# A LOW-COMPLEXITY ARCHITECTURE FOR MULTICARRIER COGNITIVE RADIO

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## ABSTRACT

The adaptability of cognitive radio enables the development of systems with several favorable capabilities that permit the opportunistic use of spectrum while maintaining cooperative coexistence in densely occupied environments. Many desirable applications of this communications technology favor a stringent minimization of the implementation resources required, even at the cost of limiting the full best-case performance or flexibility. This paper examines an approach to implementing a low-complexity, multicarrier, cognitive radio based on an adaptive sparse realization of an Interpolated Tree Orthogonal Multiplexing (ITOM) structure, along with several additional modem resource optimizations. The performance and cost tradeoffs of this unique configuration are discussed with emphasis on performance impacts.

## 1. INTRODUCTION

There exist categories of applications for which it is desirable to design a multicarrier transceiver that minimizes the cost of implementation per subband carrier. Fortunately, there are several modem architectures available for multiplexing a number of modulated carriers into the same band, the most widespread of which is Orthogonal Frequency Division Multiplexing. In its most popular flavors, OFDM efficiently partitions the band into subcarriers by using the FFT algorithm, providing several positive characteristics among the resultant channels. Indeed, the FFT computational engine is so effective that it is often still more efficient to discard many unused channels of a much larger transform than to implement the discrete channels directly.

However, in some environments other multicarrier architectures become competitive with the OFDM format, particularly when the system requires a limited number of subcarriers and places a premium on minimizing overall complexity. For instance, an interpolated tree of efficient half-band filters retains many of the advantages of the OFDM technique in a straightforward architecture that is easy to adapt. Moreover, the ITOM design easily allows mixing of different bandwidth signals within the same spectrum, a trait with some benefit when the processing overhead per carrier is high or when there is an advantage to transmitting a spectrum that does not look like OFDM.

This paper presents some key features of a modem design for a cognitive radio system based on an adaptive sparse implementation of an ITOM structure. The flexible nature of the half-band tree allows the modem to quickly generate a multicarrier spectral profile as governed by an external cognitive process, based on its datalink requirements. First, we will briefly summarize the characteristics of several modes of OFDM. Next, we will cover the construction of the ITOM, contrasting it with the OFDM polyphase channelizer in congested environments. Finally, we will go over some of the additional modem design choices made to further constrain the complexity of the design implementation.

## 2. BACKGROUND

We desire a modem structure that can service multiple channels of spectral occupancy distributed over a span of selected Radio Frequency bands. These channels can have equal or unequal bandwidths and can be located in various mixes of adjacent or non adjacent spectral bands. For argument sake, let us limit the number of bands to six with bandwidths of 1, 2, 4, and 8 MHz to be placed in a spectral span of 100 MHz with resolution increments of 1 MHz. One approach to this task is to simply build six radios with independent selectable bandwidths and center frequency. This is a rack-and-stack option in which the six radios might share physical resources such as enclosure and cooling but likely not much else. We would like to share some of the signal processing resources with the goal of obtaining real implementation economies of scale.

## 3. OFDM CHANNELIZATION

The economical IFFT (Inverse Fast Fourier Transform) and FFT processes provide the basis for the channelization of the OFDM multicarrier modulations. We will quickly consider the high-level characteristics of three separate versions: standard, shaped, and offset. More detailed


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information on each type is available within other sources [1][2].

In the standard OFDM modulator there are shaping filters external to the IFFT, but no bandwidth limiting filter following it. This gives rise to the sin(πf/NT)/(πf/NT) spectrum of the rectangular envelope. In this configuration, bandwidth efficiency is high, while Inter-Symbol Interference (ISI) and Adjacent Channel Interference (ACI) are both low. However, high side-lobe levels impair the ability to efficiently structure the spectral notches which are necessary in dense environments.

Another flavor of OFDM suitable to support the six band structure of our example is the shaped OFDM modulator and demodulator which is based on the mating of a polyphase matched shaping filter and a companion Fast Fourier Transform. In the receiver section of this structure, the FFT size defines the spacing between channel centers as $f_S/N$, where $f_S$ is the FFT sample rate and N is the FFT length. For the parameters identified above, we can operate the FFT at a 128 MHz sample rate and select a 128 point FFT to obtain the desired spectral 1 MHz resolution for spectral centers. Here 27 of the frequency bands are left vacant to act as a guard band for the transition bandwidth of an interpolator following the transform in the modulator. The polyphase filter has an equal number of paths as the FFT size, specifically 128 rows. The weights of the polyphase partitioned filter define the bandwidth of the prototype low pass filter which in turn is converted to the system channel bandwidths. The transform-based spectral partition is so efficient, that it is possible to compute the output of all 128 channels and then discard the 122 unused channels rather calculate the six channels discretely.

For this example, the bandwidth is selected to realize the maximum from the option list of 8 MHz. We now select the output sample rate of the polyphase partition which is controlled by the commutator process that feeds the polyphase portioned filter. The output sample rate must be selected to satisfy the Nyquist criterion for the widest bandwidth channel of 8 MHz. If data is being delivered to the commutator at 128 MHz rate and we want data to be pulled from the polyphase transform at an 8 MHz rate, we have to down sample 128-to-8 or 16-to-1. Thus the commutator delivers 16 input samples to the top 16 ports of the commutator process and outputs one sample from each of the selected channels formed by the transform. The data in the polyphase filter executes a serpentine shift after every 16-point input sequence to vacate the required input addresses. The output of the polyphase transform must be circularly rotated by successive multiples of the 16-point shifts of the input commutator. If the 8 MHz channel contains a signal component matching the 1, 2, or 4 MHz bandwidth, the channel output series is further processed by an 8-to-1, a 4-to-1, or a 2-to-1 filter to pull down the sample rate to the channel bandwidth.

Note that the polyphase filter structure can accommodate multiple narrowband channels implemented with a single filter that is shared over the multiple alias frequencies obtained by the down sampling mode of the polyphase structure. Similarly, a single efficient FFT is shared over all the potential bandwidths with the unused channel partitions computed and discarded. The option to accommodate multiple bandwidths is realized by a dual conversion scheme in which the channelizer forms a selected subset of time series with reduced bandwidth that has been down sampled and translated to baseband by the common aliasing process. This option is still a contender!

We also note that the reduced side-lobe levels of the polyphase filter structure when compared to standard OFDM makes notched bands practical. While ISI remains low, ACI and bandwidth efficiency suffer. Moreover, the overall complexity is increased due to the added polyphase partitioned filter.

A third flavor, offset OFDM, at the cost of some further complexity, corrects the ACI and bandwidth efficiency problems of shaped OFDM by overlapping shaped symbols by 50 percent.

## 4. ITOM CHANNELIZATION

A unique signal processing option holds the promise of an efficient channelizer implementation by pruning the processing paths that would form the unused channels of the modulator and demodulator. This option is based on a binary partition of the spectral span covered by the modem with a set of common half-band filters. This process has been dubbed the Interpolated Tree Orthogonal Multiplex (ITOM). The tree structure offers the option of accessing different bandwidth channel bands at different depths of the tree structure. In the demodulator in the example, the output of the set of binary partitions and 2-to-1 down samplers at the seventh level in the tree operates at 1 MHz, while the output from similarly processed sixth level of the tree operates at 2 MHz. Tree paths that lead to unused output channels are simply pruned from the signal flow path. The primary architecture presented in this paper addresses the performance and complexity of this alternate spectral partition method.

Like the standard OFDM modulator, the ITOM tree structure uses spectral shaping prior to the multiplexing in a bank of standard shaping filters. The tree performs the orthogonal spectral translation using aliasing inherent in the interpolation process. A baseband signal injected into the tree at any level maintains its spectral profile while still being multiplexed with other carriers into the band. The efficiency of this binary filter tree arrangement comes from the computational economy inherent in the half-band filter structure. Figure 1 shows the impulse response of a half-band filter. Note that the even indices of the impulse


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response are zero, and therefore require no operations to compute. Additionally, the even symmetry of the taps can be exploited to further reduce the number of multiplies by two [3].

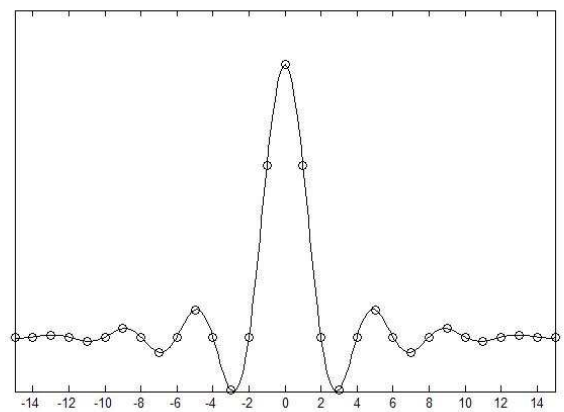


**Figure 1**. Impulse Response of a Half-Band Filter

Figure 2 shows one of the possible block diagrams of a partially populated modulator tree. Up-sampling shaping filters create the spectral profile at the input leaves of the tree. The cascaded half-band filter structure aliases the input signals to a set of center frequencies determined by the sequence of filters. The figure also shows a signal inserted into a branch at an intermediate level of the tree. Signals may be inserted into the ITOM modulator at any level, allowing the straight forward construction a diverse spectrum of various mixed bandwidths.

The final composite multicarrier spectrum possesses both low ISI and ACI, while efficiently using the available bandwidth [4]. Moreover, creating notches in the output band is possible by simply leaving the corresponding branch off the tree. Because the spectra have compact support, these empty intervals effectively null out the modulator's contribution to the composite spectrum at those center frequencies.

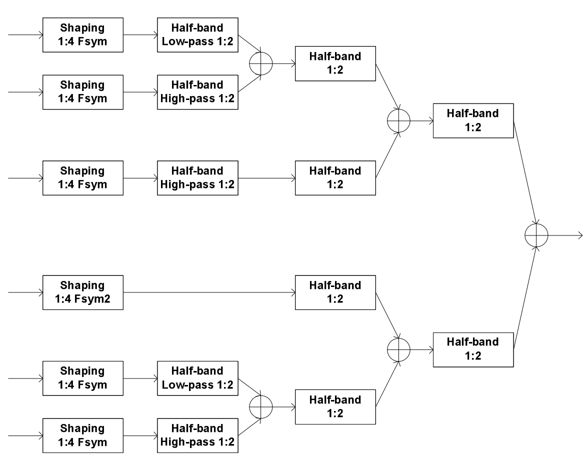


**Figure 2**. Partially Populated Modulator Tree

Figure 3 illustrates the spectrum of an ITOM signal with diverse channel bandwidths as well as unequal widths of unoccupied bands.

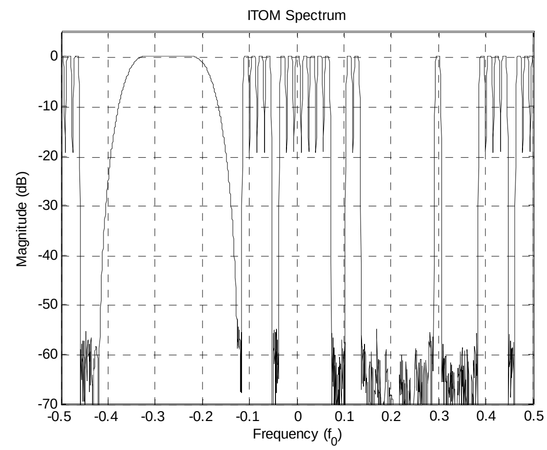


**Figure 3**. ITOM Multicarrier Signal with Mixed Bandwidths

## 5. LOW-COMPLEXITY MULTIPLEXING

Let us examine under what circumstances the tree becomes competitive with a DFT (Discrete Fourier Transform). It has been established that the number of operations needed for an FFT grows proportionally with (N log2(N)), where N can be defined as the number of bins dividing the spectrum[5]. Comparatively, the number of nodes in a full binary tree grows according to $(2^{(\log2(N)+1)} - 1) = (2N - 1)$ or order of 2N i.e., O(2N), again where N is the number of spectral bins or, equivalently, input leaves on the complete binary tree. In the ITOM, each node is a half-band filter with, say, M non-zero taps to be computed. A property of the ITOM modulator is that tracing backwards from the output towards the inputs, the computational workload per stage remains constant. Thus, the total number of operations for the full tree grows according to the function O(NM log2(N)). That is, a full binary ITOM takes O(M) times as many operations as the FFT-based channelizer to construct the composite band.

To make the comparison consistent between the OFDM and ITOM approaches, both structures should have the same full-usage N. This is equivalent to specifying that both structures have the same spectral bin widths. It should then be obvious that the ITOM is as efficient as a DFT when roughly 1/M of the tree structure is used. Figure 4 gives an example of a sparse binary tree with a single full-depth branch as well as a partially populated branch. The full-depth branch requires a cascade of log2(N) interpolated M-tap filters, for a resource usage of O(MN).


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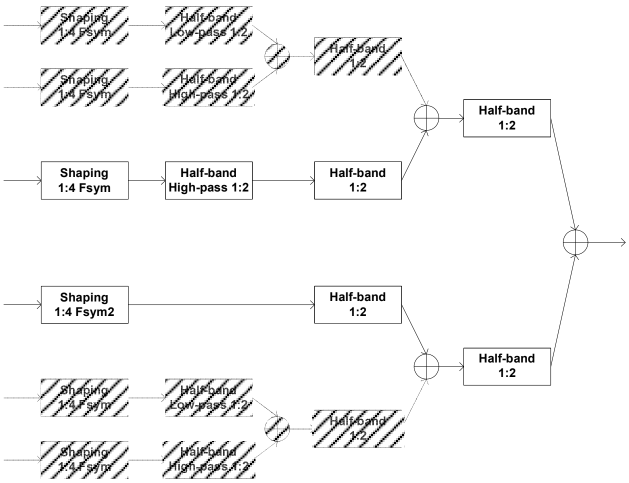


**Figure 4**. Pruned Sparse Binary Tree Structure

Consequently, there can be several advantages to using the ITOM format within a modem. By adaptively trimming the binary tree, a modem can produce non-uniform spectral bins. Moreover, by injecting signals into the tree at various levels a modem can implement mixed bandwidth carriers at any of the rates present. The ITOM structure is an interesting approach for datalink applications because it possesses low computational overhead per subband when the total number of bands is small. It can be used as the basis of adaptive modem blocks of low design complexity while providing many positive interference and efficiency characteristics.

## 6. ADDITIONAL MODEM RESOURCE OPTIMIZATIONS

Our criterion for minimizing the complexity of the design is driven by our desire to reduce the implementation footprint per subband. By judiciously imposing constraints to matched transmitter-receiver pair construction we can obtain significantly simplified architectures that minimize the resource usage per subband. We now examine what can be done to free as many resources as possible for subband receiver circuitry. Figure 5 illustrates a low-complexity approach to a multicarrier receiver structure when the number of active subbands is small.

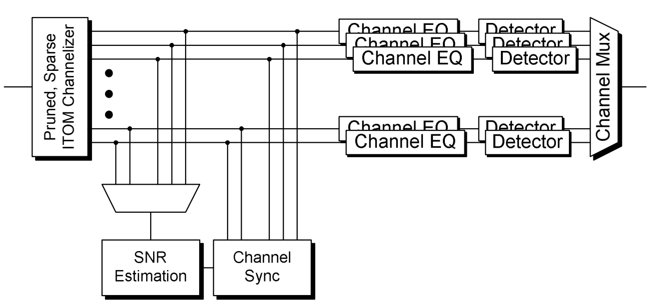


**Figure 5**. Highly Constrained Multicarrier Demodulator

### 6.1 Bandwidth Constraints

Some resource usage must be devoted to channelization regardless of the chosen filtering and multiplexing structure. We have already seen that OFDM and ITOM are inherently efficient means for providing this functionality. If we select the ITOM we note that this structure imposes power-of-two bandwidth constraints on the subcarriers. However, judicious pruning can provide flexibility in channel configuration, enabling mixed bandwidth allocations while retaining low computational complexity.

### 6.2 Carrier Frequency Constraints

Let us now consider an extreme technique for resource savings - the complete elimination of a key functional block from the receiver. We will discuss the conditions under which we can forgo carrier frequency tracking and what the trade offs are in performance are for doing so.

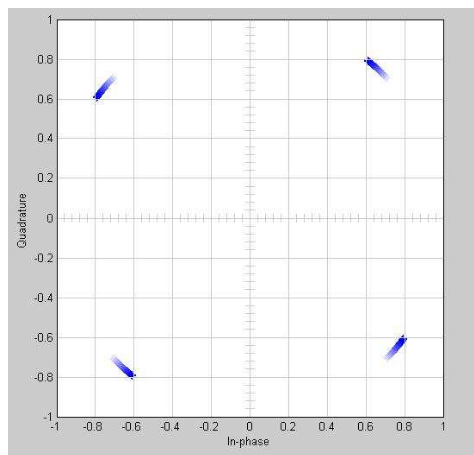


**Figure 6**. Limited Drift of Packet Length Constrained Receiver

By utilizing relatively inexpensive but high precision temperature-compensated frequency references and employing alignment constraints through limited packet or frame lengths, we can force the total frequency error in the carrier recovery process to a satisfactorily small value. For the sake of illustration let us choose to specify oscillators with total frequency error of less than ±2.5 ppm and a packet size of 2048 symbols. (By limiting the packet length we force all accumulated drift to be measured and nullified at the start of each packet via the preamble information.) Let us further assume that the synthesizers for the up and down conversion process are locked to the same reference and have a total phase noise figure on the order of -80 dBc/Hz @ 1 kHz offset. In such an architecture the worst case frequency error for an end-to-end link would be 5 ppm, and therefore the maximum rotation of the received constellation would be approximately 9 degrees over the total length of the packet as shown in Figure 6. This is the


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worst case situation and under normal Gaussian distribution the amount of drift would be less.

Comparatively the degradation of the BER performance due to the lack of frequency error compensation is similar to that of a properly compensated (de-spun) design with a SNR of ~30 dB as shown in Figure 7 below.

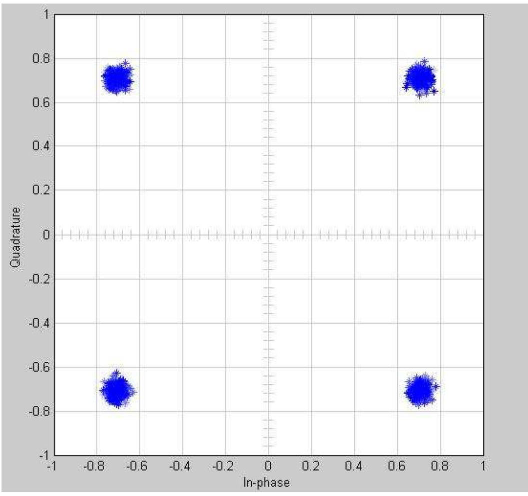


**Figure 7**. Received Data Ambiguity Due to SNR Limitations

We note that for QPSK and 16-QAM modulations the BER performance with 30 dB of signal-to-noise ratio is essentially error free: BER < 1e-15. As the SNR decreases the ambiguity due to external noise will swamp the error due to frequency drift. Thus, a reasonable trade can be made to sacrifice some optimum performance in order to gain appreciable resources per demodulator.

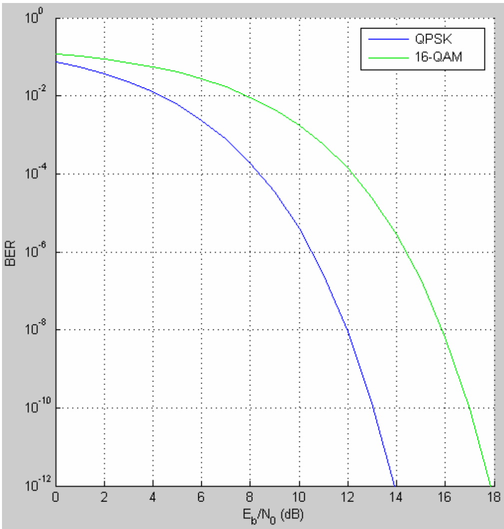


**Figure 8**. Theoretical BER Curves for QPSK and 16-QAM

To put the impact in perspective, consider a QPSK signal with 12 dB of $E_b/N_o$ the degradation in performance is equivalent to a signal which has 11.8 dB $E_b/N_o$. Standard BER curves for QPSK and 16-QAM are shown in Figure 8. At 12 dB, the BER is 0.9e-8, at 11.8 dB it is 1.7e-8 or in both cases approximately of the order 1e-8.

### 6.3 Synchronization Constraints

Operating within the constraints of the sparsely populated ITOM structure, subcarrier bandwidths (and hence symbol rates) are forced to be related by powers-of-two. Through intelligent preamble structuring, synchronization circuits can utilize the energy from all active subbands to obtain high confidence levels of symbol tracking. Information about the signal quality in each subband can be used to weight the synchronization contributions from each thereby greatly improving lock speed and accuracy.

Standard synchronization techniques employ matched filter banks that require a number of multiplication operations. Alternate approaches, however, can perform lock detection without the burden of multiplication. Oversampling the synchronization pattern in the preamble, and constraining the symbol rates to submultiples of the reference clock, allows pattern correlation at the oversample rate to be performed with simple comparison operations.

## 7. SUMMARY

Many techniques exist to reduce the complexity, and therefore the cost, of multicarrier cognitive radio implementations. Adaptive, sparse realizations of an Interpolated Tree Orthogonal Multiplexing (ITOM) architecture offer very attractive resource efficiencies due to the computational economy inherent in the half-band filter. Exploiting the symmetry and null coefficients of the filter saves significant resources and provides for adaptive bandwidth flexibility.

Cognitive processing capability allows radios to operate in crowded signal environments where the available spectrum varies in bandwidth and center frequency offsets. In many applications where adaptability is highly desirable, the radio hardware is often limited in available resources, among which are size, power consumption and processing ability. This paper presented several different techniques that we have used to reduce the complexity of multicarrier radio architectures while minimizing resource usage. By considering the system as a whole and applying strategic constraints to both the transmitter and receiver, a designer can obtain substantial simplifications while retaining flexibility and functionality.

The ITOM structure was shown to be an efficient multiplexing alternative to OFDM when the number of carriers is limited. It was also shown that careful imposition of other constraints including signal bandwidth, frequency tolerance, and packet lengths, provides substantial footprint reduction per subband carrier. Using these techniques and structures, the benefits of cognitive radio can be realized in minimal complexity implementations.


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