling tight deadlines. The real-time constraint is represented by means of a guillotine that has to be stopped.**

I. Introduction

Recently, the interest in so called machine-to-machine communications (alias internet of things) has significantly increased [1]. The communication scenario are of interest as they lead to new requirements and constraints to be met that require novel design of most layers of the communication stack [2]. One of the most challenging communication scenario in this context arrises in industrial applications and certain control systems where hard real-time constraints need to be met. Such scenarios are characterzed by rather small payload sizes that need to be delivered within a given deadline. What makes these scenarios challenging are the requirements on the outage probability which is easily in the area of 10^{-5} or below. Hence, the acceptable probability that a packet is not delivered within the given deadline is below this threshold. As typical deadlines are in the area of a millisecond, it is clear that a completely new design of a wireless network needs to be utilized. Ideally, such a novel design spans several different network layers from the physical layer up to the network layer (or above). However, one crucial design choice is the selection and implementation of the medium access scheme. This is what we address with this demo.

In particular, we present a demo where we implement a token-passing medium access scheme on top of an FPGA-based prototyping system. Token-passing MACs are known to provide real-time capability while they are also distributed in nature providing even more robustness. This comes at the price of an increased implementation complexity [3]. Nevertheless, we demonstrate that this complexity can be handled while preserving all desired features of the token-passing protocol. This is demonstrated by controlling a real-time critical process where a heavy object is falling and threatening to destroy a sensible object. Once the control systems detects the falling object, it reports back via the wireless network to the controlled, which commands countermeasures over the wireless network back to the initial device. Only if this communication is successfull, the object can be stopped. The demo shows that CSMA-type of MACs can not provide this real-feature, while our token-passing protocol is capable of managing the situation successfull. Finally, note the the demo is part of a longer-term research project where in addition suitable PHY layer, network layers and security features are investigated.

II. Demonstration Topic

The general purpose of the demonstration is to show differences between two medium access (MAC) protocols in the context of a real-time constrained transmission. The real-time constraint is represented by a falling object meaning that within a maximum time interval a critical transmission has to be finished successfully. High medium utilization is caused by a simultaneous video transmission in the same radio channel. The objective is to stop the falling object in a timely manner. This necessitates a proper MAC protocol choice.

The course of events can be briefly described as follows:

1) Pressing red button releases object.
2) While the object is falling, a real-time sensitive transmission over a wireless medium has to take place, i. e., control packets have to be exchanged between two stations over a utilized medium.
3) Timely packet reception prevents falling object from destroying another valuable object.

A visual representation of the setup is given in Fig. 1. As wireless stations we use the Wireless Open-access Research Platform [4], or, for short, WARP board. Two of these boards act as video streaming clients, the other two as real-time control stations, out of which one is coupled electrically with the actual demonstrator. Releasing and stopping the object is realized via two electromagnets that are controlled by an electromagnet controller. The first trigger is the push of the button. This not only releases the object, but also at the same time raises a signal at the first control station. Then, this station immediately after having given medium access sends out a control message. Once the second station receives that control message, it schedules a reply message for transmission in the next available medium access period. Having received the reply message, the first control station promptly raises a signal at the electromagnet controller, indicating a reverse in polarity for the second electromagnet. This pushes a metal plate into the direction of fall of the object of interest. A short summary on the main components is given in Table I.

The concurrent video stream prevents instant medium access for the control stations. How the medium access is determined

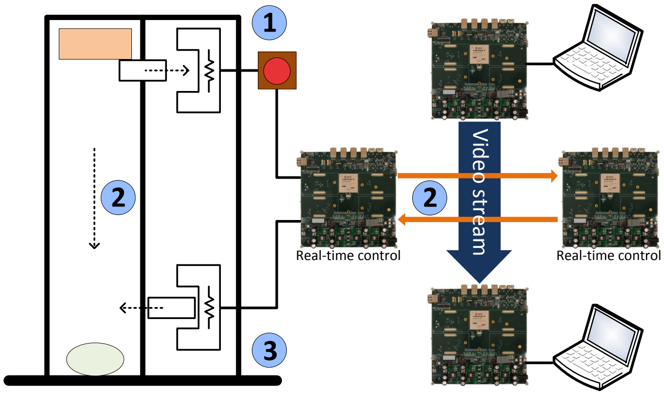

Figure 1. Experimental Setup

Hardware	Software
4 WARP boards	CSMA protocol on WARP boards
2 Laptops	TPMA protocol on WARP boards
2 Electromagnets (EM)	Video stream between laptops
1 EM controller	

Table I
DEMONSTRATION COMPONENTS

and negotiated is subject to the chosen protocol. We compare two different MAC protocols, namely the Carrier-Sense Medium Access (CSMA) and the Token-Passing Medium Access (TPMA). Both follow an entirely different transmission paradigm.

In essence, the CSMA protocol grants a station medium access if there is no energy detected on the medium. If energy is sensed, the station waits for a certain back-off period, after which it re-initiates the transmission attempt. With each unsuccessful attempt it increases the back-off period. Positive aspects of this approach are easy implementation and that there is no need for configuration among the stations. But on the other hand, this scheme provides no fairness among the stations, and, moreover, it cannot guarantee an upper bound on the delay and a transmission rate in any way. This is especially crucial whenever the medium faces high utilization. The outcome of the application of this protocol to the above mentioned hard real-time scenario is that the falling object cannot be stopped every once in a while.

In contrast to the CSMA approach, in case of the TPMA protocol medium access is granted if a station receives a special, exclusive permission, a so-called token. Thereby, the TPMA protocol can assure a minimum data rate and a maximum delay at the expense of a decrease in transmission efficiency. This means for the demonstration that the object can always be stopped. More details on the TPMA protocol can be found in Sec. III. To visualize the tight deadline, we scale the time that it took to exchange the message between the two control stations by an appropriate constant factor.

III. RESEARCH ASPECT

In order to ensure guaranteed medium access and, hence, upper bounds on the delay for transmitting packets between two stations, we follow a token passing approach. A token is a special packet that indicates the exclusive right to use a medium. In contrast to polling-based schemes, the token approach allows for a decentralized transmission scheme, and, hence, circumvent the single-point-of-failure problem. This is particularly relevant for the hard real-time regime in which high reliability and robustness is of eminent importance.

The downside of the token passing approach is a loss in efficiency since a certain amount of capacity has to be devoted to token transmission. Furthermore, the decentralization necessitates the protocol to be self-configurable and to be failure tolerant, e. g., if a station quits unexpectedly, or leaves the transmission range. These aspects require a more involved protocol than CSMA. We decided to base our protocol on the Wireless Token-Ring Protocol (WTRP) proposed in [5]. In opposition to WTRP, we explicitly assume that all stations are within the same collision domain making the token ring on a physical level essentially a token bus. On a logical level, the ring structure is preserved. Moreover, various protocol aspects had to be streamlined, removed, and added to match the hard real-time requirements.

The finite state machine describing our TPMA implementation is given in Fig. 2. The states can be divided into several categories. The states *Sending*, *Monitoring* and *Idle* form the actual core of the protocol. The other states are used for joining, leaving, and resolution of failure situations. Proper protocol operation is enforced by a set of special procedural actions encompassing exchange of special configuration packets and extensive usage of various timers. A key research aspect in the TPMA implementation is the explicit specification of an upper delay bound. In contrast to the WTRP protocol, in the TPMA all timer values are set according to this bound. Furthermore, when deriving the appropriate timer values, several failure cases are taken into account. This means that the timer values are chosen such that even in a beforehand defined worst-case scenario, the ring is still fully functional with respect quality-of-service requirements. This effectively also limits the number of stations that can be supported per ring: Demanding tighter deadlines reduces the number of stations per ring.

Further research and development problems arise in the context of the underlying hardware. Since we are using an FPGA-based development board and due to the inherent limitations in terms of computational power, we have to adapt some of the protocol aspects, especially those encompassing extensive calculations. Also, the underlying implementation of an OFDM physical layer imposes certain implementation challenges that have to be solved, e. g., the lack of an interrupt based event-handling system.

IV. SETUP REQUIREMENTS

The following listing shows the necessary space and additional facilities that are required for our demonstration:

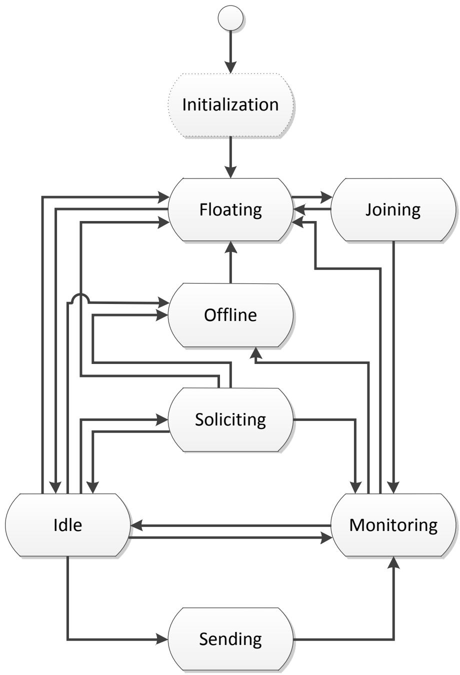

Figure 2. Finite State Machine of TPMA

- Table (at least $1.6\,\mathrm{m} \times 0.8\,\mathrm{m}$)
- 7 power sockets (preferably two different electric circuits)
- Free wireless channel in $2.4\,\mathrm{GHz}$ or $5\,\mathrm{GHz}$ ISM band

Note that especially the last item is of importance since the MAC scheme to be presented is not designed to cope with interference. The setup time of our demonstration is roughly $30\,\mathrm{min}$.

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