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Dynamic Reconfigurability of Wireless Sensor and Actuator Networks in Aircraft

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***Abstract*—The wireless spectrum is a scarce resource, and the number of wireless terminals is constantly growing. One way to mitigate this strong constraint for wireless traffic is the use of dynamic mechanisms to utilize the spectrum, such as cognitive and software-defined radios. This is especially important for the upcoming wireless sensor and actuator networks in aircraft, where real-time guarantees play an important role in the network. Future wireless networks in aircraft need to be scalable, cater to the specific requirements of avionics (e.g., standardization and certification), and provide interoperability with existing technologies. In this paper, we demonstrate that dynamic network reconfigurability is a solution to the aforementioned challenges. We supplement this claim by surveying several flexible approaches in the context of wireless sensor and actuator networks in aircraft. More specifically, we examine the concept of dynamic resource management, accomplished through more flexible transceiver hardware and by employing dedicated spectrum agents. Subsequently, we evaluate the advantages of cross-layer network architectures which overcome the fixed layering of current network stacks in an effort to provide quality of service for event-based and time-triggered traffic. Lastly, the challenges related to implementation of the aforementioned mechanisms in wireless sensor and actuator networks in aircraft are elaborated, and key requirements to future research are summarized.**

Keywords*—*dynamic network architecture, avionics, wireless sensor networks, cognitive radio, dynamic configurability

I. Introduction

In the last decades, the field of wireless communication has experienced enormous growth [1], and the necessary resources for communication (i.e. wireless bandwidth) have become increasingly scarce. The high demand on spectrum bands between 1 and 5 GHz raises the interest in efficient ways of handling communication resources, especially spectrum utilization [2]. Over time, analog systems have been replaced with their digital successors, providing higher immunity against noise and interference, better performance in optimizing resources, as well as a lower latency and compact size. Today, advanced digital communication technologies allow wireless transceivers to be used in domains that require reliable and low latency real-time data exchange, such as aerospace applications.

The use of radio communication in aircraft, known as Wireless Avionics Intra-Communication (WAIC) systems, is expected to provide means of communication in an aircraft for several wireless applications. It is becoming more popular with the release of radio spectrum band of 4.2 - 4.4 GHz for specific usage in WAIC [3]. One practical example for the use of WAIC is the implementation of wireless sensor and actuator systems in aircraft. This trend accomplishes a weight reduction, and eases the process of adding or changing sensory systems in the cabin interior. In addition, it aims to simplify layout design and reduce the cost of maintenance originated from damaging or ageing of cables. The configurable hardware technologies are regarded as promising candidates to enable the reconfiguratibility of WAIC systems.

Reconfigurability in wireless domain has first been introduced within the context of Software-Defined Radio (SDR), in which the (de)modulation of transmitter/receiver are implemented by means of software. Such flexible architectures have gained importance with the need of multi-purpose and multi-standard usage. As an example for the evolution of SDR, the concept of Cognitive Radio (CR) has been introduced in 1999 by Mitola in [4], which has constituted the fundamentals of spectrum awareness. Spectrum awareness is foreseen to play an important role in the WAIC transmission medium, since aircraft radio transmission medium is becoming more dense with the usage of Personal Electronic Devices (PEDs) and Wireless Local Area Network (WLAN) on board, as well as with the new sensory and actuator systems. In a constrained area of operation, many systems have to work together without interfering each other. Meanwhile, Communications, Navigation and Surveillance (CNS) systems with high safety and reliability requirements must operate regardless of conditions. Therefore high interference regulations must be applied. As a solution to these concerns, the use of SDR in WAIC is a novel approach which aims to bring up the reconfigurability aspects in order to optimally utilize the spectrum.

This paper reviews several methods of dynamic reconfigurability within wireless networks in aircraft. Our main motivation is to analyse methods that make the dynamic resource allocation possible in several stacks of a wireless network, i.e. from network to application level. The assessment of these aspects in the development stage aims to reduce cost of modification of the network in the implementation stage.

This paper proceeds as follows: In Section II, an overview on current data-networks and wireless technologies in aircraft is given as state of the art. In Section III, on current network the resource management possibilities and introducing a spectrum agent in an aircraft are discussed. Moreover, the feasibility of a combined event- and time-triggered paradigm and the cross-layer communication design are presented. In Section IV, challenges of aforementioned methods are summarized. Finally, the concluding remarks and future work are discussed in Section V. For simplicity, the wireless network as a term is used to address wireless sensor and actuator network.

II. State of the Art: Data Networks and Wireless Technologies in Aircraft

The data networks in avionics either wired or wireless can be evaluated according to six main system criteria: performance, reliability, security & certification aspects, cost, supportability & logistics, and flexibility & ability to evolve [5]. Wired network in aircraft has been evolved within years and nowadays Avionics Full Duplex Switched Ethernet (AFDX) has been used to provide a deterministic protocol for real-time communication [5]. One of the main features that makes AFDX remarkable is the usage of virtual links, which enables data exchange in a flexible manner with low latency, as well as adding expansion capabilities to the data network. However, in comparison to wired data networks, wireless networks are non-deterministic, which requires advanced methods to satisfy aforementioned six criteria, especially for safety-critical applications.

The interest on wireless networks in aircraft has risen in last decade. The main focus has been given to non-critical and monitoring systems with less stringent safety and reliability requirements [6] and thereby the main approach is to deploy systems or network in aircraft by inheriting the currently available Commercial-off-the-Shelf (COTS) standards [7]. The low-power sensor network is one of the inherited technologies, which is mostly investigated. Even though recent advances provide high data-rate and low latency in data exchange in the field-of low-power sensor networks, these standards are commonly used for non-critical applications [8]. Therefore, directly inheriting a standard from COTS for wireless networks, especially for safety-critical applications, is not feasible.

In this regard, tactical networks are analyzed, where data-reliability and security has been always a vital issue. Several methods, such as Direct-Sequence Spread Spectrum (DSSS) and Dynamic Spectrum Access (DSA) methods have been originated from tactical communication to overcome noise and/or malicious attacks, thereby increasing the reliability of communication. In this regard, dynamic reconfigurability to obtain reliable data in tactical networks is widely investigated. Dynamic reconfigurability is addressed in [9] not only in terms of spectrum but also of network reconfigurability, which shows the effectiveness of these methods to improve reliability and cope with dynamic changes in transmission medium that makes it a promising approach to be applied on wireless networks in aircraft to ensure reliable data communication.

III. Reconfigurability in Wireless Networks

This section presents dynamic reconfiguration approaches that represent candidate solutions for their implementation in aircraft wireless network in order to meet the requirements of avionics.

A. *Resource Management*

The resource management in wireless systems mainly deals with two resources: the wireless transceiver as a device and the transmission medium. A transceiver generally contains computing resources, memory and input/output connections. While transceivers are often manufactured as dedicated integrated circuits due to the high cost pressure, Field-Programmable Gate Array (FPGA)-based SDRs provide reconfigurable resources to enable multi-standard and multi-purpose usage. The increasing complexity and number of functions in avionics has raised the interest concerning the use of FPGA [10]. This includes its utilization for military avionics [11]. Moreover, the advantages of weight reduction and compact size make FPGAs more attractive particular in avionics [12]. Therefore, several vendors offer FPGA platforms compliant with the military and aerospace standards with low power consumption, high computation capability and reliability, as well as guidelines for certification according to DO-254 and DO-178 [12]. On top of that, vendors have begun to provide Intellectual Property (IP) cores for rapid prototyping. In particular, in wireless domain several stacks can be implemented swiftly with the use of IP cores. This reduces the time for development of complex systems.

The radio spectrum is regarded as the main resource in the context of wireless communication. The radio spectrum can be shared in different dimensions, such as time (TDMA), frequency (FDMA), code (CDMA) or by location. Traditionally, a given frequency spectrum is assigned to a certain user by the regulatory authorities for a fixed time interval or location. Due to the growth in wireless usage, the fixed granting schemes have led to inefficient use of spectrum [13]. Such a waste of valuable spectrum poses challenge for future upcoming systems. These systems must cope with strict interference avoidance schemes and will be required to move from their preferable spectrum bands to higher frequency bands. This will lead to high path-loss, a distinct disadvantage for low-power applications [2]. On these grounds, the dynamic frequency allocation (e.g. through cognitive radios) is a growing research area, which enhances the spectrum efficiency, by real-time assessment of the radio spectrum.

B. *Spectrum Awareness in Wireless Networks in Aircraft*

Observing the spectrum and reacting accordingly is the concept that has been introduced with CR. In wireless networks, with the increase of wireless traffic, the awareness of the transmission medium becomes crucial which enables identification of available resources in real-time. In addition, when the network becomes conscious of its surrounding, it may even be able to detect malicious network access attempts in the limited area of aircraft cabin. The identification and neutralization of unauthorized channel access results in a certain level of safety and security.

In general, the observation of spectrum is implemented as an additional functionality in each device (e.g. to perform a clear-channel assessment). Thus, it is anticipated that each wireless network device can be capable of sensing traffic while not actively communicating. It needs to be noted, however, that adding sensing capabilities to these devices results in a higher power consumption. Additionally, since the application device can not send the information and sense the spectrum instantaneously, it causes a delay in either the data flow or the spectrum sensing. A further drawback is the processing complexity, thereby the need of advanced hardware, which increases the cost.

Instead of adding sensing functionality to each sensor/actuator unit, the introduction of a separate spectrum sensing entity, called a Spectrum Agent (SA), with complex sensing capabilities has been proposed as a more effective approach. SAs have originally been introduced for 5th Generation (5G) Wireless Networks [14], yet their use in other network types (such as wireless networks in aircraft) appears promising. The spectrum agent is a device with wideband sensing capabilities and high performance to cope with fast computing tasks. It can provide the spectrum utilization information to the network within a short period of time. The main aim of removing cognitive features from the application is to reduce the cost of complexity and retain the low-power consumption of sensor applications in the wireless network. With the introduction of SAs, complex sensing schemes can be implemented, which provide more reliable information about the transmission medium. In addition, the extraction of overhead related to sensing from the information routing, simplifies the data flow.

C. Combined Time-and Event Triggered Scheduling

The wireless network in aircraft is the substrate for several sensor and actuator applications [15]. It needs to provide a certain flexible structure in order to fulfill the requirements of each application's traffic flows. A fixed resource assignment might result in inefficiency and poor Quality-of-Service (QoS). The interaction with the environment and reconfiguration of the resource according to the application increases the QoS, while keeping the system up-to-date with the current degradation in the network. Another aspect which has to be the considered is the occurrence pattern, which exploits the functional behavior of the system: time-triggered or event-triggered. Time-triggered applications are conducted based on pre-defined scheduling, which is suitable for quasi-deterministic application, such as monitoring tasks [16]. An example would be landing gear monitoring where the landing gear monitoring sensor is scheduled to observe the behavior of the landing gear periodically in certain flight phases. It is the advantage to assess the resource offline and devote it for the given slot of time. In wireless network in aircraft, the execution of most applications is expected to depend on the flight phase [15], so the information of the current flight phase can be used as an input for the dynamic reconfigurability, e.g. to schedule the time-triggered event. When the spectrum is not in use for the time-triggered application, it can be assigned to another application, e.g. by employing hybrid medium access control protocols that allow for the re-use of assigned time slots in case no time-sensitive traffic is being detected.

Reconfigurability can also lead to benefits for event-triggered applications in avionics. Applications like aircraft illumination control and passenger service units can be categorized as event-triggered activities. The main advantage of event-triggered networks is the capabilities of coping with the dynamic changes and responding swiftly, which keeps the network aware of its resources and accommodates these resources efficiently.

The combination of time- and event-triggered schemes is area of interest in car industry and industrial controllers [17]. The mixed architecture improves the separation between events to reduce the congestion in the network. Mixed time- and event-triggered scheduling is a rapidly growing field of interest, hence several scheduling algorithms and standards are investigated, such as slot-shifting algorithm and Time-Triggered Controller Area Network (TT-CAN). Slot shifting mechanism analyses the offline-scheduled event and finds the idle resource, in which later the event-triggered applications are accommodated. This algorithm can be a promising candidate for wireless network in aircraft.

Besides from reconfigurability the scalability can be achieved in combined-triggered networks. Therefore, a new application can be easily introduced in an existing wireless network. The scalability of a wireless network is a key requirement, since the wireless network in aircraft will be expanding rapidly with the new applications that are listed in [15]. As it is stated in Section II, flexibility & ability to evolve is one of the main system criteria in avionics, which can be held with the approach of proposed combined event- and time-triggered schemes.

D. Cross-layer Dynamic Configurability Aspects

Network stacks have been traditionally designed in a layered fashion. Cross-layer interdependencies have been intentionally excluded, in order to obtain an abstract distinction between layers and reduce the complexity of design with encapsulating layers. However, this reduces the capabilities of exchanging information between layers that may cause a reduction of QoS and increase in latency. The concept of cross-layer based reconfigurability at wireless networks in aircraft is envisioned to enable interaction between several layers and alternate parameters according to input of several layers, therefore reliability and security of the data-exchange can be improved. In this regards, the paradigm of sharing information can be carried out by using a manager or direct information exchange [18]. In the non-managed method, layers exchange information directly, whereas in the managed method, a cross-layer manager (or optimizer) is introduced to extract information and fuse into a decision unit [19]. The non-managed and managed methods can be implemented on current network stacks, but it requires modifications in functionality and interaction mechanisms of some layers. The non-managed method enables data exchange between any two layers. It does not make use of information from all layers, but it can improve the performance depending on the application [18]. Wireless networks will be designed to accommodate several sensor and actuator applications, which will require flexible structures to fulfill the requirements of each application. A fixed layered approach often results in inefficiency and poor QoS. To obtain the required QoS within a varying transmission environment, the interaction between layers is thus crucial, because decisions on data transmission depend on several parameters or measures that are obtained from several layers. Table 1 shows the parameters and functions in each communication abstract layer, which can be used to reconfigure the transmission in wireless networks. The flexibility in several layers can have the potential to improve throughput and QoS [20].

TABLE I. RECONFIGURABILITY ASPECTS OF LAYERS

Layer	Reconfigurable Parameters & Functions
Physical	Flexible hardware design, beamforming, variable transmission power, modulation and coding scheme, operating frequency.
Data Link	Scheduling, transmission rate, frame length, transmission scheme.
Network	Routing, learning traffic pattern.
Transport	Retransmission, congestion avoidance.
Application	Security mechanisms, application-dependent parameters, user interaction, QoS requirements.

Currently, security mechanisms are implemented in many layers separately, such as key exchange before establishing link in application layer. In a cross-layer design, a dedicated security plane is an approach to implement security mechanism based on cross-layer optimization [21]. The security plane consists of encryption and security mechanisms that extract information from several layers. When properly designed, it would be expected to meet the strict security requirements of wireless systems in aircraft, since the main concern while implementing wireless communication in avionics is safety and security. Moreover, in-cabin applications should fulfill confidentiality, integrity, and availability requirements to ensure the level of reliability. Fig. 1 shows the alignment of security plane with the layers in relation to the layered communication stack, and also highlights the spectrum agent. The SA observes the transmission environment and provides feedback to several layers of the communication system via the cross-layer manager. Meanwhile, the security plane carries out the security missions in several layers. All the inputs from SA and cross-layer manager are used for decision making to obtain high QoS and fulfill the requirements of each application [19].

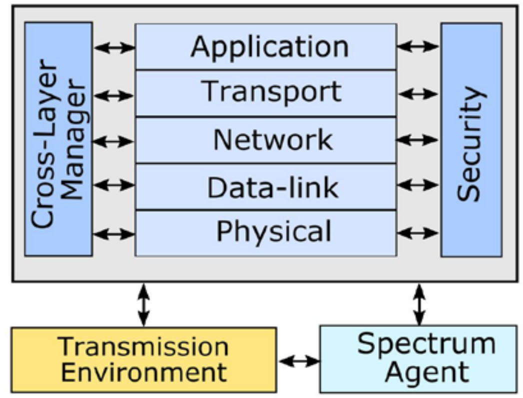

Fig. 1. Cross-layer scheme with a cross-layer manager and its relation with spectrum agent and security plane

Introducing a cross-layer manager to a system enables the seamless interaction between layers. Therefore, information collected in several layers is used to solve the problems like poor link quality or power saving constraints for low-power sensor application in aircraft. In addition, the collected information can be merged by the Spectrum Agent and more accurate decisions about the transmission environment of the wireless network can be provided. Accurate reactions to changes in transmission medium aims to improve channel quality, resulting low Bit Error Rate (BER) or latency.

IV. Dynamic Reconfiguration Challenges in Wireless Networks in Aircraft

This section presents selected challenges of dynamic approaches in wireless networks in aircraft, which need to be considered during the design and implementation phases. We particularly discuss the key problems: lack of standardization of wireless networks with features required in avionics applications, interoperability of cross-layer designs, and the increasing complexity and scalability requirements to networks with an increasing number of applications deployed in aircraft.

A. Standardization of Wireless Network with Dynamic Configurability

As every novel field of application, the standardization is a lacking area at the beginning of development of wireless networks in aircraft. With the expanding of applications, the standards reach inevitable growth, such as standards in mobile communication. Dynamic configuration is an area to be further researched and requires definition of clear guidelines and standards to accomplish to fulfill the strict certification procedures of avionics. As it is mentioned in Section II, certification aspects is one of the criteria that have to be considered starting from the concept to production stage of a system in avionics. Even though several proposals for cross-layer coupling methods are available in the area of cross-layer design [22], a common standard or approach is not available, which might not be a crucial issue for several application fields, such as home automation, but in case of avionics, standards are essential to cope with the certification process and obtain a unique system, which can be standardized world-wide.

B. Interoperability of Cross-layer Designs

There are several challenges in the field of cross–layer design related to the specific application. However, the common and fundamental challenge is the interoperability of cross-layer design with existing wireless networks standards, which are based on traditional layer-based approach. They are well-established and commonly used in several fields. The coexistence of cross-layer design with them should be clearly defined. Such as the coexistence of cross-layer designed wireless network in aircraft with WLAN on board should be further investigated to enable them to operate harmonically. To avoid the interference in Radio Frequency (RF) domain, different transmission frequencies are selected for wireless applications in aircraft. However, to overcome the signal congestion in the network, defined interoperability mechanisms are required, which is highlighted as one of the challenges.

C. Scalability of the Wireless Networks

With increase in number of WAIC applications, the wireless network in aircraft will become more complex over the years. The applications have to share the same network to accomplish their missions. As the traffic in the network increases, managing the dynamic behavior becomes more complex. As it is mentioned in Section II, one of the evaluation criteria for avionic systems is flexibility & ability to evolve. In this regards, the wireless network should be scalable to accommodate various applications. Therefore the event-time triggered hybrid approach can be a promising method to overcome scalability problems of the network.

V. Concluding remarks and Future Work

The application fields of wireless systems are expanding enormously and fixed spectrum allocation, well-established layered architectures and purely time-triggered paradigms do not fulfill the needs of advanced systems expected in future aircraft. This paper shows how dynamically reconfigurable approaches can be used to provide the foundation for the novel networking concepts required in aircraft in order to realize scalable and secure wireless sensor and actuator networks. Through the use of reconfigurable wireless architectures, a high QoS level can be attained and maintained, even when the characteristic of the transmission medium changes. Several promising techniques for dynamic reconfigurable wireless networks in aircraft have been highlighted, which are suitable for future research.

As next step, cross-layer approach with Spectrum Agent in the network is aimed to be simulated for evaluation of the performance in terms of throughput, delay and power consumption. In addition, analysing the reliability of the dynamic network under malicious attack is also considered as a part of the future research.

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