EchoRing: Meeting Hard Real-Time Constraints with Decentralized Wireless Networks

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***Abstract*—Given the rising demand for wireless solutions in the area of machine-to-machine communication, we present the novel EchoRing protocol. It is designed to serve the communication needs of industrial applications, while being optimized for the wireless channel specifically. Directly taking known principles of tethered communication to the wireless domain is likely to yield degraded performance results. Additional techniques have to be added to make known principles be able to master the challenges of wireless channel dynamics. On the other hand, the majority of currently existing wireless communication standards are developed to allow mobility on the last hop of a transmission path that originates in the Internet or a local home network. Hence, the focus is on supporting the best-effort paradigm of the data streams. However, in industrial environments this best-effort paradigm gets replaced by the need to steadily achieve very high reliabilities at very short deadlines.**

In this demonstration, we will show how industrial applications can be interconnected wirelessly despite the drawbacks of the wireless channel. The experimental setup allows to compare different medium access control protocols under varying conditions.

I. Motivation

Over the past decades, wireless solutions were mainly driven by human-to-human interactions with relaxed transmission requirements. For the emerging paradigm of fully-automated machine-to-machine communication, however, transmissions have to realized extremely reliably at very short timescales of only a few milliseconds. Applications that possess these stringent transmission requirements can be found in the areas of factory automation (discrete goods), process automation (continuous goods), smart grid synchronization, or vehicular networks [1]. Most processes in these domains are carried out with cables until now. These wired connections impose costs for installation and maintenance. Moreover, cables pose a burden on the applications with respect to flexibility.

Wireless solutions alleviate many of these restrictions and costs. They face other obstacles though. Two major challenges affecting the reliability and scalability of wireless systems are:

Wireless channel dynamics: As the transmission quality can vary significantly across the important dimensions of time, frequency, and space, the wireless channel is inherently unreliable. In contrast to cable connections whose error characteristics typically follow a slowly changing behavior (e. g., broken cable), mobility of the stations and mobility in the environment cause the transmission quality to change on a much shorter time scale. This is caused by wireless propagation effects, like multi-path fading.

Broadcast nature of the medium: While two stations need to be explicitly connected in case of tethered communication, the wireless medium interconnects all stations within transmission range automatically due to its broadcast nature. This mandates careful design of multiple access schemes to increase the transmission capacity that the wireless medium offers.

Considering the tough requirements of industrial applications, it becomes apparent that channel dynamics pose the biggest threat on a reliable transmission at very short latencies. It is clear that directly applying principles of tethered systems cannot meet the demands of industrial applications. The same applies to wireless systems designed to fulfill only relaxed constraints. Hence, we take well-known principles and adapt them to fit the application constraints on the one hand, and to respect the nature of the wireless medium on the other hand.

We propose the novel EchoRing protocol, which is an evolved token-passing scheme extended with cooperative communication techniques. The innovation stems from the fact that this protocols allows a decentralized operation of a wireless network, while ensuring very short latencies for all stations in the network. Relaying as a form of cooperative communication helps in stabilizing the network and improving the reliability of the data transmission at no additional cost: The token exchange is used for channel estimation and relay selection. Despite the overhead of maintaining a stable network, we see that this protocol is able to achieve virtually error-free transmissions for latencies of a few milliseconds. Contrary to other research in this area, we have been evaluating the applicability of the EchoRing protocol for longer periods of time using experimental setups, and thus, can confirm the suitability for the envisioned use cases.

II. Related Work

Wireless protocols can be categorized as delay-aware and / or reliability-aware with varying granularity (improve or guarantee either or both metrics) [2]. Since the biggest driver of wireless networks in the past decades was human-to-human interaction, the vast majority of protocols proposed in literature tries to decrease transmission errors while keeping delays "sufficiently" short. Surveys [1], [2] indicate that current standards, as for example `ZigBee` or `IEEE 802.11`, but also

specialized wireless protocols lack to address the requirements of industrial applications. Only few protocols were designed as being aware of delay and reliability, e. g., GinMAC [3], Burst [4], WISA / WirelessHART [5], or SERAN [6]. Unfortunately, most of them are either very specialized (e. g., known, fixed environment required), require central coordinators, or are only evaluated using simulations [7].

III. System Description

The proposed EchoRing protocol is a Data Link Layer (DLL) protocol that extends the well-known token-passing principle [8], [9]. However, the error recovery mechanisms need extensive modifications to deal with the inherently dynamic nature of the wireless channel. Transmission errors caused by multipath fading may make a link appear to be broken. Instead of immediately changing the network topology to deal with the error, the network can in certain cases stick to the current topology and recover from the error quickly. In addition to these evolved failure recovery mechanisms, we introduce cooperative relaying. By taking advantage of spatial diversity, token and data packets can be retransmitted from other stations in case of errors. In order to determine a station that relays a packet, a station needs Channel State Information (CSI). By using a token-passing medium access scheme, this CSI can be collected without any additional overhead in terms of probing packets. Furthermore, due to its frequent and periodic token exchange, the obtained CSI is accurate enough to avoid outdated information. The combination of these two techniques allows the EchoRing protocol to achieve error probabilities in the range of $1\text{E-}5$ or better for latencies of only $5 - 10\,\text{ms}$, despite using a non-optimized Physical Layer (PHY). Otherwise, the overhead of maintaining a stable ring topology results into worse system performance as compared to Carrier-Sense Multiple Access (CSMA) schemes.

The current state of the software is an advanced demonstrator. It is running on the FPGA-based Wireless Open-Access Research Platform (WARP) [10] designed to cater experimental evaluations of wireless communication protocols. Measurement campaigns of different versions of the EchoRing protocol have been tested in various environments and resulted in a better understanding of the protocol.

IV. Demonstration Description

In the demonstration, we will give the audience the possibility to test different DLL protocols and let them examine the effect of the respective protocol on the transmission characteristics. The following DLL protocols will be available for testing

- EchoRing protocol as explained in Sec. III,
- RecoveryRing protocol (no relaying functionality),
- BasicRing protocol (plain token-passing scheme), and
- CSMA protocols with different parameterizations

Four WARP boards are interconnected wirelessly by running these DLL protocols (see Fig. 1). In addition, a laptop is used to monitor the actual performance of the system. The evaluation program on the laptop allows an online analysis of

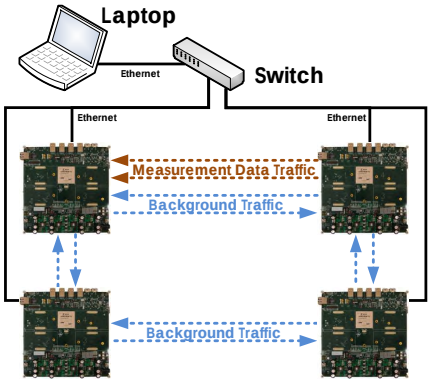

Fig. 1. Experimental scenario

- packet delivery ratio,
- delay characteristics of data packets, and the
- selection of relays.

The audience can interact and experiment with the system by choosing one of the available DLL protocols and by changing the parameters of the systems, or by covering certain transmission paths. Changeable parameters include

- data packet size,
- number of retransmissions,
- target delays,
- transmission power, or
- system load.

In order to allow the audience an intuitive way to assess the suitability of the protocol for specific use cases, we visualize which use cases can currently be supported given the current transmission conditions.

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