FILTER BANK MULTITONE:
A PHYSICAL LAYER CANDIDATE FOR COGNITIVE RADIOS

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ABSTRACT

Two muticarrier methods called filtered multitone (FMT) and cosine modulated multitone (CMT) are presented as physical layer protocols for cognitive radio networks. We compare FMT and CMT to orthogonal frequency division multiplexing (OFMD), and show that both FMT and CMT offer higher spectral efficiency. Furthermore, we show that the filter banks in the receiver front-end can also used for channel sounding according to a recently proposed channel sensing protocol. Since in cognitive radio networks, available unlicensed channel resources depend on the traffic of the licensed (primary) users, special requirements for data transmission among secondary users (SU) arise. We present simulation results for the two limiting cases of SU data transmission: optimal scheduling and multi-carrier ALOHA.

1. INTRODUCTION

The demand for ubiquitous wireless services has been on rise in the past and is expected to remain the same in future. As a result, the vast majority of the available spectral resources have already been licensed. It thus appears that there is little or no room to add any new services, unless some of the existing licenses are discontinued. On the other hand, studies have shown that vast portions of the licensed spectra are rarely used [1]. This has initiated the idea of cognitive radio (CR), where secondary (i.e., unlicensed) users are allowed to transmit and receive data over portions of spectra when primary (i.e., licensed) users are inactive. This is done in a way that the secondary users (SUs) are invisible to the primary users (PUs). In such a setting, PUs are ordinary mobile terminals with their associated base-stations. They thus do not possess much intelligence beyond the ability to communicate with their central base-stations. The SUs, on the other hand, should possess the intelligence of sensing the spectrum and use whatever resources are available when they need them. At the same time, the SUs need to give up the spectrum when a PU begins transmission.

A recent proposal [2] has suggested multicarrier communication for CR. The rationale is that any CR needs to sense the spectrum, and this involves some sort of spectral analysis. Since the fast Fourier transform (FFT) can be used for spectral analysis and at the same time act as the demodulator of an OFDM (orthogonal frequency division multiplexing) signal, OFDM has been suggested as the candidate for multicarrier-based CR systems. However, a number of shortcomings of OFDM in the application of CR have been noted in [3] and solutions to them have been proposed. To elaborate, the problems with the OFDM solution originate from the large side-lobes of the frequency response of filters that characterize the channel associated with each subcarrier. This results in significant interference among the subcarriers that originate from different SUs and between PUs and SUs. To resolve/ease this problem, [3] suggests the extension of each OFDM block with long cyclic prefix and suffix samples and the application of some windowing to reduce the side-lobes of the subcarrier channels. Obviously, this solution comes at the cost of bandwidth efficiency because excessive time should be allocated to cyclic extensions that otherwise could be used for data transmission.

In this paper, we propose and discuss methods of using filter banks for multicarrier communication in a CR setup. Two solutions are discussed. The first solution uses subcarrier bands that are non-overlapping. This method is referred to as filtered multitone (FMT) and was originally developed for bi-directional data transmission over digital subscriber lines (DSL) [4], [5]. From a bandwidth efficiency perspective, FMT may not be attractive because of guard/transition bands between adjacent subcarriers. However, it offers advantages from a simplicity point of view. The second solution uses cosine modulated filter banks (CMFB) which we refer to as cosine modulated multitone (CMT). This method is also rooted in DSL [6] and has recently been revisited and applied to wireless applications [7]. CMT offers the advantage of high bandwidth efficiency and the capability for blind equalization [7]. When multiple adjacent bands are used to carry the data of one user, overlapped adjacent bands can be separated perfectly thanks to the reconstruction property of CMFB [8].

The rest of this paper is organized as follows. FMT and CMT are reviewed in Section II. The use of FMT and CMT as spectrum pooling tools is discussed in Section III and simulation results that compare FMT and CMT with the Thomson's multitaper method (MTM) [9] are presented. We use MTM as a benchmark since it is one of the best available spectral analysis techniques [10], [11]. An initial random Medium access control (MAC) protocol for CRs is discussed in Section IV. . We conclude with a brief overview of important problems in the design of CR-networks.

2. REVIEW OF FMT AND CMT

Both FMT and CMT are filter bank based modulation techniques. The main difference between the two methods lies in the way the spectral band is used, as pictorially presented in Figure 1. In FMT, the subcarrier bands are non-overlapping. Thus, separation of different subcarrier signals/information can be achieved by conventional filtering. In CMT, on the other hand, the subcarrier bands are allowed to overlap, and separation is done through judicious design of the synthesis and analysis filters. It is obvious from Figure 1 that CMT offers higher bandwidth efficiency than FMT, since more subcarrier bands can be accommodated per unit of bandwidth.

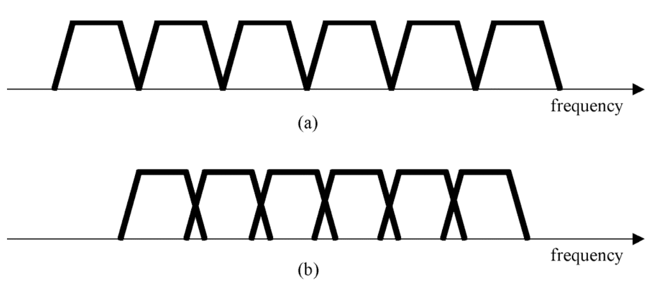

Figure 0: *A presentation of the subcarrier signal spectra of (a0 FMT and (b) CMT*

In conventional frequency division multiplexing (FDM) with non-overlapping bands - such as those in Figure 1(a) - each subcarrier signal is designed to satisfy the Nyquist condition.. In [4] and [5], to improve the bandwidth efficiency of FMT, it is proposed that the symbol rate within each subcarrier band is increased above the Nyquist rate (while the total bandwidth allocated to each subcarrier is kept constant). This introduces a notch in the spectrum of each subcarrier near the band edges. To undo the signal distortion caused by this notch, in [4] and [5] it is proposed that a linear or nonlinear (i.e., decision feedback) equalizer should be used. However, the equalizers proposed are rather complex (over 20 feedforward and feedback taps). In this paper, in order to avoid such complexity, we assume that the subcarrier signals are designed to satisfy the Nyquist condition. Note that with a moderate excess bandwidth of 25%, this is still far more efficient than the OFDM solution proposed in [2] and [3]; there, to cope with the frequency containment requirements, as much as 100% cyclic prefix overhead has been suggested. Although CMT offers a bandwidth efficiency advantage over FMT, FMT may be found to be a better choice from an implementation point of view. The distinct frequency bands of the subcarriers allow for easier handling and offer more flexibility (in particular, parallelism) in post processing of signals at the receiver. For instance, an FMT signal with hundreds, or even thousands, of subcarrier bands may be successively partitioned into smaller blocks and accordingly down-sampled to lower rates before further processing. Such a multistage implementation may prove very useful in practice.

In both FMT and CMT, assuming that each subcarrier band is narrow, subcarriers may be approximated as a channel with a flat fading gain. Hence, equalization after subcarrier separation can be established through a single tap equalizer whose tap weight should be set equal to the inverse of the channel gain. Pilot/training symbols are usually used to initially set the equalizer taps, and subsequent tracking is established through a decision directed method [12]. In CMT, the very special structure of the underlying signals allows for blind equalization, i.e., equalization without training. To explain this, we recall from [7] that the subcarrier symbols in CMT are real-valued - hence pulse amplitude (PAM) modulated - and the modulation type is vestigial side-band (VSB) modulation. The demodulator, as shown in [7], generates a complex-valued signal of the form $(s + ju)g$ for each subcarrier, where s is the transmitted symbol, u is a Gaussian like variable that arises from ISI and inter(sub)carrier interference (ICI), $j = \sqrt{-1}$, and g is the channel gain. By choosing an equalizer gain w such that the distribution of the real part of the equalized signal $[(s + ju)g] \times w$ resembles the transmitted PAM symbols, one can find the equalizer gain within a phase ambiguity of 180°. Using the constant modulo algorithm proposed by Godard [13], it is demonstrated in [7] that the equalizer gain w can be found adaptively and blindly.

To conclude, both FMT and CMT are good candidates for multicarrier transmission in a cognitive radio setup. They both offer a significant bandwidth efficiency advantage over OFDM. Comparing FMT and CMT, we believe that FMT is a better candidate from an implementation point of view. CMT, on the other hand, offers higher bandwidth efficiency and blind equalization capability.

3. SPECTRUM POOLING

A cognitive radio system must be equipped with a spectrum pooling mechanism that continuously senses the radio activity in the environment and decides which parts of the spectrum are available and thus may be used by SUs. Moreover, this task should be performed with a very high probability of correct detection over all active frequency bands in order to minimize interference with PUs. To achieve this, Weiss et al [3] have proposed a distributed spectrum pooling protocol where all the nodes (the base as well as mobile stations) participate in a channel sounding process. In essence, each node in the cognitive radio system is equipped with a spectrum analyzer for sensing of the radio activity over the band of interest. In [3], where an OFDM based cognitive radio is considered, the same fast Fourier transformer (FFT) that is used for demodulation of the "payload" signals is also used for spectral analysis. Haykin [11], on the other hand, has noted the potential problems of spectral estimation using FFT and instead has proposed the Thomson's multitaper method (MTM) [9] as a better candidate.

Here, we propose filter banks as an efficient tool for spectral analysis. On the same basis as [3], we argue that this analysis is at almost no additional cost, since in our proposed system, filter banks are running as the receiver front end. Spectral analysis can now easily be performed by calculating short-term averages of the signal power at the outputs of the analysis filter bank. To study the accuracy of such analysis, we analyze the spectral content of a multiband spectrum. Figure 2 presents spectral analysis

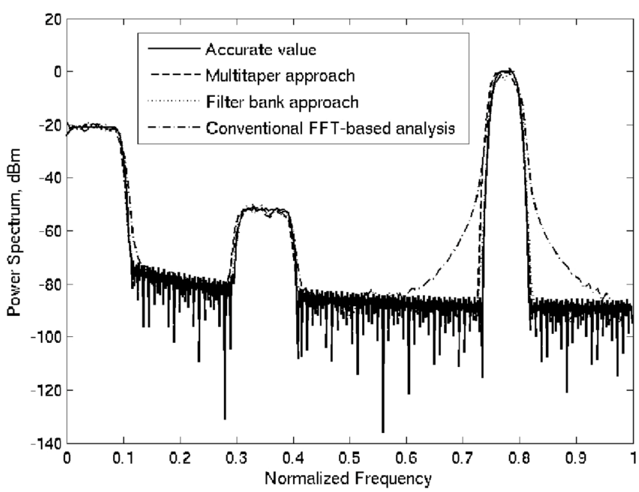

Figure 2: *A snap shot of the estimated power spectra using various methods*

results for our proposed filter bank method as well as results obtained using MTM and a conventional FFT-based approach. For MTM, we have used the MATLAB function "pmtm" which is an implementation of the Thomson Multi-Tapper. In "pmtm", blocks of length 2560 signal samples are analyzed.

For a sampling rate of 100 MHz or greater, this is a very short period of time. The time-bandwidth product parameter ("nw" in "pmtm") is set equal to 9/2. For FFT-based analysis, data blocks of length 256 are windowed using a Hanning window and analyzed and averaged over the duration of the inspected signal. For the filter bank case, we have considered a CMT system with 256 subcarrier bands and a prototype filter of length 256*6=1536. To ensure that the comparisons are done on a fair basis, the signal under inspection is passed through the CMT filter bank, decimated 256-fold, and power estimation is performed by averaging the last four samples of each subcarrier signal.

The results in Figure 2 clearly show that both MTM and the filter bank method work well in locating the occupied portions of the spectrum Both methods can recognize and differentiate signals with a power difference of 50 dB or greater. The conventional FFT-based analysis on the other hand, exhibits some leakage problems; as a result, it appears that the third band in the spectrum (the one with the highest power level) occupies a much wider band. Although the tails of the spectrum are 50 dB or lower below the actual signal level, their presence may be interpreted as a low level signal in a band adjacent to the band where the signal actually exists.

4. PAYLOAD DATA TRANSMISSION IN CR-NETWORKS

In our envisioned system, channel sounding and SU data transmission are understood as two separate processes. After the channel sounding process has been completed, the PU-free channel resources are used by the SUs for data transmission. Due to the multi-carrier nature of our physical layer (being FMT or CMT), we are able to adopt the sounding protocol proposed by Weiss et. al in [3]. In this protocol, subcarriers used for PU transmissions are identified by the SUs in a distributed manner and are signaled across the SU network by boosting a single complex symbol on the occupied subcarriers. A central unlicensed base station (UBS) is responsible for combining the sensing information into a single allocation vector (ALV), which is then broadcast to all SUs. This process is necessary to ensure that with high probability, unlicensed transmissions do not interfere with the licensed users. In our model, the UBS is also the sink for all SU payload data.

In general, any form of SU channel access (sounding as well as payload transmission) is restricted to time slots, which are fractions of the PU-packet time.

In the following, we investigate into the performance of random versus scheduled SU payload transmission to gain a better understanding of the possibilities and limits of cognitive radio networks. In essence, random subcarrier access according to a multi-carrier ALOHA method is the simplest, "most random" technique imaginable in this environment. On the other hand, "optimal" scheduling (optimal in a sense that no request messages are ever lost/delayed) which ensures a minimum retainable SU data rate, represents the other end of the protocol spectrum – a fully controlled SU network.

In our traffic model, the secondary and primary users are modeled as Poisson processes with packet rates λ_s and λ_p respectively. As soon as a certain number of packets in the users' infinite transmission queues are exceeded – herein the threshold is set to 40 packets – the SUs enter the payload transmission stage according to either the scheduled or the random scenario. Furthermore, packet lengths are trimodally distributed with packet sizes of 50, 500 and 1500 bytes and probabilities of occurrence of $p=0.5$, $p=0.4$ and $p=0.1$. This packet length distribution models Internet backbone traffic fairly well [14]. In the random as well as the scheduled system, the total available bandwidth is *12.8MHz* which is then divided into $N = 512$ subcarriers of $B=400kHz$ bandwidth. Out of these 512 subcarriers, each active primary user occupies $W=32$. Note that λ_p and λ_s denote aggregate arrival rates, that is the sum over all assigned/chosen groups of subcarriers. As an example, in this case, PUs can have up to 16 groups of subcarriers. $\lambda_{p,\ effective} = \lambda_p/16$.

We further assume that the system is memoryless; that is users disappear from the network as soon as their queues have been emptied and remain silent until the packet threshold is exceeded again. Also, we assume a noiseless, non-fading channel environment and perfect power control.

4.1 CHANNEL SENSING

In both our scenarios and according to [3], channel sensing is performed every T_s = 5 milliseconds. After each sensing period, the number of available subcarriers for SU payload transmission is given by $n(t) = N - W \times p(t)$, where $p(t)$ is the number of active primary users at time t, W is the number of subcarriers per primary user. Furthermore, the total available bandwidth $c(t)$ is given by $c(t) = n(t) \times B$, where B denotes the bandwidth per subcarrier.

4.2 SCHEDULED SU DATA TRANSMISSION

After channel sensing is complete, admission control is performed by the UBS on the pool of the $n(t)$ subcarriers that have been determined temporarily idle in the PU channel sounding process.
We assume that resource request messages are never lost and are not subject to packet collisions.

The subcarriers are assigned by the UBS in a TDMA, round robin fashion: at each time slot, all the subcarriers are assigned to a single user. In this, our protocol is similar to the CDMA/HDR scheme [15] where all channel resources are allocated to the user with the best channel environment.

Any given SU will only be accepted/can only remain in the system if it is guaranteed a minimum rate R_{min} over the duration T_s. The maximum number of active SUs in the system follows accordingly,

$$k(t) = \frac{c(t)}{R_{\min}}$$

in which $k(t)$ denotes the maximum number of users that can be accommodated. Note again, that $k(t)$ only depends on the activity of the PUs.

Also, let us denote the number of active SUs as $s(t)$; if $k(t)$ is less than $s(t)$, $s(t)-k(t)$ users are selected by the UBS to be in backlog for the following SU transmission period. If, however, $k(t)$ is greater than $s(t)$, $k(t)-s(t)$ (new) users can be admitted into the network.

4.2.1 SIMULATION RESULTS

In our simulations, secondary users are only granted access to the network, if a minimum rate requirement R_{min} of R_{min}=400kbps can be guaranteed.

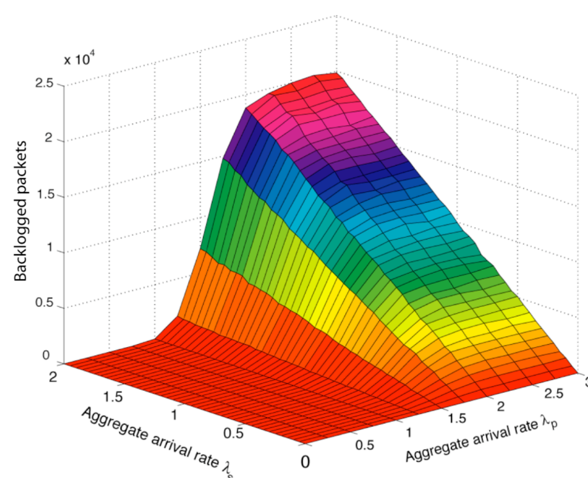

Figure 3: *Assignment scheme, aggregate backlogged packets for all SUs as a function of aggregate SU and PU arrival rates* λ_s *and* λ_p.

As shown in Figure 3, starting from $\lambda_s=\lambda_p=0$, even with increasing λ_s, SU transmission delay measured in backlogged packets, essentially remains zero up to λ_p =1.5.

After this load point, the minimum rate requirements cannot be fulfilled anymore. Now, for a fixed nonzero λ_s, the aggregate SU backlog is monotonically increasing as the traffic of the primary users increases.

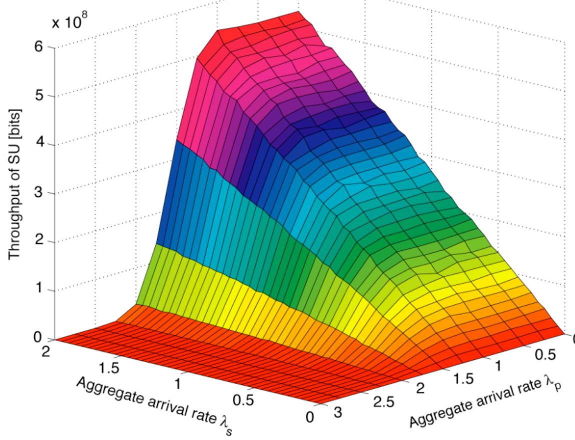

Figure 4: *Assignment scheme, aggregate throughput for all SUs in [bits/s] as a function of aggregate SU and PU arrival rates λ_s and λ_p*

Similarly, as shown in Figure 4, the throughput of the secondary users increase linearly with λ_s, as long as the arrival rate λ_p of the primary users stay below $\lambda_p = 1.5$. For higher values of λ_s at $0<\lambda_p<1.5$ the throughput of the SU network will eventually saturate as all available subcarriers have been assigned. Obviously, as λ_p increases, the maximum possible throughput for the secondary users decreases and eventually goes to zero. It is important to note, that this (optimal) scheduling scheme allows achieving the capacity of the channel, making it one corner stone of possible protocols for CR networks.

4.3 MULTI-CARRIER ALOHA SU DATA TRANSMISSION

In our assignment scheme, SUs are serviced as long as sufficient channel resources are available. Backlog/delay is only caused by denied resource requests due to insufficient channel resources.

In contrast to this, in our random accessing scheme, delay is primarily caused by packet collisions.

As described in Section 4, as soon as the number of packets in the users' queues exceeds 40, the SUs randomly select $W=10$ subcarriers out of the ones determined free. In essence, this solution is a multicannel ALOHA protocol. After serial-to-parallel conversion, messages corresponding to one packet are distributed randomly over a number of different subcarriers. Let p_l be the probability that subcarrier l is chosen and let A_t be the set of $n(t)$ available subcarriers, at time t. Then, we have

$$p_l = \frac{1}{n(t)}, \quad \text{for every } l \in A_t$$

From here we calculate the throughput T for all SUs per subcarrier as:

$$T = \frac{\lambda_s}{n(t)} e^{-\frac{\lambda_s}{n(t)}} \qquad (1)$$

We do not assume the use of coding over subcarriers; that is, as soon as *one* subcarrier has been chosen by more than one SU, we assume that the transmissions by all involved SUs are lost.

Define the indicator function θ:

$$\theta = \begin{cases} 1 & \text{if a subcarrier belongs to more than one group} \\ 0 & \text{else} \end{cases}$$

Note that θ modulates the collision probability as a function of group size W of contiguous subcarriers, $s(t)$ and $n(t)$. As a result, the effective throughput T_{eff} becomes:

$$T_{\text{eff}} = n(t) \times T \times \Pr\left\{\theta = 0 \middle| \left(n(t), s(t), W\right)\right\} \qquad (2)$$

Note that only in the trivial case when $n(t)=N$, implying that $\lambda_p=0$ and W is small, the conditional probability in (2) simplifies to the classical multichannel ALOHA equation. In all other cases, $n(t)$ and $s(t)$ can be modeled as a homogeneous Markov chain. In the following, we will present simulation results based on (2).

4.3.1 SIMULATION RESULTS

Figures 5 and 6 present simulation results for the ALOHA scenario.

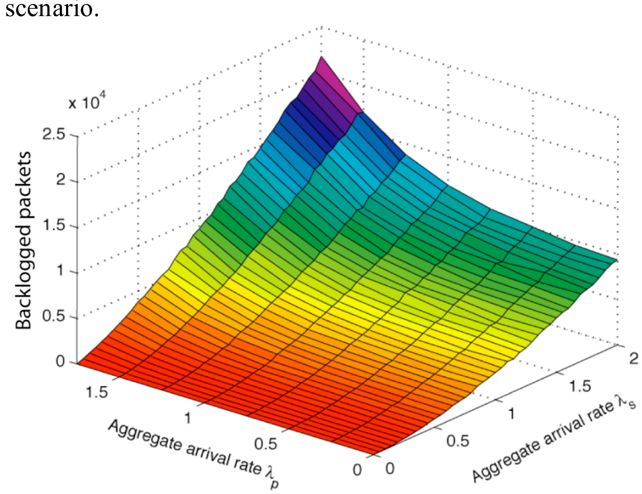

Figure 5: *Random scheme, aggregate backlogged packets for all SUs as a function of aggregate SU and PU arrival rates λ_s and λ_p.*

Since now, SU payload transmission is not only limited by PU transmissions but also SU/SU collisions, aggregate backlog/delay is only zero when $\lambda_p=\lambda_s=0$.

In essence, the system suffers from the instability problems of ALOHA networks [16]. As expected, as the SU and PU arrival rates increase, system backlog increases monotonically.

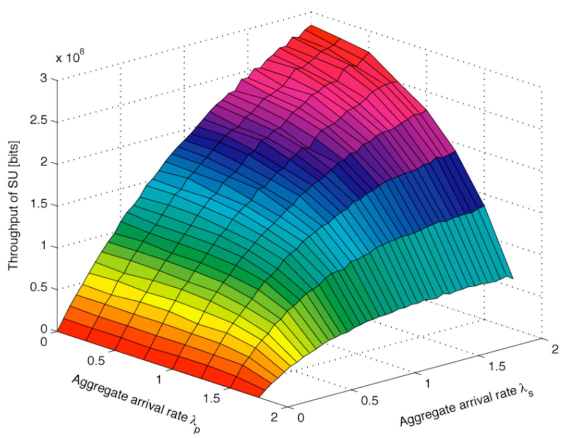

Figure 6: *Random scheme, aggregate throughput for all SUs in [bits/s] as a function of aggregate SU and PU arrival rates λ_s and λ_p*

Figure 6 presents throughput results for varying λ_s and λ_p. Starting from $\lambda_p=0$, the curvature of the SU throughput surface shows the typical ALOHA-shape. As the throughput of the primary users increase, the achievable throughput of the SUs decreases dramatically and is always strictly lower than the throughput achievable with the assignment scheme.

5. CONCLUSION

We presented a novel physical layer approach to multi carrier cognitive radios based on filter bank multicarrier modulation. Two possible modulation candidates named FMT and CMT were introduced. These methods have previously been studied in the application of xDSL technologies. In contrast to OFDM-based solutions, FMT and CMT allow for more efficient usage of spectrum in a multi-user cognitive radio setup. We also proposed filter banks as an efficient tool for spectral analysis. Furthermore, we proposed two possible corner stones of SU payload transmission protocols: optimal scheduling and generic, multicarrier ALOHA. Due to the instability of the multi-carrier ALOHA protocol, a realistic accessing scheme for SU payload transmission should incorporate some sort of SU coordination such as distributed SU channel sounding [13]. Future work focuses on investigation of the cross-layer aspects of FMT/CMT based cognitive radio systems and the development of novel SU data transmission protocols [13].

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