Digital Communications
hrsg. von Prof. Dr.-Ing. Peter Adam Höher

Alaa Mourad

On the Coexistence of Bluetooth and WLAN for On-board Infotainment Applications

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On the Coexistence of Bluetooth and WLAN for On-board Infotainment Applications

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For my mother, who left me in 2017, my father, Mayssa, Iyad, Fikrat, Karim and Mira

Preface

I still remember my first days at the university of Kiel, it did not stop snowing for few weeks. Although I used to like the snow, it did not take me long to hate it. I have not seen the sun for few months, furthermore, living in a new country, it was not easy to start master studies. However, I tried to focus more on studying and suddenly I was adopted to everything new and the life moved forward.... For sure big thanks to Laila who supported me during my master studies, which was not easy for her as well.

After my master degree, I was sure that I want to do a doctorate but the time was not suitable for that. Although I got many offers to do a PhD at my university, I took the risk and I said no. This was not an easy decision but well sometime you have to be brave and take such a decision in life. However, I was sure that I will return to the university for a doctorate one day.

I worked after that for two years then I thought this is the best time to take a step towards my dream and do a doctorate. Well, this was not an easy decision as well, changing from a team leader to a poor PhD student was not easy! But I took the risk again. The first few months as a PhD student at BMW group was very difficult then everything was better in the second year. I would like to thank all my colleagues and friends at BMW for supporting me especially: Saad Hafsa, Tobias Diekmann, Daniel Appadurai, Roman Roor, Svenja Meisnner, Thomas Meisnner, Mariam Jaber, Walter Bronzi and Alexander Krebs.

I would like to thank Prof. Peter Adam Hoeher who supported my during my master and doctorate studies, I appreciate your time and help. Many thanks to Prof. Hazem Refai who gave me the chance to do an internship at the university of Oklahoma in the USA. I would like to thank my best friends at university of Oklahoma, especially Omar al-Kalaa and Siraj Muhammad. Of course I want to thank my family, although my mother can not read this but I am sure she is in the sky and proud of me, my father, without him I could not continue my studies abroad.
Life moves on, one journey is finished, many new journeys are on their ways...

Alaa Mourad

Munich, 17.02.2019

Kurzfassung

Fahrzeugführer und deren Mitfahrer erwarten heutzutage eine nahtlose Integration ihrer Mobilgeräte in das Fahrzeug Infotainment System. Diese Erwartungshaltung stellt einen neuen Entscheidungfaktor bei der Wahl eines Telematiksystems und dem Kauf eines Fahrzeugs dar. Um diesem Anspruch zu genügen, widmen Fahrzeughersteller diesem Feature besondere Aufmerksamkeit und stellen bedienungsfreundliche und vielseitig verwendbare drahtlose Kommunikationstechnologien in ihren Fahrzeugen bereit. Diese Dissertation betrachtet die Verwendung des weit verbreiteten IEEE 802.11 und des Bluetooth Funksystems im unlizensiertem und eng frequenzbegrenztem 2.4 GHz Band. Ein besonderes Hindernis für Koexistenz in diesem Band stellt der Aspekt der Mobilität des Fahrzeugs und die hohe Anzahl von Empfanggeräten in dem räumlich begrenzten Innenraum des Fahrzeugs dar.

In dieser Arbeit werden umfangreiche Messergebnisse aus praktischen Versuchen vorgestellt. Die Mehrkanalinterferenz zwischen mehreren WLAN Drahtlosnetzwerken zwischen nebeneinander positionierten Fahrzeugen mit Antennenpositionen an verschiedenen Verbauorten des Fahrzeugs wurden hierfür untersucht. Das Mehrantennenprotokoll (MIMO) des 802.11 Standards wurde unter Berücksichtigung mehrerer Leistungsmodi untersucht. Ebenso wurde der Bluetoothempfang in WLAN Interferenzszenarios untersucht. Im Gegensatz zu bekannten Arbeiten war die Grundlage zu dieser Arbeit die vollständige Auslastung des WLAN Netzwerkes auf den Kanälen 1, 6, und 11. Die daraus erhalten Ergebnisse verdeutlichen, dass das Auftreten von Kollision unvermeidlich ist. Ebenso zeigte sich, dass das am weitesten verbreitete Verfahren, Adaptive Frequency Hopping (AFH), nicht geeignet ist, um eine Linderung des Problems zu erreichen. Messergebnisse aus einem Laborversuch verdeutlichten, dass music streaming und hands-free calling im Bluetoothnetzwerken hierduch besonders beeinträchtigt sind.

In Feldversuchen wurden die Auswirkungen der Reisegeschwindigkeit von Fahrzeugen untersucht. Aus diesen lässt sich die Erkenntnis gewinnen, dass die Funkinterferenz selbst bei hohen Geschwindigkeiten nicht vernachlässigbar ist. Testfahrten in Ingolstadt zeigten hierzu deutliche Auswirkungen insbesondere bei Fahrten durch die Innenstadt auf, in der sich eine große Anzahl von WLAN Hotspots befanden. Im Gegensatz dazu zeigte sich, dass der Effekt auf Autobahnfahrten vernachlässigbar ist.

Um den Bluetoothempfang in Mehrwegeausbreitungsszenarien innerhalb von Fahrzeugen zu verbessern, wird hierzu ein Bluetooth Detektor mit niedriger Komplexität zur Implementierung vorgeschlagen, der auf dem Post Detection Integration (PDI) Prinzip basiert. Hierzu wurden Physical Layer Simulationen zwischen WLAN und Bluetooth durchgeführt. Die Messergebnisse aus diesen Simulation zeigen auf, dass bei hohem signal-to-interference-plus-noise ratio (SINR) der PDI Detektor den Bluetoothempfang deutlich verbessern kann.

Weiterhin wird in dieser Arbeit ein Bluetooth Busy Scheduler (BBS) Koexistenz Mechanismus vorgestellt. Dieser Mechanismus verbessert die hands-free Telefonie Performanz in einem durch WLAN gestörtem Szenario innerhalb des Fahrzeugs durch ein Synchroneous Connection Oriented (SCO) basiertes Stützverfahren. Hierbei wird ein scheduling Signal zur Synchronisation der Funknetze durch einen speziellen Sender in das Fahrzeug eingebracht, mit dessen die Verwendung von Bluetooth bei niedrigem bis mittlerem Durchsatz des WLAN Netzes deutlich verbessert werden konnte.

Stichwörter: Koexistenz, Bluetooth, WLAN, Interferenz

Abstract

Car drivers and their passengers have come to expect seamless integration of their personal consumer electronic (CE) devices with their car's infotainment system. This new demand makes telematics a decision factor for consumers choosing between different car models. In response, car manufacturers are giving this feature increased attention, migrating user-friendly, flexible wireless communication systems into their car designs. This dissertation reports on widely used IEEE 802.11 and Bluetooth solutions operating in the spectrum-scarce 2.4 GHz unlicensed industrial, scientific, and medical (ISM) radio band. Facilitating their coexistence is challenging, primarily due to the unique mobility effect in the automotive environment, as well as the high density of devices often located in a small geospatial area.

In this work, extensive real-word measurements are reported. WLAN co-channel interference in the automotive domain was studied by measuring interference between neighboring cars equipped with an antenna positioned in various locations. 802.11 standards with multiple input multiple output (MIMO) and power control solutions are examined. Bluetooth performance under WLAN interference was also investigated. Unlike previous work, the research reported herein centers on the effects of WLAN occupying the entire 2.4 GHz spectrum (i.e., channels 1, 6, and 11). Results suggest that collisions are unavoidable. The most widely adapted mechanism for coexistence, namely adaptive frequency hopping (AFH), was shown to be ineffective at mitigating the problem. Lab measurements for both Bluetooth hands-free calling and music streaming illustrate that Bluetooth performance is strongly affected.

Real-world experiments testing the mobility effect of automobile traveling at various speeds, including relatively high speeds, indicate measurable interference. Test drives in Ingolstadt, Germany illustrate significant consequences from surrounding WLANs on on-board networks, especially in the city center where a significant number of WLAN hotspots are deployed. Conversely, the effect during highway travel is negligible.

A low-complexity, Bluetooth detector based on post detection integration (PDI) was proposed to improve Bluetooth performance in multipath channels, such as those in an in-car environment. Physical layer simulation for coexistence between Bluetooth and WLAN was performed. In high-density deployment scenarios, collisions between the two systems is inevitable. In high signal-to-interference-plus-noise ratio (SINR) region, the PDI detector yields good performance, but bit error rate (BER) saturation is visible.

A Bluetooth busy scheduler (BBS) coexistence mechanism is also presented in this work. This technique aims at protracting the in-car performance of Bluetooth hands-free calling using a synchronous connection oriented (SCO) link in the presence of high WLAN

interference from the surrounding environment. By leveraging a special transmitter to deploy a scheduling signal synchronized with an in-car Bluetooth SCO deterministic traffic pattern, Bluetooth performance was significantly improved, and the effect on WLANs operating with low to medium throughput was limited.

Keywords: Wireless coexistence, interference, Bluetooth, WLAN, infotainment systems

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