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Coexistence issues for a 2.4 GHz wireless audio streaming in presence of bluetooth paging and WLAN

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Abstract. Nowadays, customers expect to integrate their mobile electronic devices (smartphones and laptops) in a vehicle to form a wireless network. Typically, IEEE 802.11 is used to provide a high-speed wireless local area network (WLAN) and Bluetooth is used for cable replacement applications in a wireless personal area network (PAN). In addition, Daimler uses KLEER as third wireless technology in the unlicensed (UL) 2.4 GHz-ISM-band to transmit full CD-quality digital audio. As Bluetooth, IEEE 802.11 and KLEER are operating in the same frequency band, it has to be ensured that all three technologies can be used simultaneously without interference. In this paper, we focus on the impact of Bluetooth and IEEE 802.11 as interferer in presence of a KLEER audio transmission.

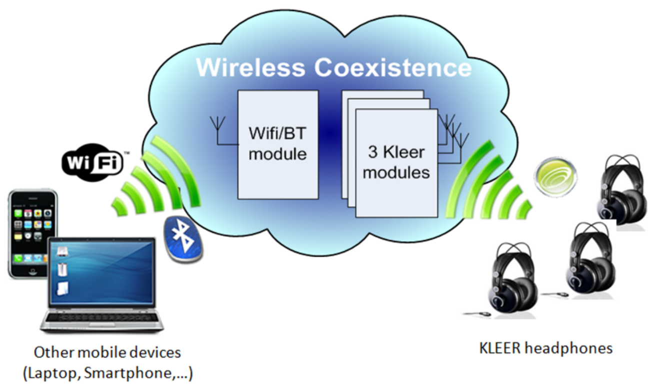

Figure 1. Considered wireless architecture.

1 Introduction

This paper addresses the impact of an IEEE 802.11b/g and a Bluetooth system on a KLEER audio transmission. The considered wireless architecture includes a WiFi (IEEE 802.11b/g) combo module and three independent KLEER sources which allow three independent audio streams (see Fig. 1).

KLEER from SMSC is a short-range radio interface in the 2.4 GHz frequency band that is designed for lossless 44.1 kHz-sampled 16 bit stereo audio transmission in full CD quality (see SMSC, 2007a, b; Devries et al., 2009; Mason et al., 2009). A lossless audio compression is used to reduce the required net data rate of 1.4112 $\mathrm{Mb\,s^{-1}}$ to approximately 1 $\mathrm{Mb\,s^{-1}}$ on average. But the short term compression ratio depends on characteristics of the audio signal. Therefore the full data rate of 1.4112 $\mathrm{Mb\,s^{-1}}$ has to be supported to achieve lossless full CD quality audio streaming. KLEER is using 16 equally spaced RF channels from 2.403 to 2.478 GHz (having a frequency spacing of 5 MHz) and each channel occupies an RF bandwidth of 3 MHz. For independent audio streams, each stream requires its own RF channel. Thereby KLEER is offering a gross data rate of 2.37 $\mathrm{Mb\,s^{-1}}$. The resulting excess net data rate is required for retransmission of corrupted packets in case of interference. An audio buffer ensures a continuous audio stream in case of packet loss. KLEER uses a configurable buffer size of up to 100 ms. The buffer size has to be high enough to assure a sufficient number of hops to find a channel without interference. As additional coexistence mechanism for interference mitigation, KLEER uses a dynamic frequency diversity to change the

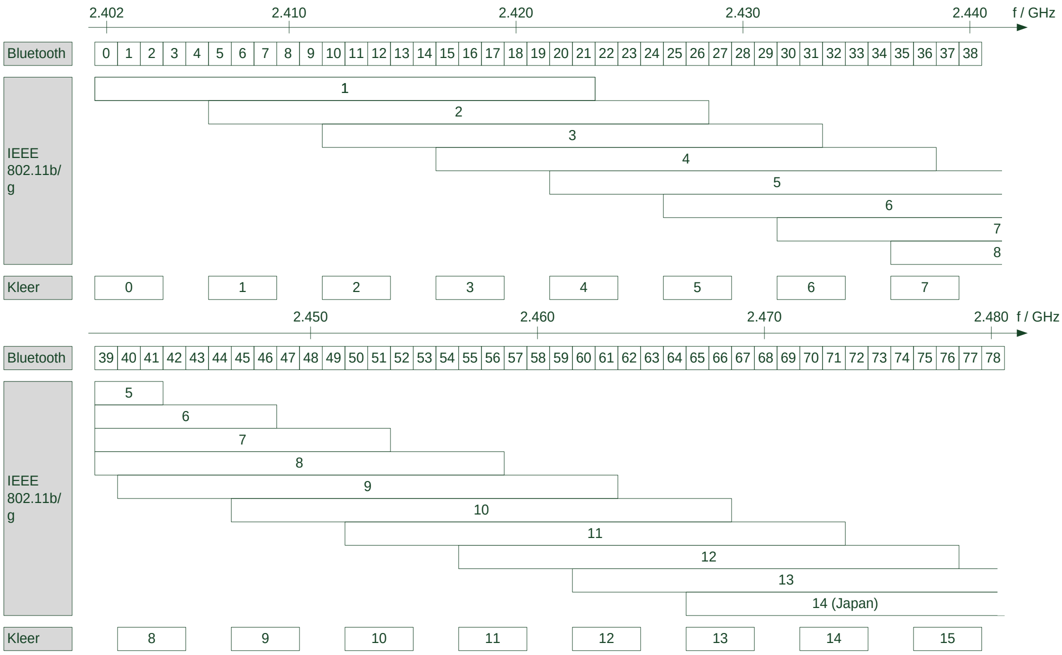

Figure 2. Bluetooth, IEEE 802.11b/g and KLEER channels in the 2.4 GHz-ISM-band.

Table 1. Comparison of wireless technologies.

	KLEER	Bluetooth	IEEE 802.11b	IEEE 802.11g
Gross data rate [Mbit s^{-1}]	2.37	1/2/3	1/2/5.5/11	6/9/12/18/24/ 36/48/54
Max. transmit power [dBm]	1.5	– 20 (class 1) – 4 (class 2) – 0 (class 3)	17	17
20 dB-bandwidth [MHz]	3	1	16	17
Channels	16 (non-overlapping)	79 (non-overlapping)	13 (partly overlapping)	13 (partly overlapping)
Modulation	MSK	GFSK/DQPSK 8DPSK	DBPSK/DQPSK 16-QAM/64-QAM	BPSK/QPSK/
Miscellaneous	None	Frequency Hopping	Spreading/Code Keying	OFDM

current channel if it is experiencing bad channel conditions. A channel change has to be initiated if the retransmission bandwidth is not able to cope with the packet loss rate over a defined period of time. At the audio sink side (at the wireless headphones), Kleer uses antenna diversity by switching two orthogonal polarized antennas which provides additional interference mitigation in small scale fading for in-vehicular communication. In Table 1 all important details on KLEER are shown and compared to Bluetooth and IEEE 802.11b/g. Figure 2 shows the channel distributions of Bluetooth, IEEE 802.11 and KLEER in the ISM-band.

In the first section, the impact of an IEEE 802.11b/g interferer is discussed and measurement results are presented. The next section analyzes the impact of a Bluetooth interferer in connected and connecting state using an analytical packet error model. Typical Bluetooth states are classified according to their impact on a KLEER transmission. It turns out that Bluetooth page state is very critical regarding interference. The following section gives details about the packet timing and the hopping sequence during page state. Furthermore, the characteristic behavior of a page hopping sequence is discussed. In the last section, a statistical analysis is done to carry out a relevance analysis concerning the impact of Bluetooth page state on KLEER.

2 Impact of IEEE 802.11b/g on KLEER

In the network architecture considered in this paper, IEEE 802.11 is using channel 6 with a center frequency of 2.437 GHz. An IEEE 802.11b/g channel occupies a 20 dB-bandwidth of approximately 16/17 MHz. According to the channel map, shown in Fig. 2, four KLEER channels overlap completely and one partly with a single IEEE 802.11 b/g channel. This assumes an IEEE 802.11 bandwidth of 22 MHz according to a more conservative bandwidth definition which is often used in literature. We used KLEER evaluation boards to analyze the impact of an IEEE 802.11 b/g interferer on a KLEER audio streaming. This allows disabling KLEER's dynamic channel switching. By applying an IEEE 802.11 b/g signal on a KLEER transmission we could evaluate the signal to interferer ratio (SIR) at which audio dropouts occurs. For a SIR region of 1 to −20 dB, audio dropouts occurred in up to four KLEER channels (out of 16) in presence of IEEE 802.11b/g traffic. The exact number of disturbed channels (channels where audio dropouts occur) depends on the interferer signal (either IEEE 802.11b or g) and the overlapping spectral power density of the interfering signal in a KLEER channel. Regarding the SIR values, it is important to note that IEEE 802.11b/g is transmitting with a maximum power of 20 dBm compared to KLEER with 1.5 dBm. Therefore a SIR of −20 dB represents almost equal path loss conditions between KLEER victim receiver and KLEER transmitter and IEEE 802b/g transmitter, respectively. Under more unfavorable path loss conditions even more than four KLEER channels can be disturbed. For SIR values between −20 and −30 dB, IEEE 802.11b disturbs five KLEER channels. On the opposite side, KLEER is not affected at all by IEEE 802.11b/g for SIR values higher than 1 dB. Considering the difference in transmitting power between IEEE 802.11 and KLEER, interference is likely in an in-vehicular environment. Therefore KLEER has to avoid IEEE 802.11b/g signals. But if only a limited number of the total 16 channels are affected by IEEE 802.11 signals, KLEER's dynamic channel switching (DSC) is an effective method to avoid the disturbed channels. Our measurements showed that DSC enables KLEER to dynamically change the affected channels during an IEEE 802.11 disturbance with an SIR of −30 dB without audio quality degradation.

3 Impact of Bluetooth on KLEER

KLEER needs a minimum SIR of about 13 dB to prevent audio dropouts in presence of a constantly transmitting Bluetooth GFSK-signal. The SIR difference compared to IEEE 802.11 signals can be explained by the lower spectral bandwidth of Bluetooth. In contrast to IEEE 802.11, Bluetooth communication standard uses Frequency Hopping Spread Spectrum (FHSS) which combines TDMA (Time Division Multiple Access) and FDMA (Frequency Time Division Multiple Access). The TDMA divides the channel in 625 µs slots resulting in 1600 slots s^{-1}. For the connecting state (inquiry or paging) also half slots of 312.5 µs are used. The FDMA is dividing the ISM band in 79 channels of 1 MHz width starting at 2.402 and ending at 2.480 GHz. Each packet is transmitted in a different channel than the previous packet following a pseudo-random hopping sequence. In Bluetooth specification version 1.2, Bluetooth Special Interest Group (SIG) introduced Adaptive Frequency-hopping (AFH) as additional coexistence mechanism for connected devices (Bluetooth SIG, 2004). When AFH is in use, channels which are classified as "bad" are removed from the hopping sequence. The Bluetooth core specifies a minimum number of 20 RF channels. In presence of an interfering FHSS communication system – like Bluetooth – with uniformly distributed channels over the whole band, a channel switch is unnecessary and even bares risks: a channel change always implies a data overhead and reduces the net data rate. Moreover, the Bluetooth channel classification is influenced negatively by a constantly switching system. In best case, Bluetooth will classify the channels inside the current KLEER channel as "bad" and stop using these channels. Therefore, the interference is only temporary during the Bluetooth AFH-adaptation time. Nevertheless, KLEER's retransmission bandwidth has to be able to compensate the packet loss during an occurring Bluetooth interference to provide overall coexistence. To calculate the resulting packet loss, the packet distribution in time and frequency has to be known. As Bluetooth supports multiple applications in different profiles, the paper focuses on typical in-vehicle scenarios:

- paging/inquiry,
- A2DP audio streaming (ACL connection type),
- hands-free telephony (SCO connection type),
- and connected state without any data transmission.

The measurements were conducted with evaluation boards using an Ellisys Bluetooth sniffer. In Table 2 the average packet distribution in time and frequency is shown.

Comparing the slot rates for both directions as worst-case interference scenario, it shows that paging/inquiry achieves by far the highest slot rate, however, with very short packets of only 68 µs length. In order to make a statement of the interference impact, it is necessary to calculate the resulting packet error rate. According to Golmie (2006), an analytical approach is used to model the occurring interference. Figure 3 shows the timing of the desired packets with respect to the interfering packets seen at the victim's receiver. The model assumes that the desired and interfering packets are sent periodically in a fixed time period of T_{sig} and T_{int}. This simplifies the calculation, but is only valid in case of paging/inquiry and SCO connection. But nevertheless, it also gives a reasonable estimation for the other cases. The packet length is denoted with t_{sig} and t_{int} .

The variable Δt defines the time offset between a desired and an interfering packet. Assuming that Δt is uniformly distributed, the average number that an interfering packet hits a desired packet in time can be calculated, as follows:

$$h_i = \frac{t_{\text{sig}} + t_{\text{int},i}}{T_{\text{int},i}}. \tag{1}$$

Table 2. Average packet distribution in time and frequency for different Bluetooth states; data derived from an exemplary measurement using Ellisys Bluetooth sniffer.

State	Packet distribution time			Packet distribution in frequency domain
	Average Slot rate (Master to Slave)	Average Slot rate (Slave to Master)	Average Slot rate (both directions/all packet types)	
Page/Inquiry	1 slot/ID-packet (68 µs)	–	1 slot/ID-packet (68 µs)	Divided in A/B trains with a simultaneous use of 16 channels
A2DP audio streaming	approx. 16 slots/2-DH3-packet (1.4 ms mainly 2-DH3 packets are used)	approx. 8.4 slots/ NULL-packet (126 µs)	approx. 5.5 slots/packet	20–79 channels with AFH
Hands-free	12 slots/2-EV3-packet (392 µs mainly 2-EV3 packets are used) + ca. 40 slots/NULL-packet (NULL 126 µs)	12 slots/packet (mainly 2-EV3 packets [392 µs])	+ ca. 70 slots/packet (NULL packets [126 µs]) approx. 4.8 Slots/packet	20–79 channels with AFH
Connected state without data transmission	40 slots/POLL-packet (126 µs)	40 slots/packet (NULL-packets [126 µs])	20 Slots/packet	20–79 channels with AFH

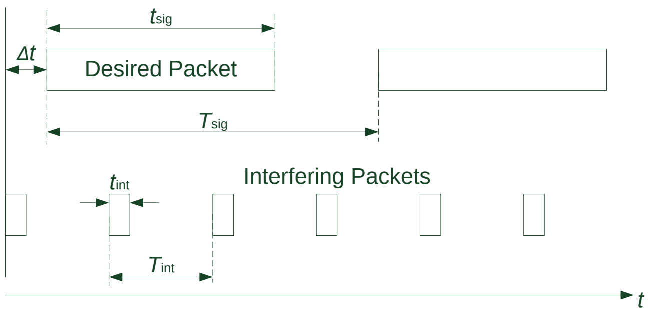

Figure 3. Collisions at the victim's receiver.

Considering different interfering packets $i = 1, 2, 3, .., M$ the total number is a sum of the individual numbers.

$$h = \sum_{i=1}^{M} \frac{t_{\text{sig}} + t_{\text{int},i}}{T_{\text{int},i}} \tag{2}$$

Assuming that every collision in time and frequency causes a packet error, the packet error rate is:

$$\text{PER} = \begin{cases} h \cdot \dfrac{n_{\text{int}}}{n_{\text{total}}} & \text{if } h \leq \dfrac{n_{\text{total}}}{n_{\text{int}}} \\ 1 & \text{if } h > \dfrac{n_{\text{total}}}{n_{\text{int}}} \end{cases}, \tag{3}$$

where n_{total} is the total number and n_{int} the number of channels overlapping with the desired signal. The channel distribution is assumed to be uniformly distributed. The above mentioned formula assumes that the collision in time and frequency are independent. Even if not all assumptions of the packet error model are completely valid, it gives a sufficient well estimation of the interference. Using the derived model and assuming a KLEER packet length of 1.3 ms an average packet error rate can be calculated. For A2DP, Hands-free and no data transmission two different interfering scenarios shall be regarded: in both scenarios, three BT channels are overlapping with a KLEER channel. But one scenario assumes BT to use all 79 channels and the other only 59 channels. The latter represents a situation where AFH avoids 20 channels due to additional IEEE 802.11 interference. In both cases, only co-channel interference with three BT channels inside one KLEER channel is considered. For Bluetooth paging/inquiry 16 channels are used simultaneously in one interval of 10 ms. A characteristic of the paging/inquiry sequence is that the adjacent channels always remain unused. More details about the characteristics of Bluetooth page state are given in the next section. Considering co-channel interference using KLEER's channel bandwidth of 3 MHz three cases have to be distinguished: no interference occurs and one or two channels out 16 are disturbed. The resulting probabilities that a BT packet hits a KLEER packet are shown in Table 3.

The table clearly shows that the critical states are page/inquiry with a possible packet error rate of 13.7 and 27.4 % in average. For Bluetooth connected states, the probabilities lie between 0.2 and 2.8 % which can be compensated by retransmitting the lost packets. The reader could notice that the interference due to paging/inquiry is not relevant as it is a very rare event. This is true for inquiry but not for page state: sometimes it is desirable that a device is able to connect at anytime. For example, in a vehicle the head unit enters periodically the page state every 20–30 s if no device is connected. In such a case, interference from Bluetooth paging has definitely to be excluded. As KLEER's retransmission bandwidth is not able to cope with the packet error rates for noise-equivalent audio signals which cannot be sufficiently compressed. Thus, KLEER's DSC has to be capable to find

Table 3. Average probability that a Bluetooth packet hits a 1.3 ms long KLEER packet in frequency and time for different Bluetooth states.

State	BT channels inside KLEER and total # of channels	Average probability that a BT packet hits a KLEER packet in time and frequency		
		Packet from Master	Packet from Slave	Packet either from Master or Slave
Page	0 of 16	0%	0%	0%
Inquiry	1 of 16	13.7%	0%	13.7%
	2 of 16	27.4%	0%	27.4%
A2DP	3 of 79 (only BT)	1.0%	1.0%	1.0%
audio	3 of 57 (BT & IEEE 802.11)	1.4%	1.4%	2.8%
Hands-free	3 of 79 (only BT)	1.1%	1.0%	2.1%
streaming	3 of 57 (BT & IEEE 802.11)	1.4%	1.3%	2.7%
Connected	3 of 79 (only BT)	0.2%	0.2%	0.4%
state w/o data	3 of 57 (BT & IEEE 802.11)	0.3%	0.3%	0.6%

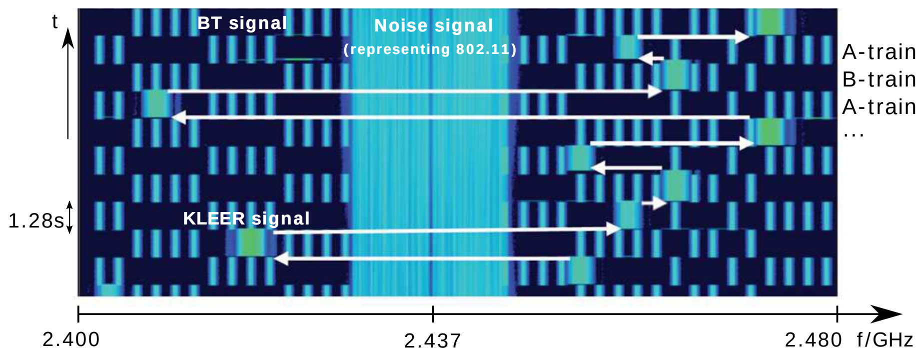

Figure 4. Constant channel switch of a single KLEER transmission in presence of BT paging and IEEE 802.11b/g – measurement done with signal generator and cable setup.

a free channel fast enough without audio degradation. To analyze the coexistence capabilities of KLEER in presence of BT paging/inquiry we generated a BT page state sequence using a vector signal generator. The sequence was generated with a periodic interval of 1.28 s long A and B trains. As BT paging always leaves a region of 16 MHz free, we added a noise signal to fill this gap. This bad case interference scenario was applied to a KLEER transmission. The power ratios are chosen in such a manner that a collision in frequency and time leads very likely to a packet loss. To manage this bad case scenario KLEER has to be able to constantly switch in a free channel. The Fig. 4 shows the measured power density of the described scenario against frequency and time in a waterfall plot.

As shown in Fig. 4, KLEER initiates a channel switch if the Bluetooth page sequence changes from A to B train and vice versa. After every train change, KLEER is able to find an undisturbed channel without any audio degradation. Under these difficult conditions, KLEER's channel switching algorithm is working well.

4 Statistical interference analysis of page (inquiry) sub state

As shown in the last section Bluetooth page (inquiry) sub state is a very serious interferer. For a Bluetooth connection setup the master sends two 68 µs long ID packets each second slot. The ID packets are spaced by 312.5 ms. Each packet is sent on a different frequency according to a short pseudo-random hopping sequence with a total period length of 2^{16} slots (= 40.96s). The hopping sequence is determined by the ULAP of the Bluetooth device which is paged. In case of inquiry, the ULAP is usually derived from the general Access Code (GIAC). A total page (inquiry) hopping sequence consists of 32 dedicated wake-up frequencies. These 32 frequencies are divided into two partial sequences of 16 frequencies. The page (inquiry) hopping sequence does not use a hop adaptation. During an interval of 10 ms the master transmits sequentially ID packets at 16 frequencies. The partial sequences – the so called A and B trains – are shifted by half of a page sequence period (= 40.96s/2). In modes R1 and R2, the trains are repeated 128 and 256 times (1.28 and 2.56 s) to assure that the slave is able to detect at least one message. After one repetition, it is switched to the other

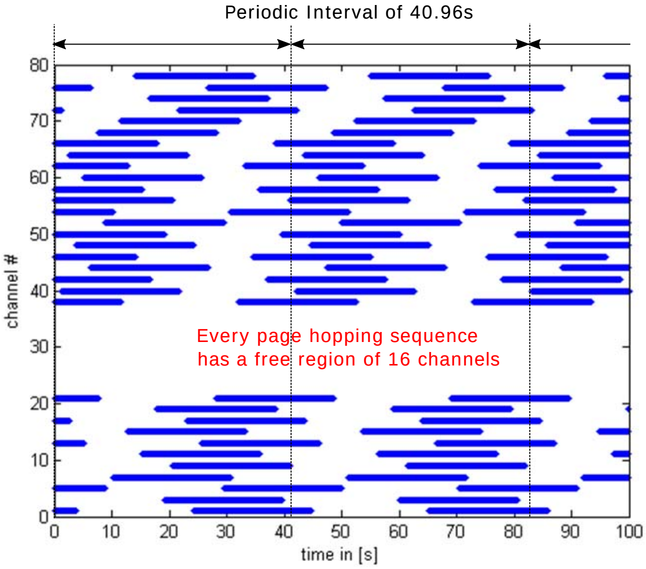

Figure 5. Exemplary Hopping sequence in page state for ULAP = 0x8B6949.

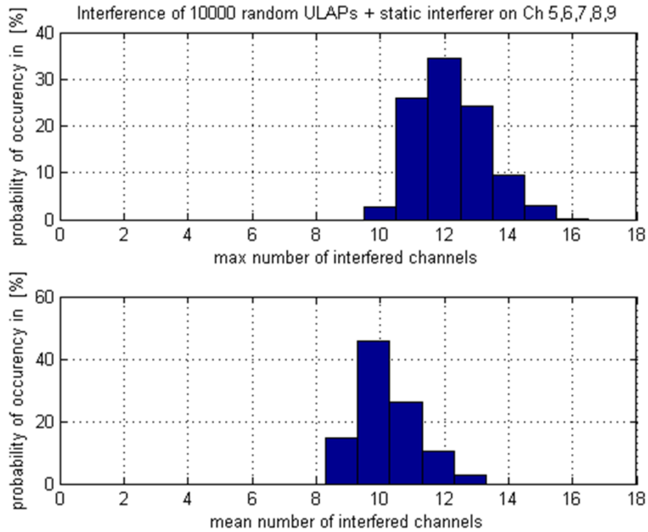

Figure 6. Number of disturbed channel by a Bluetooth page state with probability of concurrency calculated with 10 000 different Bluetooth device addresses.

train. Figure 5 shows the used channels of an exemplary page hopping sequence.

The figure illustrates the characteristics of a page (inquiry) hopping sequence:

- The sequence always leaves a region of 16 channels free.
- There is a gap of at least one frequency between two used channels.
- The page/inquiry hopping sequence repeats every 40.96 s.
- Every 1.28 s one (out of 16) frequencies changes. Between 20.48 s (= 16 × 1.28 s – phase difference between A and B train) two different sets of 16 channels are used.

As described before, every page hopping sequence uses 16 channels per train and has a free region of 16 frequencies. The spectral location of the free region depends on the Bluetooth device address and is uniformly distributed (for random device addresses). Furthermore, we know that an IEEE 802.11b/g signal is able to disturb up to 5 KLEER channels – assuming only co-channel interference. Assuming a bad case scenario, an IEEE 802.11b/g signal lies into the free region of the page hopping sequence. In an absolute worst-case scenario, the 16 frequencies of A or B train are disturbing the remaining 11 KLEER channels outside IEEE 802.11. In this case, all 16 KLEER channels are disturbed either with the IEEE 802.11b/g signal or the paging signal. KLEER would constantly initiate channel switches without the chance to find a free channel – at least during a single page train of 1.28 or 2.56 s. It is important to know the probability of occurrence for this worst case scenario to evaluate the relevancy. Based on 10 000 calculated page hopping sequences with random ULAP addresses a statistical analysis was performed. For every ULAP address 32 sequences of 16 frequencies were calculated to cover all possibilities over time. In total 320 000 page hopping sequences were calculated and statistically evaluated. Figure 6 shows the probability of occurrence for the number of interfered channels. In the upper figure the probability is given for the maximum number (considering the 32 possible sequences over time for one ULAP address). The lower figure shows average number of interfered channels.

As result it can be stated that the above mentioned worst-case situation is possible: the statistical probability that IEEE 802.11b/g and Bluetooth page state overlap with all 16 KLEER channels is about 0.02 %. In other words, two out of 10 000 randomly generated ULAP addresses are manifesting this behavior. In such a case, the interference on all channels occurs during 1.28 of 40.96 s. It should be emphasized that this worst-case situation only occurs if several factors come together:

- Bluetooth is enabled at the vehicle's head unit (HU) without any connected device.
- IEEE 802.11b/g packet load is high and the SIR is low enough to disturb five KLEER channels.
- The critical sequence is appearing while paging is active.
- A packet collision between a Bluetooth ID packet and a KLEER packet leads very likely to a KLEER packet loss.

Table 4. Possible solutions for paging interference

Solution	Realization	Effect
Increase KLEER's retransmission bandwidth	– Increase net data rate – Decrease amount of transmit data (e.g. using adaptive lossy compression in case of interference)	A channel switch becomes unnecessary with a sufficient retransmission bandwidth
Increase KLEER's number of channels	Decreasing KLEER's channel spacing of 5 MHz	A larger number of channels increases the chance of having non-disturbed channels
Improve SIR at the victim's receiver	– Increase KLEER's Tx power – Decrease Bluetooth Tx power (in page state)	Increasing the power of the desired signal or reducing the power of the interferer signal improves the SIR at the victim's receiver

From a customer view, a page state interference is incomprehensible as Bluetooth is switched off at the mobile device and only IEEE 802.11 as single system is used simultaneously with KLEER. In such a situation the customer cannot understand why he is experiencing audio dropouts. If there is more than one KLEER connection active, of course more than one free channel is needed. At maximum three independent streams (on three channels) are possible. The probability that three or more channels are disturbed during a page state is already 12.4 %. Thus is it certainly necessary to take steps to minimize the interference in such a critical state. Table 4 gives an overview of possible measures for interference reduction: beside of the pure technical aspects, it was important for Daimler to avoid time-consuming costly firmware and hardware changes. Considering the cost and interference aspects, the following two measures were taken: the audio level was lowered digitally on the transmitter's side to improve the audio compression rate. A smaller amount of transmit data increases the retransmission bandwidth. By adjusting the channel switch algorithm to the new retransmission bandwidth, a channel change become more unlikely during page state even if one Bluetooth channel lies inside the KLEER channel. It must be taken into account that an audio level reduction implies an increase of the audio quantization noise. Additionally to the reduction of the audio level, the Bluetooth transmit power was reduced during page/inquiry state to avoid packet loss in case of packet collision. In an in-vehicle situation the distances to the mobile device are very short (typically below 3 m) which usually allows a certain power reduction. First antenna based measurements on random positions inside a vehicle cabin showed that a power reduction of up to 20 dB does not affect the connect ability of Bluetooth devices.

5 Conclusions

In this paper we evaluated the coexistence of KLEER, a proprietary wireless standard in the 2.4 GHz-ISM-band used for audio transmission in full CD quality, in presence of Bluetooth and IEEE 802.11b/g. KLEER provides a coexistence mechanisms with packet retransmission and dynamic channel switching (DCS). The DCS is able to cope with static (or slowly switching) interferers like IEEE 802.11b/g without audio degradation. Unavoidable packet loss of a frequency hopping spread spectrum (FHSS) Bluetooth system in connected state can be compensated by retransmitting lost packets. The missing packets are compensated using a buffer management. The investigation showed that a very serious interference scenario consist of a Bluetooth system in page state in combination with an IEEE 802.11b/g link. This case is particularly critical when the Bluetooth master device enters periodically the page state to allow a connection of slave devices at any time. In an absolute worst-case scenario, all 16 KLEER channels can be disturbed either by Bluetooth ID packets or IEEE 802.11b/g packets. Two out of 10 000 ULAP addresses are showing this worst-case behavior. Measures are presented to improve the coexistence in this situation. Most of the publications concerning interference are dealing with systems operating in connected state. But this study shows that it is also important to include unconnected states into a full coexistence investigation. Under certain conditions Bluetooth connecting state (paging/inquiry) can be more critical as connected states. The packet rate of Bluetooth paging is approximately five times higher compared to typical connected states as Hands-Free telephony or A2DP streaming. Furthermore, the packets are sent over the whole band (only a region of 16 MHz is free) without channel adaptation (AFH) for interference mitigation. Another important aspect is that a user is not able to understand a Quality-of-service (QoS) degradation during page state interference as it occurs when Bluetooth is switched off at his mobile device. The interference issues of Bluetooth page state should also be viewed from the interferer side. For interference mitigation, methods are needed to avoid interference from other devices sharing the same band – but as second coexistence objective the interference on other devices should be minimized as well. During a single page sequence of 1.28 s (2.56 s) Bluetooth master device sends 2048 (4096) identical 68 bit-packets in a very high rate containing a high amount of redundant information. On the slave's side, this is favorable as the scan time can be minimized and thus energy saved. But for other systems, this could cause serious interference as shown in this paper. An approach to minimize the interference without changing the connecting procedure, is to adaptively reduce the transmit power during the connection state. It has however be assured that the devices are close enough to each other that a reduction in transmit power will not affect the ability to connect devices.

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