Efficient Signaling of Spectral Resources in Spectrum Pooling Systems

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Abstract—**Public mobile radio spectrum is a scarce resource while wide spectral ranges are only rarely used. Here, we consider a new strategy called Spectrum Pooling enabling public access to these new spectral ranges without sacrificing the transmission quality of the actual license owners. By temporarily leasing their spectrum during idle periods the license owners could tap new sources of revenue. We favor a modified wireless LAN as rental system. Especially OFDM based WLANs like IEEE802.11a and HIPERLAN/2 are suitable for an overlay system like spectrum pooling as they allow a very flexible frequency management on a carrier-by-carrier basis. The modifications of these standards comprise many areas of the physical and MAC layer. Idle frequency subbands can be detected by spectral power measurements conducted in each single participating mobile terminal. Hence, the volume of measurement data can become very high. Signaling this overhead in ordinary data frames would leave only few resources left for useful data and would be very error-prone. In this paper, we show that the signaling of spectral resources can be performed in the physical layer that has been harmonized for both considered standards. The basic idea is the superposition of emitted radio power for the signaling instead of creating new higher layer frames for the measured data. Furthermore, a robust method to broadcast information on spectral resources back to the mobile terminals is presented.**

Keywords— **Radio resource management, spectrum pooling, OFDM, wireless LAN**

I. Introduction

THE success of future wireless systems will depend on the concepts and technology innovations in architecture and in efficient utilization of spectral resources. There will be a substantial need for more bandwidth as wireless applications become more and more sophisticated. This need will not be satisfied by the existing frequency bands being allocated for public mobile radio even with very evolved and efficient transmission techniques. Measurement campaigns [1] have shown that wide ranges of potential spectral resources are used only very rarely. In the presented approach that is called spectrum pooling, different spectrum owners (e.g. military, trunked radio etc.) bring their frequency bands into a common pool from which rental users may rent spectrum. The notion spectrum pool was first mentioned in [2]. It reflects the need for a completely new way of radio resource management like in [3]. Interesting aspects of the spectral efficiency gain that is obtained with the deployment of spectrum pooling were discussed in [4].

A potential rental system needs to be highly flexible with respect to the spectral shape of the transmitted signal. Spectral ranges that are accessed by licensed users have to be spared from transmission power. OFDM modulation is a candidate for such a system as it is possible to leave a set of subcarriers unmodulated. Thus, providing a flexible spectral shape that fills the spectral gaps without interfering with the licensed users. A schematic example of this method is given in Fig. 1. Refer to [5] for a detailed description. Furthermore, spectrum pooling systems are not supposed to compete with existing and upcoming 2G and 3G standards. They are rather meant to be a complement in hot spot areas with a high demand for bandwidth (e.g. airports, convention centers etc.). Hence, it is straightforward to apply modified versions of OFDM based wireless LAN standards like IEEE802.11a [6] and HIPERLAN/2 [7].

There are many modifications to consider in order to make wireless LANs capable of spectrum pooling. They range from front end via baseband processing [8] to higher layer issues. One important task when implementing spectrum pooling is the periodic detection of idle subbands of the licensed system delivering a binary allocation vector as shown in Fig. 1. A detailed description of how to perform this in an optimal fashion is given in [9]. We propose an approach where any associated mobile terminal of the rental system conducts its own detection. This detection is the first step in a whole protocol sequence that is illustrated in Fig. 2. Having finished the detection cycle, the results are then gathered at the access point as visualized in Fig. 2b). The received information can be processed by the access point which basically means that the individual binary (allocated/deallocated) detection results are logically combined by an OR operation.

Thereafter, a common pool allocation vector which is mandatory for every mobile terminal is broadcast in a last phase as shown in Fig. 2c). It is shown in [9] that this distributed technique is more reliable and yields a higher system throughput than only having the access point conduct a spectral detection. However, if the collection of the detection results is realized by sending a MAC layer data packet for each mobile terminal, the signaling overhead will be very high as the number of mobile terminals can be as high as 250 in the considered wireless LAN systems.

Now, one could reduce the number of detecting mobile terminals. Unfortunately, this approach has several drawbacks. The random choice of the detecting rental users would not guarantee an optimal spatial distribution of the detecting mobile terminals. The transmission of these results would still take a lot of time and their correct reception is disturbed by rental users that have accessed their subbands since the last detection cycle. One further problem is the redundancy in the measurement data.

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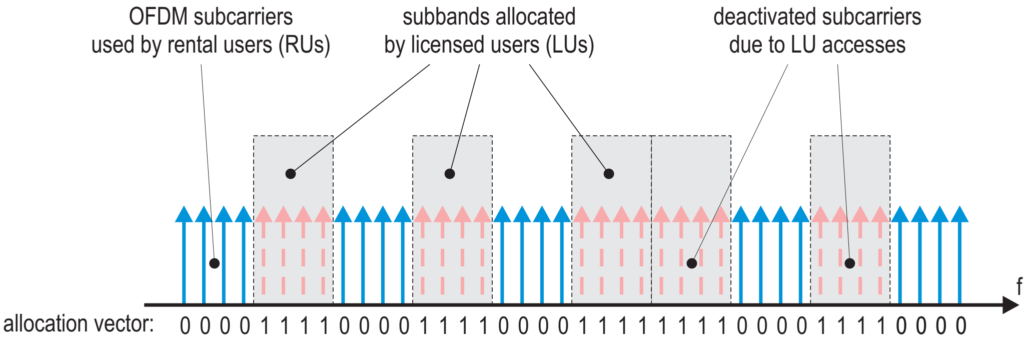

Fig. 1. Schematic example of an OFDM based spectrum pool

Several mobile terminals can encounter the same constellation of licensed user accesses. We investigated techniques like the adaptive tree walk protocol [10] to reduce the amount of measurement data packets but none of them was satisfactory with respect to duration and robustness.

This paper presents an approach where the signaling is carried out in the physical layer saving a lot of transmission time for useful data packets and providing more reliability in the detection result. Our collection technique that is called boosting protocol is divided into two different phases. In the first phase, subbands are signaled that are newly accessed since the last detection cycle. A detailed description is given in section II-A. The second phase is dedicated to signaling subbands that have become idle since the last detection cycle. This phase is more complex than the first one. Reasons for this and an explanation of the algorithm is subject of section II-B. Having processed all the individual spectral measurements, the access point has to broadcast information on the current allocation situation in the pool. This allocation vector is mandatory for the data transmission until the next detection cycle. A very robust and yet fast method for the broadcast phase is presented in section III.

II. Collection of the Measurement Data

A. First Phase of the Boosting Protocol

The basic idea behind the first phase is quite simple. Having performed their detection, the mobile terminals compare their detection result with the mandatory allocation vector that was broadcast by the access point after the last detection cycle. If a mobile terminal encounters a spectral access by a licensed user to a certain subband which was not announced by the access point, then it transmits complex symbols at maximum power level (e.g. $1 + j1$) on these OFDM carriers where the *new* licensed user accesses were detected. This results in a power amplification of the licensed user signal. The remaining OFDM carriers are spared from energy by transmitting complex zeros $(0 + j0)$.

The access point continues to detect the incoming signal which is a superposition of the transmitting licensed users and all the boosting signals of the mobile terminals. Thus, the licensed user signal has a boosted power level resulting in a higher detection probability at the access point. This boosting period T_{B_1} has to be long enough in order to obtain the desired level of detection reliability. However, it is to be kept as short as possible as the boosting of the mobile terminals decreases the SNR of the licensed system. This trade-off is subject to further investigations.

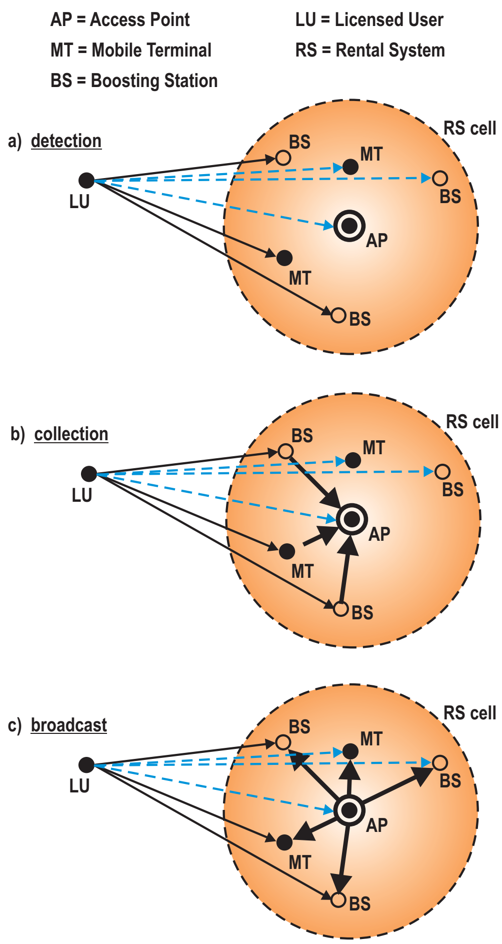

Fig. 2. Protocol cycle of detection, collection and broadcast

This approach kills two birds with one stone. First, the detection results of all mobile terminals are gathered simultaneously. Hence, the transmission of an individual data frame containing the detection results for each mobile terminal is not necessary.

This results in a substantial decrease of signaling overhead. Secondly, the additive superposition of the boosting signals replaces the necessary logical OR operation of the individual detection results at the access point and makes buffer memories dispensable.

Fig. 3a depicts an exemplary common pool allocation which has been broadcast by the access point after the last detection cycle. After a new detection, an individual mobile terminal may encounter a new individual pool allocation as shown in Fig. 3b. One subband was newly allocated by a licensed user (dark gray). Another one was deallocated (light gray). The rest of the pool allocation remains unchanged. As described above, the OFDM carriers representing the newly allocated subband are boosted (Fig. 3c). This results in a much higher detection probability at the access point. Quantitative analytical and simulative evaluations of the relation between the received signal power and the detection probability are given in [9].

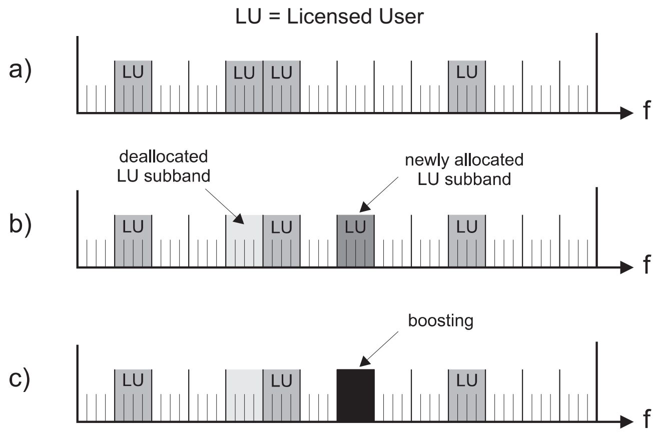

Fig. 3. Process flow of the first phase of the boosting protocol

B. Second Phase of the Boosting Protocol

The second phase of the boosting protocol is there for the signaling of the deallocated subbands of the licensed system (light gray in Fig. 3b). If one wants to exploit the benefits of the described boosting technique for this task, one encounters the following problem. Unfortunately, the additive superposition of spectral power can only perform a logical OR operation as described in section II-A. However, a certain subband can only be considered deallocated if *every* mobile terminal delivers this detection result which actually requires a logical AND operation. One solution to this problem is *not* signaling the *de*allocated subbands by boosting them, but signaling the ones that remain allocated (logical negation).

As we do not want to disturb the licensed system, this signaling is conducted on the idle OFDM carriers from the last detection cycle (white ranges in Fig. 3a). Therefore, a one-to-one mapping between allocated subbands and idle subbands is necessary which is known in every mobile terminal. The mapping algorithm is illustrated in Fig. 4a. The first allocated subband

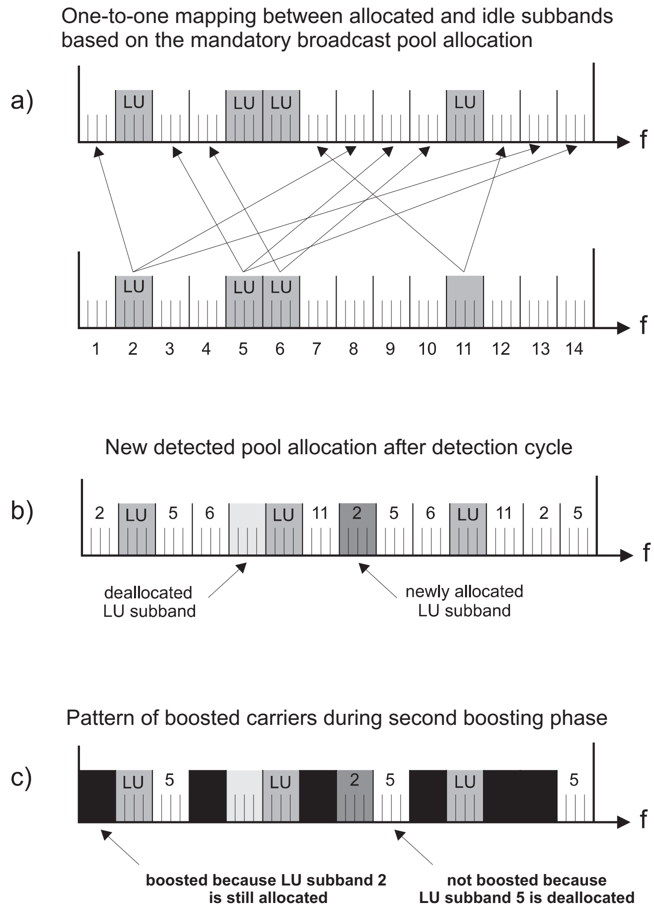

Fig. 4. Mapping and boosting during the second phase

is mapped to first idle subband. Then, the second allocated subband is mapped to second idle subband and so on. In the sequel, two different cases are conceivable.

First, there are more idle subbands than allocated subbands. In this case, the mapping can be cyclically continued until there are no more idle subbands left. This results in a redundant and thus more reliable detection at the access point. Secondly, if there are more allocated subbands than idle subbands, the second phase of the boosting protocol must be extended in the time direction by further boosting frames. The duration of each of these frames is the same as the temporal length of the first boosting phase. The same trade-off between detection reliability and temporal overhead applies for the second phase as described in Sec. II-A. The allocated subbands that could not be mapped to an idle subband in the first frame are mapped to a second frame starting with the first idle subband again. If there are only few idle subbands, this temporal extension has to be repeated until every allocated subband could have been mapped.

The result of the mapping is shown in Fig. 4b. The numbers denote the allocated subbands mapped to the idle subbands. Now, only the subbands that remain allocated are boosted (black in Fig. 4c). The idle subbands that have been mapped to subband number 5 are *not* boosted as subband number 5 has been deallocated (light gray in Fig. 3b). The access point knows the

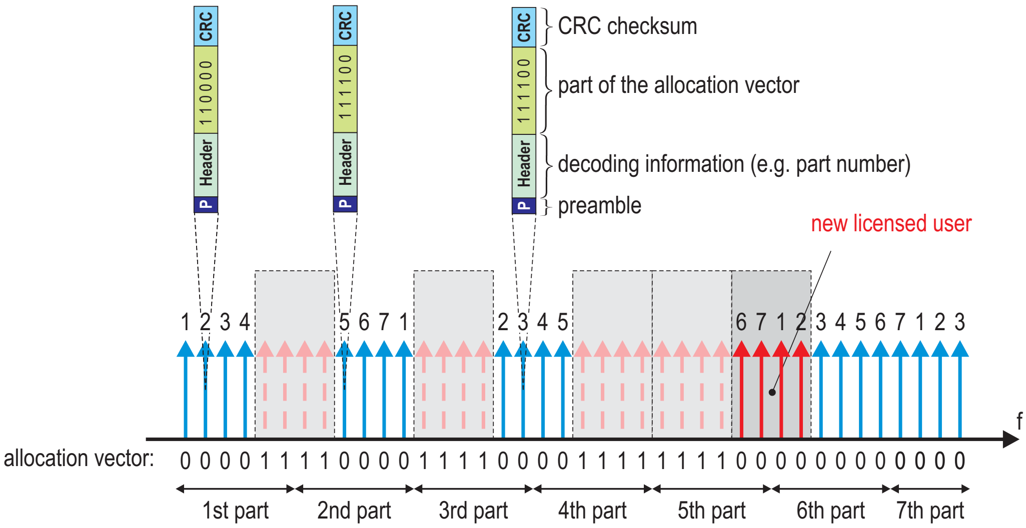

Fig. 5. Broadcast method for the allocation vector

one-to-one mapping algorithm and is able to detect the superposed signal of all measuring mobile terminals.

However, one cannot neglect that this method has two minor drawbacks. The duration T_{B_2} of this second phase of the boosting protocol is not constant in time but depends on the actual number K of allocated subbands. If one assumes that one frame of the second phase has the same duration as the first phase T_{B_1}, one can express T_{B_2} as:

$$T_{B_2} = T_{B_1} \cdot \left\lceil \frac{K}{N-K} \right\rceil, \tag{1}$$

where N is the total number of licensed user subbands in the pool and $\lceil x \rceil$ denotes the smallest integer value greater than x. Another downside is that newly allocated subbands coincide with mapped subbands as one can see at subband 8 in Fig. 4c). These subbands must be ignored by the access point. In case of redundant signaling, other subbands can be considered for the decision whether or not a certain subband was deallocated by a licensed user e.g. subbands 1 and 13 in the depicted example. In case of non-redundant signaling, the access point needs to assume that the subband is still allocated. Fortunately, this (not necessarily wrong) decision only holds for one detection cycle as the mapping changes due to the new licensed user constellation. Hence, the only drawback is that the rental system cannot use all potential subbands for the duration of one detection cycle. The licensed system does not encounter any interference with this method.

III. Broadcasting the Allocation Vector

Once the boosting protocol has finished, the access point has knowledge about the actual pool allocation. The task is to distribute this information among all associated mobile terminals *and* the ones that want to get associated. The presented boosting technique cannot be applied as the transmission between access point and mobile terminals on each carrier is not reliable due to multipath fading. It is very important that every mobile terminal receives the *same* allocation vector because otherwise the licensed system would be disturbed or the transmission within the rental system would fail. Hence, the access point must feature a very reliable and still fast transmission scheme for this task. The last valid allocation vector forms the basis for the choice of frequency ranges that can be used as it is the only guaranteed system wide information. The most actual measurements from the latest detection cycle cannot be used as they can differ individually.

A straightforward way of solving this problem might be encapsulating the new allocation vector in a regular MAC packet and using a powerful channel coding scheme. The problem with this method is that a licensed user might have accessed its subband since the last detection cycle. This results in a substantially increased bit error rate. This drawback gets even worse the larger the number of OFDM carriers per licensed user subband is. The bit error rate can easily be in the order of 10^{-1}. No known error correction technique can cope with such a bad raw bit error rate.

Hence, a new method is proposed as illustrated in Fig. 5. First, the allocation vector is cut in parts. Each of these parts, a cyclic redundancy checksum (CRC) and the corresponding coding redundancy form one packet. In the depicted example, the allocation vector is cut in 7 parts which are transmitted serially in the time direction on one specific OFDM carrier. Of course, at low transmission rate i.e. BPSK and code rate $1/2$. Each packet is not only transmitted on one single OFDM carrier but their transmission is cyclically repeated (at least three times) in the frequency direction. The numbers on each OFDM carrier in Fig. 5 refer to the specific part of the allocation vector which is transmitted on the corresponding carrier. The triple redundancy guarantees that the receiving mobile terminal still has two further OFDM carriers to get the information from in case that one carrier is temporarily faded. Newly accessing licensed users pose another interfering source as the old allocation vector still applies. This distortion can also be overcome by the redundancy in the frequency direction. Hereby, the access point has to make sure that each packet and its redundant copies do not interfere with too many new licensed user. The individual position of a packet within the OFDM carrier range does not matter as each packet carries its specific number. Hence, they are always identifiable without the a priori knowledge of their respective positions.

Since the single packets are broadcast on one carrier only, they can be decoded *without* the valid allocation vector. Therefore, a mobile terminal only needs to decode the bits on *every* carrier. The carriers that are occupied by licensed users deliver no useful information which is recognized by the CRC. This is substantially important for mobile terminal which are not yet associated to the rental system as they do not have the latest valid allocation vector available. One further problem is the choice of an appropriate preamble which can provide time and frequency synchronization in presence of licensed users and *without* the knowledge of the allocation vector. However, this problem was addressed and solved in [8].

There are still some parameters to be optimized in order to make the broadcast as fast as possible e.g. the number of parts the allocation vector is split into. Furthermore, it is not yet clear whether a fixed or a flexible partitioning is better. However, there are general restrictions that limit parameter space. In [8] it is shown that 16 is the minimum number of OFDM carriers at which a rental system can still be operated. The redundancy level of the broadcast shall be 3 as mentioned above. The length of the CRC should be greater than 8 bit in order to ensure a sufficient error recognition performance.

No. of OFDM carriers per LU	1	2	4
fixed partioning (4 parts)	22	16	13
fixed partioning (5 parts)	21	16	14
flexible up to 8 parts/pool free	20	17	16
flexible up to 8 parts/pool busy	24	19	17

TABLE I
LENGTH OF THE BROADCAST PACKETS IN BIT

Two calculation examples clarify the difference between fixed and flexible partitioning. We assume a number of 48 useful data carriers like in the considered wireless LAN standards [6], [7]. In this example, we consider an OFDM based pool where one licensed user subband is covered by one OFDM carrier. Hence, the allocation vector has a length of 48 bits. Splitting into 4 parts results in chunks of 16 bits per broadcast packet. Two further bits are required to identify the respective part and 8 bits are used as CRC resulting in 22 bits after all. If one allows the partitioning to be flexible, not only an identifier for the part is necessary but the overall number of parts as well. Considering flexible partitioning of up to 8 parts leads to 2*3bits=6bits for the identification. If the pool is completely free it is straight forward to apply the maximum number parts i.e. one ends up with chunks of the allocation vector of 48bits/8=6bits. Combined with an 8-bit CRC, this results in 6+6+8=20bits. If the pool has reached its maximum occupancy (16 carriers left) one can only split into 5 parts in order not to violate the redundancy level. In this case the overall packet length is $\lceil 48/5 \rceil$+6+8=24bits.

As one can see from table I, flexible partitioning is only useful in pools with small numbers of OFDM carriers per licensed user subband and low occupancy. Licensed user accesses of a width of one or two carriers are unfavorable anyway. This leads to a higher mutual interference between rental and licensed system due to crosstalk effects of the FFT/IFFT operation is the OFDM transceiver as will be published in an upcoming paper. Thus, fixed partitioning with 4 parts is the best method. Additionally, it does not require empty pools for maximum efficiency. Of course, the expected occupancy of a pool has to be considered during the design stage of a spectrum pooling system. Applying this method together with the preamble scheme (48μs) proposed in [8] results in the overall temporal durations of the allocation vector signaling that are listed in table II.

No. carrier per LU	1	2	4
fixed partioning (5 parts)	224	176	152

TABLE II
LENGTH OF THE BROADCAST PACKETS IN μS

Having in mind a detection cycle of 2ms as proposed in [9] one can see clearly that the proposed method for the signaling of the allocation vector yields a considerable overhead of the order of 10%. However, this overhead is necessary to achieve the required reliability in a spectrum pooling system. If one wants to increase the security even further one could also have the access point transmit the allocation vector again immediately after our proposed scheme but this time in a regular data packet. Then, all participating mobile terminals decode this data packet and only transmit own packets in case of a match between the allocation vectors they received with the two different methods.

IV. CONCLUSION

An efficient method for the signaling of spectral resources in spectrum pooling systems was proposed. The presented approach allows a maximum number of mobile terminals to conduct spectral measurements providing the best possible diversity gain for the detection of spectral accesses of the licensed users. The efficiency is in its avoidance of signaling in the MAC layer which would be time consuming and error-prone. All spectral measurements can be gathered at the access point *at the same time* by exploiting the additive superposition of spectral power. The interference with the licensed system is kept minimal as only newly allocated subbands are boosted for a very short period ($<100\mu$s). Deallocated subbands are signaled without interference with the licensed system using a special mapping algorithm. Furthermore, a very robust and yet fast method of broadcasting allocation information in a spectrum pool even to not yet associated mobile terminals was presented.

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