# Reliable Link Maintenance in Cognitive Radio Systems

Daniel Willkomm, James Gross and Adam Wolisz
Telecommunication Networks Group
Technische Universität Berlin, Germany
Email: {`willkomm|gross|wolisz`}`@tkn.tu-berlin.de`

*Abstract*— **Recently, secondary usage of spectrum has been considered in order to better exploit spectral resources and overcome the under-utilization of licensed spectrum. Since the licensed user still keeps primary access rights to its spectrum in such a secondary usage scenario, potential Secondary Users (SUs) have to vacate the spectrum in case the licensed user claims it. In order to maintain the quality of the secondary communication nevertheless, efficient mechanisms for link maintenance are needed. In this paper we present a general model for link maintenance in secondary usage scenarios. We state that the traditional way of adding redundancy to improve the communication not necessarily works in secondary usage scenarios. Furthermore we present performance results of a link maintenance approach applied to a secondary usage system based on opportunistic spectrum sharing, which verifies our assumptions [1].**

## I. INTRODUCTION

According to frequency allocations of regulatory bodies around the world, few frequency resources (if not any at all) are currently available for future wireless applications. For example, the U.S. **F**ederal **C**ommunications **C**ommission (FCC) frequency chart [1] indicates that there are even multiple allocations over all frequency bands. A rational consequence of this situation would be that RF activity is quite high at most frequency bands. However, current measurements show very little usage of the allocated frequency bands, for example at frequencies between 3 and 6 GHz in down-town Berkeley [2] as shown in Figure 1.

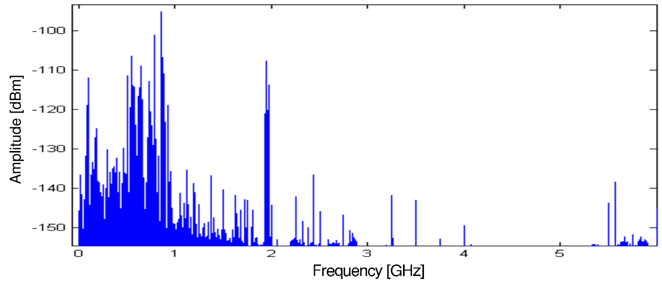

Fig. 1. Snapshot of the spectrum utilization up to 6 GHz in an urban area.

Assuming a growing demand for wireless data transmission within the next years, this discrepancy may lead to significant economic draw-backs. Already today there is the notion that radio frequency resources are scarce, holding down the deployment of new wireless services as well as increasing the price of existing ones. These problems will increase as the demand for data transmission will increase in the future. The traditional way of dealing (allocating and technically using) with radio resources will amplify the problems observed today.

From a technical perspective the major underlying problem is the mostly *exclusive* allocation of radio frequency resources. Any usage of radio frequency resources by a single transmitter is limited in time and space. However, frequency resources are reserved without any respect to these physical limitations. This leads to the fact that at certain times or locations only few radio frequencies are used, while the majority of the resource is not used. Spectral efficiency could be increased significantly if secondary usage of these (temporarily and spatially) free resources could be enabled. Conceptually, a licensed user – called **P**rimary **U**ser (PU) – would still own its spectral resources and have primary access rights, however, so called **S**econdary **U**sers (SUs) could use these spectral resources under certain conditions.

There are two fundamental issues regarding the secondary usage of spectrum, namely the **detection** of PU usage by SUs and the **maintenance** of the SU communication in case a PU appeared.

The **detection** of PUs comprises the following tasks. Firstly, how does an SU know whether a PU is using its spectrum or not? An SU has to know, which frequencies are currently unused and available for secondary usage. Additionally, while using a certain spectrum, an SU has to be informed or detect when the corresponding PU wants to use this spectrum, so that the SU can free the spectrum giving precedence to the PU. To ensure the unimpaired operation of PUs is fundamental for the deployment of secondary usage concepts. Basically, two different concepts have been discussed for the detection of PUs, **negotiated** spectrum sharing and **opportunistic** spectrum sharing.

In **negotiated** spectrum sharing the PU will explicitly announce the usage of its spectrum. A PU explicitly informs the SU about its intention to make use of its spectrum. However, this would require the change of legacy systems in order to enable secondary usage. Another possibility would be a policy based approach – e.g. as described in [3], [4] – where the usage of PUs is defined a priori. This approach would lead to a rather

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[1] This work has been supported by the German research funding agency "Deutsche Forschungsgemeinschaft (DFG)" under the graduate program "Graduiertenkolleg 621 (MAGSI/Berlin)".

conservative, static secondary usage and not optimally exploit the temporarily unused spectral resources. On the other hand negotiated spectrum sharing ensures a completely interference-free communication, since all spectrum claims are announced or defined a priori.

**Opportunistic** spectrum sharing is an automatic detection of PU activity by monitoring the spectrum with highly sensitive devices. These devices could either be the SUs themselves or a trusted third system, which announces PU appearance. This concept leads to a highly flexible and dynamic secondary usage where the SU can adapt to the *local* behavior of the PU. An advantage of this approach is that no changes have to be made to legacy systems. The PU is not aware of the secondary usage of its spectrum. A drawback is that there are short interference periods that occur due to the necessity of sensing the PU signal. Those interference periods are very short, i.e. they do not impair the communication of the PU. However, since SUs will operate with very low power levels in order to decrease the interference to PU systems as well as to increase the spatial re-usability of spectrum, interference from PUs will most likely corrupt the payload data of the SU communication on the interfered spectrum. Secondary systems following the opportunistic spectrum sharing approach are commonly referred to as **C**ognitive **R**adio (CR) systems. Examples of such CR system designs can be found in [2], [5], [6].

The issue of **maintenance** of SU communication is still an open one. As PUs might reclaim currently used spectrum of SUs, SU data communication is interrupted, potentially eliminating any service expected by users of the secondary system. Although PUs will reclaim their spectrum randomly, reliable schemes are required which still enable the provision of service for the communication among SUs to some extent.

The appearance of PUs on spectral resources currently used by the SU communication will require the SUs to restructure their communication link. This takes time and ultimately reduces the secondary system performance. Hence, SUs should reduce the probability of PU appearance in the currently used spectral resources, which also reduces the probability of link maintenance. A simple way to achieve this is to lower the spectral resources used for the communication. On the other hand the payload data should contain some redundancy to be robust against bit-errors (among others due to interference by PUs) and to be able to temporarily compensate the loss of spectral resources due to the reclaim by a PU. Obviously this is in contradiction to the goal of lowering the probability of link maintenance as explained above.

This trade-off basically exists for *any* secondary usage concept. The choice of the right dimension for the SU communication link depends though on several parameters, which might vary strongly for different implementations. In this paper, we introduce a general model for link maintenance and study this trade-off for a specific secondary usage system relying on a CR architecture. To our best knowledge, this issue of link maintenance has never been investigated and published before.

The remainder of this paper is organized as follows. In Section II we describe the secondary usage concept and define the general link maintenance model. Furthermore, we specify the assumptions for the investigations in this paper. In Section III we introduce means to compensate **P**rimary **U**ser **I**nterference (PUI) and show performance analysis results in Section IV. We conclude in Section V.

## II. SYSTEM MODEL

In this Section we first introduce the general secondary usage model followed by the general model for link maintenance. Afterwards, we explain the specific assumptions made for our simulation setup.

### *A. Secondary Usage Model*

The secondary usage model we consider is based on a system architecture called **CO**gnitive **R**adio for usage of **V**irtual **U**nlicensed **S**pectrum (CORVUS) described in [2], [6], [7]. The system covers a certain bandwidth $B$ where $B$ can range from tens of $\mathrm{MHz}$ up to several $\mathrm{GHz}$. Within this spectral range several **P**rimary **U**sers (PUs) legally own different parts of the spectrum – called Primary User **F**requency **Band**s (F-Bands) – resulting in a *theoretical* occupancy of the whole spectrum. However, as different PUs do not always use all their spectrum at a certain time and location this *temporarily* unused spectrum is available for secondary usage.

**S**econdary **U**sers (SUs) within this model use these temporarily available spectral resources to satisfy their own communication needs. In order to do so the whole bandwidth is divided into $N$ sub-channels, each with a bandwidth of $b = B/N$ to form a **spectrum pool**. The size of the sub-channels should be selected such that a single sub-channel is a rather small part of any F-Band in the spectrum pool.

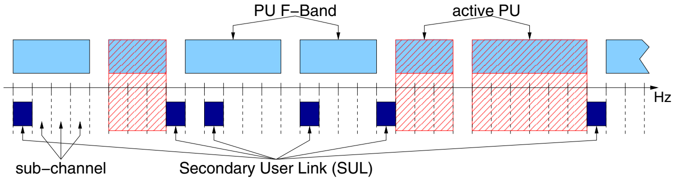


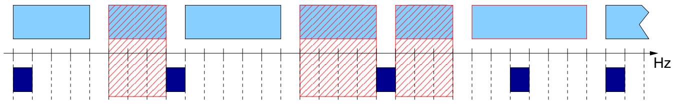
Fig. 2. Spectrum pool

Figure 2 shows the basic idea of the secondary usage concept. Although the whole spectrum is licensed, only some PUs are active at a certain time. Out of the remaining sub-channels currently not used by a PU, SUs select a set of sub-channels to build a **S**econdary **U**ser **L**ink (SUL) that they use to satisfy their own communication needs. An SUL is a set of sub-channels, changing dynamically depending on the PU activity on the used sub-channels. As soon as a corresponding PU wants to make use of his spectrum all SUs have to immediately vacate the corresponding sub-channels giving precedence to the PU.

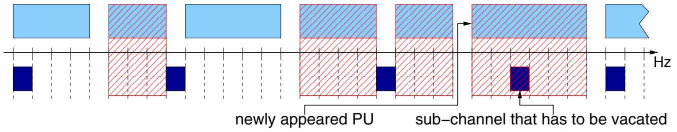
The question within this scenario is how to achieve a reliable continuous communication among SUs despite the loss of used sub-channels due to the reclaim by a PU. We propose two means to decrease the influence of PUs reclaiming their spectral resources.

*1) Sub-channel selection:* An intelligent selection of sub-channels for an SUL can decrease the influence of the appearance of individual PUs on used spectral resources. The sub-channels selected for an SUL should be scattered over multiple F-Bands. Ideally an SUL consists of only one sub-channel per F-Band. This principle ensures a low impact of the appearance of a PU. As only one sub-channel is used from any F-Band, also only one sub-channel has to be vacated in case a PU appears.

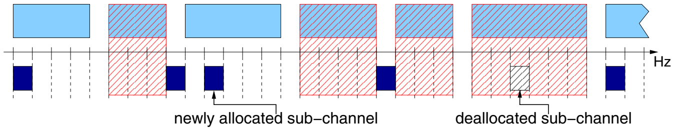
*2) New sub-channel acquisition:* In order to maintain the data-rate requested by the user the SUL needs to compensate the loss of spectral resources due to the appearance of PUs on currently used sub-channels. Every time a sub-channel has to be excluded from the SUL a **link maintenance** period is executed where a new sub-channel is immediately acquired in order to maintain the data-rate of the SUL. This procedure of SUL reconfiguration is shown in Figure 3. As mentioned above the selection of new sub-channels should be such that no two sub-channels of one F-Band are used for the same SUL.



a) SUL consisting of 5 sub−channels



b) Appearance of a PU



c) reconfigured SUL

Fig. 3. Reconfiguration of an SUL

## B. Link Maintenance Model

The process of link maintenance takes time, which cannot be used for data transmission and thus degrades the performance of the SUL. In our system model time is slotted into frames of length $t_{\text{frame}}$. For the general model we use the frame structure as shown in Figure 4.

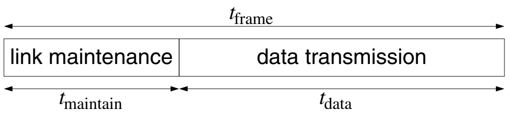


Fig. 4. Frame structure

Within $t_{\text{frame}}$, $t_{\text{maintain}}$ denotes the time reserved for link maintenance. Each time a sub-channel has to be excluded from the SUL a new one needs to be acquired in order to maintain the data-rate of the SUL. So every time a new sub-channel needs to be acquired, $t_{\text{maintain}}$ has to be executed. $t_{\text{data}}$ is the period of the frame reserved for payload data transmission. Payload data transmitted during one time frame is referred to as a **message** whereas the payload data transmitted on one single sub-channel is referred to as a **packet**. Note that in case no sub-channels got lost, the link does not have to be maintained and a time frame only consists of $t_{\text{data}}$.

In our model the sub-channel exclusion probability ($p_{\text{x}}$) is the probability for a sub-channel to be excluded from the SUL. Apart from the appearance of a PU – denoted by the **P**rimary **U**ser appearance probability ($p_{\text{a}}$) – there are other reasons why a sub-channel might be excluded from an SUL. Those include temporal fading and interference by other non-primary communications. Generally speaking a sub-channel with a “bad quality” should be excluded from the SUL, denoted by the probability that a sub-channel should be excluded due to bad quality ($p_{\text{q}}$). Using the above defined probabilities, $p_{\text{x}}$ can be expressed as

$$p_{\text{x}} = p_{\text{a}} + p_{\text{q}} \ . \tag{1}$$

Using $p_{\text{x}}$ and assuming an SUL consisting of $N$ sub-channels, we can calculate the link maintenance probability ($P_{\text{m}}$). $P_{\text{m}}$ denotes the probability that at least one sub-channel of the SUL cannot be used anymore and consequently the link has to be maintained, i.e. a new sub-channel has to be acquired. $P_{\text{m}}$ is the complement to the probability that no sub-channel has to be excluded from the SUL and thus can be expressed as

$$P_{\text{m}} = 1 - (1 - p_{\text{x}})^N \ . \tag{2}$$

The appearance of other SUs on a used sub-channel (included in $p_{\text{q}}$) may result in **S**econdary **U**ser **I**nterference (SUI), i.e. the corruption of the signal and thus the packet loss due to bit errors. Accordingly the appearance of a PU ($p_{\text{a}}$) may result in **P**rimary **U**ser **I**nterference (PUI) and in a packet loss due to bit errors as well. Note that PUI is only possible in the case of opportunistic spectrum sharing. In the case of negotiated spectrum sharing, the negotiation of spectrum use should ensure non-interfering communications of primary and secondary users.

Apart from the packet error probability due to interference ($p_{\text{i}}$) including the packet error probability due to **P**rimary **U**ser **I**nterference ($p_{\text{i}}^{\text{PU}}$) and the packet error probability due to **S**econdary **U**ser **I**nterference ($p_{\text{i}}^{\text{SU}}$), data packets can also be corrupted due to noise denoted by the packet error probability due to noise ($p_{\text{n}}$). Equation 3 finally shows the general packet error probability ($p_{\text{e}}$).

$$p_{\text{e}} = p_{\text{n}} + p_{\text{i}} = p_{\text{n}} + p_{\text{i}}^{\text{PU}} + p_{\text{i}}^{\text{SU}} \tag{3}$$

## C. Specific Assumptions

For the investigations in this paper we assume a secondary usage model using opportunistic spectrum sharing. It is the sole responsibility of the secondary system to detect primary usage of the spectrum and to ensure the unimpaired operation of the PUs. This is achieved locally in each SU by sensing the spectrum to detect any PU using its spectrum and by exchanging these sensing results with the communication peers. This model implies that a PU can interfere with an SU communication resulting in packet errors due to PUI denoted by the packet error probability due to **P**rimary **U**ser **I**nterference ($p_{\mathrm{i}}^{\mathrm{PU}}$).

Once a PU appears on a used sub-channel it interferes with the SU communication most likely resulting in a corruption of the data sent on this sub-channel. We propose to use redundancy codes to protect data messages from the corruption due to PUI. An appropriate amount of redundancy added to the SUL enables the receiver to reconstruct data messages even if some sub-channels got interfered by a PU and the corresponding data packets got corrupted.

We assume only one single point-to-point SUL. We do not study the influence of different SU communications within the same spectrum pool (no multi-user scenario; $p_{\mathrm{i}}^{\mathrm{SU}} = 0$). The two SUs communicating use a dedicated control channel, called **G**roup **C**ontrol **C**hannel (GCC), for the exchange of control information. The SUL is assumed to be already established, i.e. link setup is not studied. In our scenario payload data is transmitted only from one peer to the other. The receiving peer does not have payload data to be sent. It is assumed that the transmitter has always data to be sent.

For the simulation results presented, we extend the frame structure of Figure 4. In this frame structure – shown in Figure 5 – $t_{\mathrm{maintain}}$ is divided into three parts, namely $t_{\mathrm{sens}}$, $t_{\mathrm{control}}$ and $t_{\mathrm{acquire}}$. During $t_{\mathrm{sens}}$ the whole spectrum pool is scanned in order to detect PU activity. Subsequently – within $t_{\mathrm{control}}$ – the sensing information has to be exchanged between the communication peers to achieve a consistent view which sub-channels have to be excluded and which can be used for communication. This control information is exchanged using the GCC. $t_{\mathrm{acquire}}$ denotes the time reserved for the acquisition of new sub-channels. Note that $t_{\mathrm{acquire}}$ is only necessary if one of the control messages sent during $t_{\mathrm{control}}$ indicates that some sub-channel got interfered by a PU. If no sub-channel has to be excluded from the SUL, no new one needs to be acquired and consequently $t_{\mathrm{acquire}}$ is not needed. In this case the next data message can be send right away. Finally, $t_{\mathrm{data}}$ is the time length of one message transmission on the current SUL.

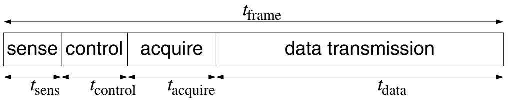


Fig. 5. Frame structure

The transmission and modulation scheme used at the physical layer is assumed to dynamically adapt to the changing conditions of the wireless channel. We assume some coding scheme to be applied to the payload data in order to make the transmission robust against bit errors. Thus, for the further discussion we neglect the effect of packet errors due to noise ($p_{\mathrm{n}} \approx 0$).

Furthermore, we assume some algorithm to choose the sub-channels to be merged to the current SUL. We do not focus on the exact decision algorithm. Given a certain number of sub-channels needed for message transmission, the assignment algorithm provides a valid set of sub-channels (which might minimize the total transmit power required).

The above defined scenario creates a simplified model for link maintenance. With $p_{\mathrm{i}}^{\mathrm{SU}} = p_{\mathrm{n}} = 0$, Equation 3 simplifies to

$$p_{\mathrm{e}} = p_{\mathrm{n}} + p_{\mathrm{i}}^{\mathrm{PU}} + p_{\mathrm{i}}^{\mathrm{SU}} \approx p_{\mathrm{i}}^{\mathrm{PU}} \ , \tag{4}$$

i.e. the only source of bit errors considered is **P**rimary **U**ser **I**nterference (PUI). Without interference from other SUs and the above proposed transmission scheme also Equation 1 can be simplified to

$$p_{\mathrm{x}} = p_{\mathrm{a}} \ , \tag{5}$$

since the appearance of a PU is the only reason that a sub-channel has to be excluded from the SUL. Furthermore PUI (the appearance of a PU on a sub-channel) completely corrupts the signal, as the SU system operates with quite a low **S**ignal-to-**N**oise **R**atio (SNR) in general. Consequently the data sent on this sub-channel is lost. This assumption implies

$$p_{\mathrm{e}} = p_{\mathrm{x}} = p \ . \tag{6}$$

## III. COMPENSATING **P**RIMARY **U**SER **I**NTERFERENCE

The only source for message errors in the system under investigation is **P**rimary **U**ser **I**nterference (PUI). The probability of a PU appearance for any sub-channel is given by the sub-channel interference probability ($p$). In other words, $p$ can be regarded as the sub-channel utilization by the PU. We assume a homogeneous interference probability for all sub-channels. In addition, the interference probability for different sub-channels are assumed to be independent (no correlation in the frequency domain). There is also no correlation of $p$ in time, i.e. the sub-channel interference probability is independent for consecutive frames.

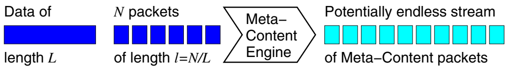


Fig. 6. Meta-Content generation

In this work we use redundancy codes based on Meta-Content$^{\mathrm{TM}}$ as described in [8] and shown in Figure 6. In order to transmit data of length $L\,\mathrm{bit}$, it has to be divided into $k = L/l$ input symbols. The Meta-Content engine then produces a potentially limitless number of encoding symbols (= data packets), which are sent to the receiver. The ability to produce an endless stream of Meta-Content symbols is a special property of a class of rateless erasure codes called LT codes [9]. Once the receiver obtained at least $K > k$ of these encoding symbols, it can completely recover the $k$ input symbols. Note that it does not matter, which of the produced Meta-Content symbols are used for the reconstruction of the original data. The $k$ input symbols can be recovered from *any* $K$ Meta-Content symbols. For LT codes a Meta-Content symbol overhead of 5% is sufficient, in order to reconstruct the data at the receiver ($K = 1.05 \cdot k$) [8].

The redundancy approach applied to our system is as follows. In order to simultaneously transmit a data segment of length $L\,\mathrm{bit}$, this segment is divided into $k = L/l$ input symbols for the encoder. Assuming that one encoded symbol (= one packet) is sent per sub-channel, the minimum number of sub-channels needed for the SUL is $N = K$, since at least $K$ encoded symbols are required in order to completely retrieve the original data at the receiver. Using only $N$ sub-channels, however, would cause the transmission to fail in case only one single sub-channel is reclaimed by a PU. In order to make the SUL robust against the corruption of data packets due to the appearance of PUs, $X$ redundant sub-channels are added to the SUL, resulting in a total number of $S = N + X$ sub-channels for an SUL. This means that up to $X$ arbitrary sub-channels can be interfered by a PU without degrading the goodput of the SUL.

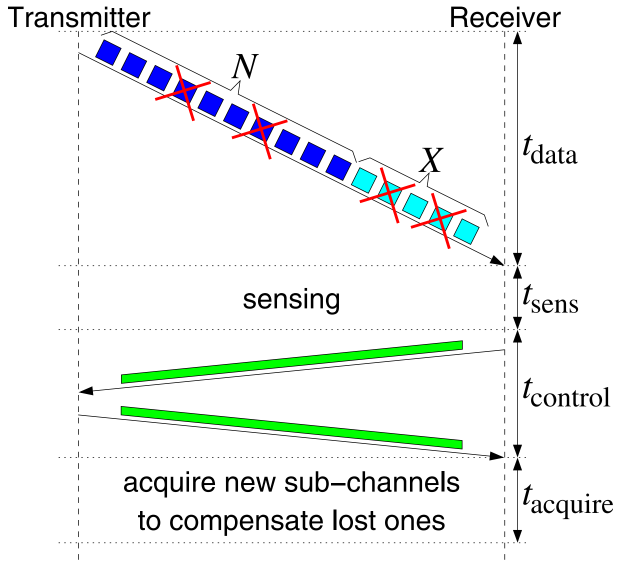


Fig. 7. Message sequence chart for one frame period $t_{\text{frame}}$

The general idea of our approach is shown in Figure 7. The transmitter takes a message consisting of $N+X$ packets, where $X$ represents the number of redundant packets. The $N + X$ packets are then sent to the receiver using an SUL with $N + X$ sub-channels. During transmission, some of the packets may get lost due to PUI on some of the used sub-channels (indicated by the crosses in Figure 7). In this example, the SUL uses five packets of redundancy ($X = 5$) and four packets got lost, so the message can be reconstructed at the receiver out of the arriving packets. After sending of the data, transmitter and receiver both perform spectrum sensing to determine which sub-channels of the SUL need to be dropped due to interference by a PU. Subsequently, transmitter and receiver send a control message on the GCC containing all used sub-channels that are interfered by a PU. The next step is the maintenance of the SUL ($t_{\text{acquire}}$), i.e. the acquisition of new sub-channels. If one of the control messages sent contains at least one sub-channel that has to be excluded from the SUL, a new one needs to be acquired during the $t_{\text{acquire}}$ period in order to maintain the goodput of the SUL. Only if both – sender and receiver – did not detect any PUI on one of the used sub-channels, the time needed to acquire new sub-channels ($t_{\text{acquire}}$) can be omitted and the next message can be sent right away.

## IV. PERFORMANCE ANALYSIS

The primary metric we investigate in this paper is the average goodput ($G_{\text{bit}}$ [bit/s]) of the SUL. This metric is investigated with respect to the number of redundant sub-channels ($X$) and the sub-channel interference probability ($p$).

### A. *Analysis*

In order to compute the goodput we need the probability that a message cannot be reconstructed at the receiver. The message can be reconstructed at the receiver, if at least $N$ packets are successfully received. That means, if more than $X$ packets ($X + 1,\ X + 2,\ \ldots,\ X + N$) get lost due to PUI, the message cannot be reconstructed and thus has to be sent again. Consequently, the message error probability ($P_{\text{err}}$) computes to

$$P_{\text{err}} = \sum_{i=1}^{N} \binom{N+X}{X+i} p^{X+i} (1-p)^{N-i} \ . \tag{7}$$

Additionally to the message error probability ($P_{\text{err}}$) we need the link maintenance probability ($P_{\text{m}}$). $P_{\text{m}}$ is the probability that the SUL has to be maintained, i.e. the probability that at least one of the sub-channels used by the SUL got acquired by a PU during the last frame period resulting in the need to acquire a new one. According to Equation 2, $P_{\text{m}}$ for our investigated scenario computes to

$$P_{\text{m}} = 1 - (1-p)^{N+X} \ . \tag{8}$$

Using Equation 8, the average length of a frame computes to:

$$t_{\text{frame}} = t_{\text{sens}} + t_{\text{control}} + P_{\text{m}} \cdot t_{\text{acquire}} + t_{\text{data}} \ , \tag{9}$$

which results in the goodput of this approach in bit per second as shown in Equation 10.

$$G_{\text{bit}} = \frac{(1 - P_{\text{err}}) \cdot N \cdot b_{\text{sc}} \cdot t_{\text{data}}}{t_{\text{sens}} + t_{\text{control}} + P_{\text{m}} \cdot t_{\text{acquire}} + t_{\text{data}}} \tag{10}$$

### B. *Parameterization*

The scenario we investigate aims at the support of a peer-to-peer **U**ser **D**atagram **P**rotocol (UDP) stream with a data-rate of $1.66\,\mathrm{Mbit/s}$[2]. This would enable the transmission of a **M**oving **P**icture **E**xperts **G**roup (MPEG) encoded video stream with a resolution of 720x576 pixel and a frame-rate of $25\,\mathrm{frames/s}$. Depending on the chosen MPEG standard, the quality achieved

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[2] The data rate of $1.66\,\mathrm{Mbit/s}$ already includes the $5\%$ overhead needed due to the use of the LT redundancy codes.

would be comparable to broadband TV (for MPEG-2) or DVD (for MPEG-4) quality.

The operation range for the scenario is a spectrum pool from 3 to 6 GHz resulting in a total bandwidth of $B = 3\,\text{GHz}$. According to the measurements of Figure 1 the utilization for the 3 to 6 GHz band is less then 1%, which would result in $p < 0.01$.

**O**rthogonal **F**requency **D**ivision **M**ultiplexing (OFDM) is used as a transmission scheme for the physical layer. Each sub-carrier is modulated with **B**inary **P**hase-**S**hift **K**eying (BPSK) in combination with a rate $1/2$ convolutional coder. This results in quite reliable data transmissions per sub-channel even at low SNR values. Thus, the transmit power can be kept relatively low, which is an important issue to reduce potential SU interference to primary systems. As the attenuation per sub-channel varies due to fading, shadowing and path loss effects, the transmit power can be reduced by means of dynamic power loading. We assume that such a scheme is applied per sub-channel to guarantee a bit error probability per sub-channel of $10^{-6}$.

The size $b$ of a single sub-channel corresponds to the size of an OFDM sub-carrier ($b = 0.3125\,\text{MHz}$) in an IEEE 802.11a [10] system resulting in a total amount of $B/b = 9600$ sub-channels in the whole spectrum pool. The OFDM symbol length is $3.2\,\mu\text{s}$, to which a guard interval of $0.8\,\mu\text{s}$ is added. As there are no differences in the quality of individual sub-channels, the same modulation scheme, and thus, also the same bitrate ($b_{\text{sc}}$) is used for all sub-channels. The assumed BPSK modulation with a code rate of $1/2$ results in a bitrate of $b_{\text{sc}} = 125\,\text{kbit/s}$ per sub-channel. For the frame structure we assume $t_{\text{sens}} = t_{\text{control}} = t_{\text{acquire}} = t_{\text{data}} = 1\,\text{ms}$.

Using the above defined values and Equation 10 the minimum number of sub-channels ($N$) needed to achieve a goodput of $1.66\,\text{Mbit/s}$ computes to $N = 40$, in case no packets get lost and no link maintenance has to be done ($P_{\text{err}} = P_{\text{m}} = 0$).

### *C. Performance Results*

Figure 8 shows the goodput plotted against the number of redundant sub-channels ($X$). All graphs show a maximum, i.e. a maximal goodput for a specific $X$. This observation verifies our assumption that there exists a tradeoff between the probability of link maintenance and the probability of message errors. A bigger amount of redundancy used does not necessarily result in a bigger goodput. A bigger amount of redundancy used also results in a bigger bandwidth requirement, which increases the probability of link maintenance. Link maintenance in turn lowers the goodput of the SUL.

In the investigated scenario the maintenance of the SUL, i.e. the time needed to acquire new sub-channels, costs time, which cannot be used for data-transmission and thus degrades the goodput of the system. The same applies for the retransmission of messages. If the redundancy added to the message is not sufficient so that the message cannot be reconstructed at the receiver, it has to be sent again, also reducing the goodput of the system. There is a tradeoff between the probability that a message cannot be reconstructed at the receiver and the probability that the link has to be maintained.

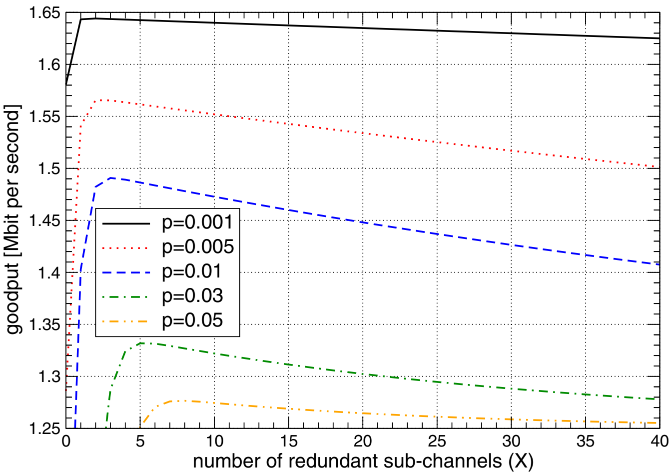

Fig. 8. Goodput against number of redundant sub-channels ($X$)

For a large number of $X$, i.e. a big amount of redundancy added to the SUL, transmission is very reliable and thus the probability of re-sending messages is small. On the other hand, a large number of $X$ results in a large total number of sub-channels used for the SUL, which increases the probability that a sub-channel has to be excluded from the SUL due to PUI and thus increases the probability of the need to maintain the link and acquire new sub-channels. For a small number of $X$ it is the other way round. The probability of re-sending messages is bigger due to the reduced redundancy added, but the probability of link maintenance is lower due to the smaller total number of sub-channels.

This tradeoff results in the local maximum of each graph shown in Figure 8. In order to achieve the maximal goodput possible it is crucial to choose the optimal amount of redundancy.

Another observation from Figure 8 is that the link never reaches the desired goodput of $G_{\text{bit}} = 1.66\,\text{Mbit/s}$. Even for $p = 0.001$ the maximum goodput only comes close to but does not reach the desired goodput. The reason for that is shown in Figure 9. It shows the goodput for different $X$ plotted against the sub-channel interference probability ($p$) and compares it to the maximum goodput possible. The maximum goodput is a plot of the goodput using the optimal $X$ for each $p$. For the given system parameters, the goodput thus can never be in the grey shaded area in Figure 9. The maximum goodput shows the influence of the link maintenance on the goodput of the system. For low $p$ ($p < 0.001$) the link rarely has to be maintained and the maximum goodput achievable is close to the theoretical capacity of the channel ($G_{\text{bit}} = 1.66\,\text{Mbit/s}$). With an increasing $p$ the link maintenance probability also increases until for $p = 0.08$ the link always has to be maintained and the maximum goodput thus drops to $G_{\text{bit}} = 1.25\,\text{Mbit/s}$. For a non-zero sub-channel interference probability ($p \neq 0$) we thus cannot dimension the SUL with the minimum number of sub-channels of $N = 40$ if we want to achieve the desired

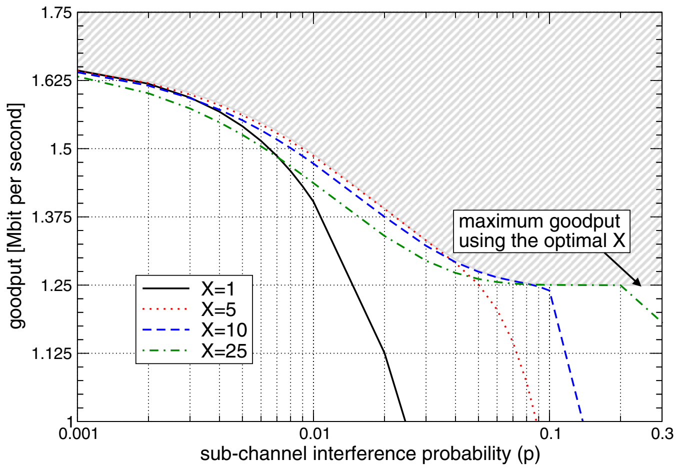

Fig. 9. Goodput against sub-channel interference probability ($p$)

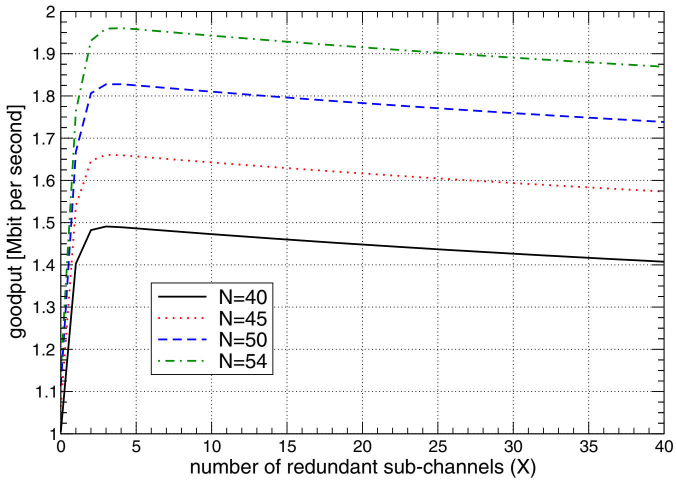

Fig. 10. Goodput for different $N$ ($p = 0.01$)

goodput of $G_{\text{bit}} = 1.66\,\text{Mbit/s}$.

One way to assure the support of the desired goodput by the SUL would be a conservative worst case dimensioning, i.e. to assume that the link always has to be maintained. For the example of a target bitrate of $G_{\text{bit}} = 1.66\,\text{Mbit/s}$ this would result in $N = 54$ sub-channels. However, this approach would waste a lot of bandwidth and transmit power in case of low to medium sub-channel interference probabilities. Figure 10 shows the goodput using different numbers of sub-channels ($N$) for a sub-channel interference probability of $p = 0.01$. The conservative dimensioning with $N = 54$ would result in a bandwidth requirement of $B_{\text{SUL}} = 18.125\,\text{MHz}$ (using the optimal $X$) and be able to support a bitrate of $G_{\text{bit}} = 1.96\,\text{Mbit/s}$, which is bigger than the actual requirement. Using only $N = 45$ sub-channels on the other hand perfectly matches the goodput requirement of $G_{\text{bit}} = 1.66\,\text{Mbit/s}$ but only uses a bandwidth of $B_{\text{SUL}} = 15\,\text{MHz}$, which is more than $17\,\%$ less than using $N = 54$ sub-channels. In order to build bandwidth efficient SULs, $N$ thus has to be chosen adaptively depending on $p$.

An adaptive selection depending on $p$ is even more crucial for $X$. Figure 9 shows the impact of choosing a sub-optimal $X$. Using $X = 5$ redundant sub-channels almost achieves the maximum goodput up to a sub-channel interference probability of $p = 0.04$ whereas for higher $p$ the goodput drops drastically. Using $X = 25$ redundant sub-channels in contrast only achieves a sub-optimal goodput for low $p$ of up to $p = 0.08$ and only can closely approximate the maximum goodput for higher $p$. This means that choosing $X$ too big would not only result in a waste of bandwidth but also in a degradation of the goodput.

## V. CONCLUSIONS

In this paper we investigate the concept of secondary usage of spectrum. Specifically, we focus on the reliable link maintenance within CR systems. We show that – in contrast to traditional wireless systems – for CR systems an increase of redundancy (i.e. bandwidth) not necessarily results in a more reliable transmission.

First we introduce a general model for link maintenance applicable to basically any secondary usage system. Furthermore we present performance results for a link maintenance approach applied to a more specific CR system architecture. The approach presented is able to compensate the temporal losses of sub-channels used for SU communication due to the reappearance of PUs on those sub-channels. The results achieved can be applied to any CR system based on opportunistic spectrum sharing using the presented sub-channel approach and a separate control channel for the maintenance of links.

We show that there is an optimal number of redundant sub-channels ($X$), i.e. an optimal amount of redundancy for any sub-channel interference probability ($p$), which can achieve a maximum goodput. This result is in contradiction to most other systems where an increasing amount of redundancy added to a system usually also increases the performance, i.e. the goodput, as transmission becomes more reliable. However, as **P**rimary **U**ser **I**nterference (PUI) is the major source for transmit errors, a new system trade-off has to be taken into consideration. Increasing the amount of redundancy decreases the error probability of the message but increases the probability to maintain the link. Link maintenance costs time. Thus, the message error probability and link maintenance probability have to be balanced, depending on the message size, the interference probability and the timing relations (link maintenance ($t_{\text{acquire}}$), sensing ($t_{\text{sens}}$) and payload transmission ($t_{\text{data}}$) durations). Qualitatively, this system behavior is new compared to traditional wireless systems and influences the dimensioning of the bandwidth requirements significantly.

Further investigations in this area include the refinement of the PU interference model. As a PU F-Band usually covers several sub-channels, the interference probabilities of adjacent sub-channels should be correlated. Additionally, the link maintenance model should be applied to secondary usage systems using negotiated spectrum sharing and the influence of a proper sub-channel selection algorithm should be investigated. Another area is the investigation of a multi-user scenario. Multiple SU communications could select the same sub-channels and thus would interfere with each other. Means to prevent harmful interference of different SU communications should be developed.

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