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Addressing the Dynamic Range Problem in Cognitive Radios

Jing Yang, Robert W. Brodersen and David Tse

***Abstract*—The discrepancy between perceived spectrum shortage from the FCC allocation map and the actual abundance of available spectrum is a motivation for Cognitive Radios, which locate and transmit in the unused or lightly used bands. If a digital approach is taken to provide the necessary radio flexibility to exploit this sparsity, there is a challenging dynamic range requirement in the analog to digital conversion, since there are large interfering signals which are effectively in-band and can not be removed by fixed RF pre-filtering.**

Using a mixed analog digital system architecture which uses multiple low accuracy ADCs with digital adaptive filters, it is possible to increase the effective dynamic range of the input by subtracting off the unwanted signals in the time domain.

***Index Terms*—adaptive signal processing, dynamic range reduction, interference cancellation, cognitive radios**

I. Introduction

WHILE it is commonly believed that there is a crisis of spectrum availability at frequencies that can be economically used for wireless communication [1], measurements clearly show this is a misconception (Fig. 1) [2]. For example, the actual utilization in the 3~4 GHz band is 0.25%, and drops to 0.13% for 4~5 GHz and does not exceed 5% in 5~6GHz. While all the bands have allocations, it is clear that the allocations are not all being utilized. The Cognitive Radio (CR) approach is to treat these allocated users as Primary Users and to avoid them through a strategy of sensing to find the unused bands and then to transmit while the primary user remains absent [3].

At the CR transmitter, this sensing and transmission function is performed over the widest possible bandwidth consistent with implementation constraints to give the highest probability of detecting unused spectra. The unique sensing function of Cognitive Radios therefore forces the receiver front-end to provide wideband signal reception, from the antenna to the Analog to Digital Converter (ADC) which will have a GHz sample rate if GHz bandwidths are to be exploited.

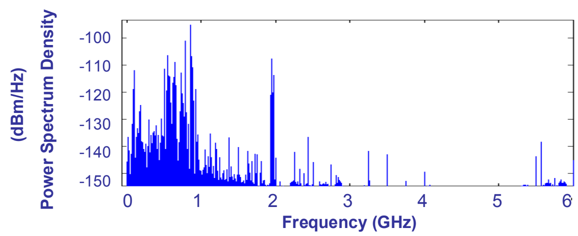

Figure 1. Snapshot of current utilization up to 6GHz received from a wideband antenna showing the actual availability of spectrum.

In this very wide band, there may be interfering signals that are much stronger than the CR signal of interest, resulting in signal to interference ratios as low as -50dB. This requires a large dynamic range for the front-end circuitry and in particular for the ADC which must accommodate the large interfering signals while still provides sufficient quantization performance for the weak CR signal.

Fig. 2a represents a typical radio system. The automatic gain control (AGC) is used to present a full scale signal to the signal path ADC so that all bits of the ADC are utilized. However, because the interfering signal is strong, the gain is limited and the CR signal cannot be amplified enough to achieve sufficient quantization accuracy. For example, to achieve a 20dB signal to quantization noise ratio, the required resolution of the ADC would be on the order of 12 bits or greater if there is an SIR of -50dB. This level of accuracy, with GHz sample rate results in an essentially infeasible ADC implementation if there are power and cost constraints [4], since the power and ADC complexity rises nearly exponentially with the number of bits.

To reduce the interfering signals to a level that doesn't result in such difficult dynamic range requirements, an approach is to estimate the interference signal and simply subtract it off from

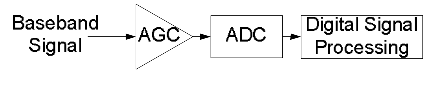

Figure 2 a). Typical baseband radio system.

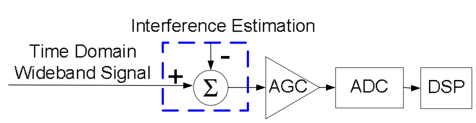

Figure 2 b). An approach to time domain interference cancellation.

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The authors are with Berkeley Wireless Research Center, Wireless Foundation, Department of Electrical Engineering and Computer Science, University of California, Berkeley, Berkeley, CA 94704 USA. E-mail: {yangjing, rb, dtse}@ eecs.berkeley.edu

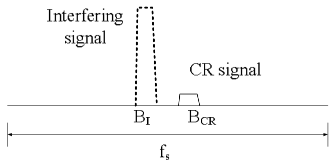

Figure 3. The interfering and CR signal features.

the main signal path. Among all the degrees of freedom, we have investigated interference cancellation in the time domain, due to the special property of the wideband reception for the CR signal. Interference is mitigated on a sample by sample basis as shown in Fig. 2b. By this way, we can eliminate the large interfering signals, therefore reduce the dynamic range requirements on the signal path ADC to the level needed for simply decoding the CR signal (e.g., the 20dB level in the example mentioned previously).

To be able to estimate the interference and separate it out from the CR signal of interest, there must be some features that distinguish the CR signal from the interference. We exploit two such distinguishing features, summarized in Fig. 3. First, we assume the interference is significantly stronger than the CR signal. This allows us to estimate the interference accurately by directly quantizing the wideband signal, with little error caused by the presence of the weak CR signal. Second, we assume that most of the power of the CR signal is outside the bandwidth of the interference. In fact, the second feature is sufficient, but not necessary. We will discuss more in Section III.

There is an interesting analogy between our approach and the information theoretic analysis of the interference channel [5]. It has been shown that very strong interference is almost innocuous as no interference at all. This comes from the fact that when the interfering signal has a high signal to noise ratio compared to the signal of interest, it can be accurately reconstructed, treating the signal of interest as noise, and then subtracted off [6].

Measurements indicate most of the strong in-band interference can be treated as narrow band with respect to the GHz CR bandwidth. Therefore, due to the high oversampling ratio of interfering signal, there exists a high correlation between samples. This correlation provides us with a further gain in estimating the strong interference without actually decoding it.

The paper is organized as follows: Section II develops the mixed signal architecture for a time domain cancellation system and discusses the critical analog design issues including the delay element and mixed signal design requirements. Cancellation digital processing techniques are illustrated and explained in Section III. In Section IV, the proposed system is evaluated through simulation under different environments, and the results show the effectiveness of the dynamic range reduction and feasibility of circuitry implementation.

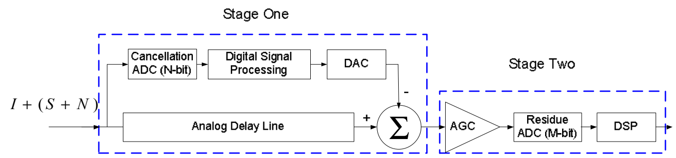

Figure 4. Feedforward architecture for time domain interference cancellation.

II. MIXED SIGNAL ARCHITECTURE

Fig. 4 illustrates a proposed radio front-end architecture which uses active cancellation of strong interferers to reduce the dynamic range requirements of our proposed CR receiver. An estimation of the interference is created in the cancellation path to be used for subtraction of the strong interference and thus reduces the dynamic range requirements of the ADC in the signal path (the Residue ADC).

We consider an input signal composed of the CR signal of interest, strong in-band interference and thermal noise. The input signal branches into two paths, one of which immediately quantizes through a high speed low resolution ADC (the Cancellation ADC). The active interference cancellation is achieved through the use of an adaptive linear filter and reconstruction digital to analog converter (DAC) in the cancellation path. Since the ADC, digital signal processing (DSP) block and DAC involve a processing delay, t, this same delay must be added to the main signal path to align the signals in the two branches for proper cancellation. The analog delay line has linear phase for the entire band of interest, so that the group delay can be constant. The noise level added through the delay line should be sufficiently below the CR signal level to retain high sensitivity for detection.

The whole system can be regarded as a selective AGC which amplifies the CR signal, but not the interfering signals. This technique allows two low-resolution ADCs with N and M bits to substitute for a single high-resolution ADC of greater than $N + M$ bits. The system is composed of two basic mixed signal stages. Stage one involves the interference subtraction, with its output (residue signal) including the CR signal, the cancellation error and noise. Stage two then amplifies this residue to full scale of the Residue ADC, and performs additional digital filtering to pass only the CR signal.

III. CANCELLATION DIGITAL PROCESSING

The digital signal processing in the cancellation path are required to estimate the interfering signals, while ignoring the CR signal, so that it is not also subtracted off along with the interfering signals. After the signal is quantized by the relatively low N-bit resolution Cancellation ADC, a white quantization noise will be added. As mentioned before, since it is assumed that the interfering signals are narrow band signals, a high oversampling ratio of the interfering signal can be exploited in the estimation.

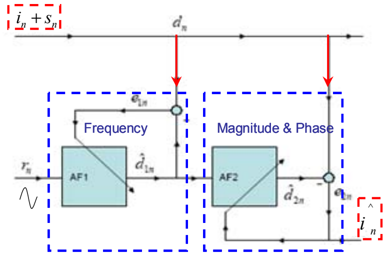

Figure 5. Dual Adaptive Filter block diagram.

The more accurate the interfering signal can be estimated, the more effectively it can be cancelled and hence the larger gain could be in the AGC before saturation will occur in the following Residue ADC. The goal is to be able to amplify the CR signal to full scale of the ADC so that the full *M*-bits of the Residue ADC will be available for quantizing the CR signal.

To measure the estimation accuracy, the time domain sample-by-sample difference between the interfering signal and its estimation needs to be tracked. We use the mean squared error (MSE) to estimate the power level attenuation achieved for the strong interference and for the in-band noise.

A. Dual Adaptive Filter (AF)

When the interfering signal is narrow band, the high oversampling ratio enables the reference signal to be a sinewave for an adaptive filter, which is a special feature for the Cognitive Radio systems. Ideally, the filter would only pass the band where there is interference and strongly attenuate other bands.

To estimate the interfering signal and deal with the time-varying environment, we choose to use a two stage adaptive filter process [7], after comparing the single and dual filter approach (Fig. 6). The first stage uses the time varying behavior of the normalized least mean square (NLMS) adaptive filter with a large step size to produce a frequency locked estimation of the interference. The large step size therefore enables us to track the time-varying interferer by rapidly adapting to any changes in the interfering signal, such as occurred with data modulation or with the burstiness of the interferer. This stage adapts in a single step, which results in an extremely short settling time. The second stage uses NLMS with a small step size as an approximation to the ideal Wiener filter [8] to correct the phase and magnitude of the output from the first stage and produce an interference estimate suitable for cancellation. It operates more conventionally using a small step size to ensure that the pass band of the filter around the interference frequency is narrow enough to provide the least possible distortion to our CR signal and minimum filtered quantization noise.

To ensure the same group delay over the entire bandwidth, a linear phase filter is required. This is accomplished by forcing the coefficients in the adaptive filter to be symmetrical.

B. Processing Gain and Interference Attenuation

It is possible to achieve extra processing gain by filtering out

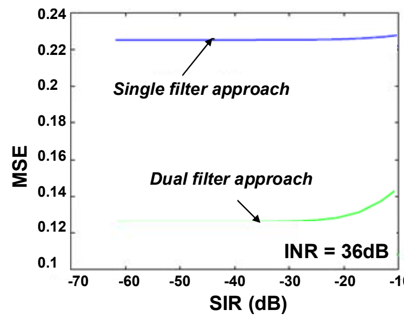

Figure 6. System performance comparison: MSE of a dual adaptive filter is less than twice the single adaptive filter approach and is less sensitive to the environment.

the quantization noise outside of the interference band, which would contribute significant power to the residue after the subtraction of the interfering signal. We also achieve additional processing gain when the CR signal is narrow band. By using a very narrow band digital filter around the center frequency of the CR signal, the quantization error from the Residue ADC can be significantly reduced by a digital bandpass filter.

In the following analysis, we measure the processing gain and the interference attenuation by computing the MSE throughout the receiver signal path. Without loss of generality, we assume the power level of a single existing in-band interferer to be P_I, and that of the CR signal to be P_{CR}. Both are assumed to have a flat spectrum over their own signal bands with $P_I >> P_{CR}$ (Fig. 3). The bandwidth of interest is f_s, which is assumed to be wide compared to the interfering and the CR signals. The overlap bandwidth between the interfering signal and CR signal is B_{OL}, with B_I and B_{CR} the bandwidths of interfering and CR signals respectively. We assume $B_{OL} << B_{CR}$ so that most of the energy of the CR signal is outside the bandwidth of the interferer.

In contrast to ADC's, power efficient, high-resolution, and high-speed DAC's are significantly easier to implement [9]. Thus, we assume the DAC's resolution is sufficiently high that no quantization noise is added by the DAC in the cancellation path.

MSE will be dominated by quantization of the interfering signal, which in the case of an *N*-bit low resolution ADC is approximately,

$$MSE_1 = P_I \cdot 2^{-2N} \qquad \ldots(1)$$

When there is little overlap between the interfering signal and the CR signal, namely, $B_{OL} << B_{CR}$, the dual AF will ideally have a transfer function which is narrow enough to pass only the interfering signal. The stop band attenuation is assumed sufficiently large that the quantization noise outside of the interference band and the CR signal would then be absent from

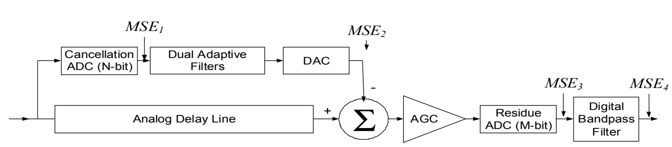

Figure 7. The system architecture and MSEs interested in the cancellation.

the filtered interference estimation. After reconstruction by DAC, the MSE will be reduced to the following:

$$MSE_2 = MSE_1 \cdot \frac{B_I}{f_s} = P_I \cdot 2^{-2N} \cdot \frac{B_I}{f_s} \quad \ldots(2)$$

The thermal noise added by the high resolution delay line element in the main path is significantly below the CR signal level. After subtracting the interference estimate from the delayed main signal, the residue becomes the CR plus the error in estimating the interference. This residue has the power of $MSE_2 + P_{CR}$.

By exploiting the AGC to amplify the residue up to the full scale of the Residue ADC, this low resolution converter would produce a MSE equal to:

$$MSE_3 = (MSE_2 + P_{CR}) \cdot 2^{-2M} \quad \ldots(3)$$

After stage one, a sharp narrow band digital filter could be applied to pass only the CR signal band, so that final MSE becomes:

$$MSE_4 = MSE_3 \cdot \frac{B_{CR}}{f_s} \quad \ldots(4)$$

Substituting (2) and (3) into (4), we get

$$\begin{aligned} MSE_4 &= (P_I \cdot 2^{-2N} \cdot \frac{B_I}{f_s} + P_{CR}) \cdot 2^{-2M} \cdot \frac{B_{CR}}{f_s} \\ &= P_I \cdot 2^{-2(N+M)} \cdot \frac{B_I \cdot B_{CR}}{f_s^2} + P_{CR} \cdot 2^{-2M} \cdot \frac{B_{CR}}{f_s} \end{aligned} \quad \ldots(5)$$

Clearly, it can be seen that the equivalent resolution of the interfering signal could eventually become more than $N + M$ bits and there is a processing gain of the product of two oversampling ratios. Furthermore, almost the full resolution of the Residue ADC can be used for subsequent processing of the CR signal. When the interfering signal is mitigated to the level of CR signal, there will be only 3dB degradation in SNR from the front-end.

For comparison, without interference cancellation, a single ADC would lead to an MSE of

$$MSE_{BL} = (P_I + P_{CR}) \cdot 2^{-2M} \cdot \frac{B_{CR}}{f_s} \quad \ldots(6)$$

with quantization noise of strong interference dominates. Our approach indicates that it is possible to reduce the interference further by a factor of $2^{2N} \cdot f_s / B_I$, so that the MSE caused by the interference would be on the order of the quantization noise of the CR signal. Thus, the total MSE is significantly reduced.

The MSE attenuation determined above presents an upper limit to what can be achieved in an actual implementation, due to the estimation error and limitation of number of taps used in the dual AF, the imperfectness of the digital filter, and the AGC clipping or limited amplification of the residue.

C. CR Signal Protection

The requirement to protect the CR signal is of great importance. In our approach, when the CR signal is buried in the quantization noise, the dual AF is very insensitive to it. But when it becomes relatively strong, such as in an environment with medium to low interference, it is no longer possible to distinguish the interfering and the CR signal through magnitude. Although dynamic range is not problematic in those situations, suitable measures have to be taken to protect the CR signal. In the circumstance when CR signal is transmitted upon a UWB interfering signal, protection of CR signal would be essential.

There are many ways to prevent CR signal from appearing in the cancellation path. The control channel of the CR system might be able to share the information in which band the transmitter is transmitting [10]. We can then add a digital notch filter in the cancellation path. Among other degrees of freedom available, spatial domain beamforming [11] can create a notch at the direction that the CR signal is coming. We can also code the signal as random noise over a wide bandwidth, such as CDMA, so that dual AF will have no difficulty in ignoring the signal of interest.

D. Overlapping between UWB and Narrow Band signals

Although so far we have assumed most of the power of the CR signal is outside the interference band, our approach can be extended to the case when there is significant overlap between the bands of the interference and the CR signals.

For instance, if a narrow band CR signal is transmitted within the band of a UWB interfering signal, the overlap bandwidth $B_{OL} = B_{CR}$, thus the Primary User would not incur any significant interference. The interfering signal, which is large in time domain, can be cancelled at the CR receiver by protection over the entire CR signal band in the DSP of the cancellation path. The DSP filters away the CR signal from the estimate of the interference, so that only the CR signal remains after subtracting the estimation from the original signal, thereby maximizing the SNR at the back-end. The protection would only be possible if the CR signal has the significantly higher power spectrum density, which indicates $P_I / B_I << P_{CR} / B_{CR}$. Therefore the cancellation error from the subtraction dominates over the error generated through overlapping.

Another extreme case is when a CR transmitter transmitting a low power UWB signal on top of a narrow band strong Primary User, so that the CR signal could be treated by the Primary User as noise. With $B_{OL} = B_I$, but $B_{OL} << B_{CR}$, a scheme of passing the entire interference band in the DSP of the cancellation path would mitigate the Primary User signal at the CR receiver without producing unrecoverable distortion to the signal of interest.

IV. Performance Evaluation

The simulation is set up using a tunable 3~7bit Cancellation ADC, a 10-tap 1.0-stepsize first stage together with a 10-tap 0.01-stepsize second stage dual AF, an 8-bit DAC, a tunable 4~6bit Residue ADC, and an precisely tuned delay for the analog subtraction. The original incoming signal includes an FSK modulated complex CR signal, a moderate sinusoidal interferer and a strong FSK modulated interferer. Sampling speed for the ADCs and DAC is 1G sample/s.

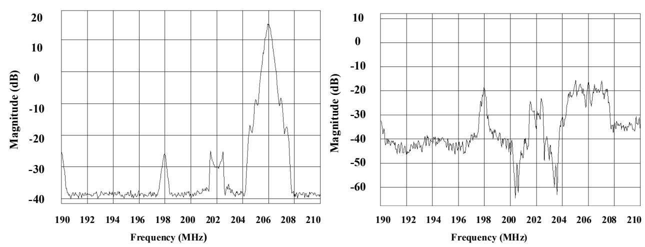

Figure 8 a). The incoming signal. Figure 8 b). The power spectrum after interference cancellation.

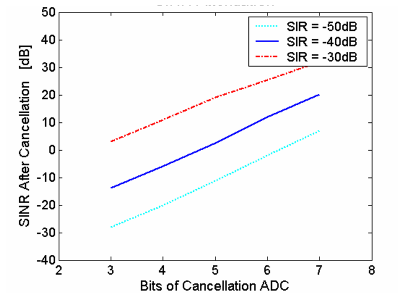

Figure 9. In different environments, Signal to Interference and Noise Ratio (SINR) can all be greatly improved even by using a low resolution ADC.

A. *Simulation Results*

First, we inspect our proposed system by receiving a strong FSK modulated interfering signal, a moderate sinusoidal interferer and a FSK modulated complex CR signal. The narrow band FSK signal has strong correlation between samples, which facilitates accurate estimation. FSK modulation inherently has time-varying characteristic, which could display the dynamic behavior of the CR signal. Fig. 8 are simulation results which verify the advantage of dynamic range reduction. We can attenuate the strong interference and reduce the dynamic range to the Residue ADC by almost 35dB, thus extending the effective number of bits for this system by nearly 6 bits. It is also observed that our system is not sensitive to the interfering signal that is on the same order of the CR signal.

B. *Signal to Interference and Noise Ratio Analysis*

Removing the sinusoidal interferer, the relationship between improved CR signal to interference and noise ratio (SINR) and number of bits used in the Cancellation ADC is investigated for three different signal to interference ratios (SIR). Fig. 9 presents, for a single 1MHz wide interfering signal, the SINR improvement as we increase the resolution of the ADC.

The curves' slope in Fig. 9 indicates that the incremental of SINR is 39dB when ADC resolution increases by 4 bits, which is 9.75dB per bit of the Cancellation ADC. This is more than a conventional ADC, in which each additional bit gives an SNR improvement of 6dB. The extra 3.75dB is attributed to the narrower bandwidth and the improved capability of the adaptive filter to reject quantization noise as the resolution of the Cancellation ADC increases.

The adaptability is limited when resolution of the Cancellation ADC is low, since the pass band bandwidth is relatively wider than that of the interfering signal. As a result, the quantization noise after the subtraction contributes comparably to the error in interference cancellation in the SINR. The more bits the Cancellation ADC has, the more gain we get by exponentially decreasing the in band noise.

The processing gain from oversampling is evident when the slope becomes 6dB/bit, thus, interference error dominates the denominator of the SINR. As an example, when SIR is -30dB, a 6-bit ADC results in a SINR after cancellation of 26dB. The interfering signal has been attenuated by 56dB, which is equivalent to 9.3 bits; the extra 3.3 bits come from the oversampling ratio as a result of the processing gain as explained in Section III. The gain is less than the theoretical gain (oversampling ratio of 500 implies 4.5bits of additional gain). This is mainly because we can not form a brick-wall filter that strictly passes only the interfering signal, and therefore leads to a decreased attenuation.

Another observation is for a given SIR, less resolution in the Cancellation ADC actually simplifies the design. Because even without filtering, the dual AF will be insensitive to the CR signal, which are buried in the quantization noise.

As we increase the number of bits, we will finally reach a point where additional bits don't bring us any benefits without active reduction of the CR signal in the cancellation path. For instance, when the Cancellation ADC has 6 bits, in an environment with an SIR of -20dB, if we calculate the slope of the curve, the attenuation rate drops to less than 6dB/bit. This comes from the dual AF which begins to consider the desirable CR signal as interference, since we are doing a blind adaptation.

C. *Time Domain Peak Magnitude Ratio Analysis*

To find the effective resolution for the CR signal, we calculate the residue signal at the input to the AGC of the second stage which includes the CR signal, the cancellation error of the interference and the filtered quantization noise. The AGC is assumed to amplify this composite signal to full scale of the Residue ADC, indicating that the CR component will still be less than full scale. This fraction will depend on the time domain peak magnitude ratio between the CR signal and the residue as in Fig. 10. If the ratio becomes less than one, it will result in a loss of effective bits from the Residue ADC for the CR signal.

We are expecting that as the CR signal becomes weaker, more bits in the Cancellation ADC should be used to attenuate the interference signals. At the same time, this leads to a reasonable peak magnitude ratio for limiting the requirement of the Residue ADC to keep maximum detection sensitivity.

D. *Effective Bits from the Dynamic Range Reduction*

By combining two stages, our simulation shows the overall system Effective Bits from the Dynamic Range Reduction (EBDR) is close to $N+M$, as shown in Table I, if the gain of the

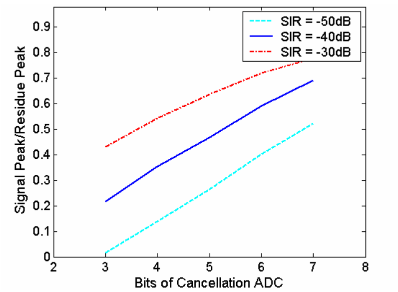

Figure 10. The time domain peak ratio of the CR signal to the Residue, which will determine the effective AGC gain to the CR signal of interest.

AGC is set equal to 2^N. With a notch filter added to protect the CR signal, we lose a fractional bit of EBDR, because the notch filter adds in-band colored noise. Optimizing the resolution in the Cancellation ADC can avoid such degradation by CR signal protection strategies and ensure that the AF is not able to track the CR signal.

Also, we observed from the simulation, when using the FSK modulation for the interference, as the frequency of the interfering signal is modulated, there is a transient edge effect at the symbol boundaries. At these random transitions, there will be large error peaks. Therefore the gain of the second stage AGC may be limited by these spikes. If they can be made sufficiently short in duration by fast adaptation of the AF, it is possible to simply clip them without significant distortion of the CR signal because of the high oversampling.

Table II summarizes the implementation specifications. A 6-bit Residue ADC is used to accommodate the drop in peak magnitude ratio due to spikes and clipping, and provide a worst case effective resolution of 3 bits for the CR signal. Our approach reduces the dynamic range by more than 40dB when SIR reaches as low as -50dB. The power and cost are significantly decreased compared to an equivalent system with one single ADC of 11.6 effective number of bits.

V. CONCLUSION

By using the time domain interference cancellation, it is possible to reduce narrowband interferers so that an in-band signal can be more effectively detected. By using a mixed signal architecture, which contains two low resolution ADC's, it is possible to effectively act as a high-resolution ADC in terms of the ability to resolve a small desired signal in the presence of a large interfering signal.

TABLE I
OVERALL EBDR FOR DIFFERENT SIRS USING DIFFERENT RESOLUTION ADCS

SIR=-40DB

ADC resolution Cancellation ADC + Residue ADC	Without Notch Filter	With Notch Filter
3bits+4bits	8	7.9
4bits+4bits	9	8.8
5bits+4bits	9.9	9.4
7bits+4bits	10.2	9.8

SIR=-50DB

ADC resolution Cancellation ADC + Residue ADC	Without Notch Filter	With Notch Filter
4bits+4bits	9.2	8.6
5bits+4bits	10.4	9.7
7bits+4bits	11.5	11

TABLE II
SYSTEM SPECIFICATION SUMMARY

SIR	>-50dB
Cancellation ADC	1GHz / 3~6bits
Residue ADC	1GHz / 6bits
DAC	1GHz / 8bits
AGC Gain	<40dB
Maximum Dynamic Range Reduction	>40dB
Overall EBDR	11.6bits

REFERENCES

[1] http:// www.fcc.gov/oet/info/database/spectrum
[2] J. Yang, "Spatial Channel Characterization for Cognitive Radios," M. S. thesis, Dept. of EECS, University of California, Berkeley, 2004.
[3] D. Cabric, S. M. Mishra, R.W. Brodersen, "Implementation issues in spectrum sensing for Cognitive Radios," in *Proceedings of 38th Annual Asilomar Conf. on Signal, Systems and Computers*, Nov. 2004.
[4] R. H. Walden, "Analog-to-digital converters survey and analysis," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 4, pp. 539-550,1999.
[5] A. B. Carleial, "A case where interference does not reduce capacity," *IEEE Trans. On Inform. Theory*, vol. IT-21, pp. 569-570, Sept. 1975.
[6] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press, 2005
[7] A. A. Beex, J. R. Zeidler, "Interference suppression with minimal signal distortion," in *IEEE ICASSP.*, vol. 6, pp. VI-225-8 .
[8] B. Widrow, *Adaptive Signal Processing*, Prentice Hall, New Jersey, 1985.
[9] B. Razavi, *Principles of Data Conversion System Design*, IEEE Press, 1995
[10] R. W. Brodersen, A.Wolisz, D. Cabric, S. M. Mishra and D. Willkomm. White paper: CORVUS: A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum. Technical report, 2004.
[11] A. Poon, R. W. Brodersen, D. Tse, "Degrees of freedom in multiple antenna channels: A signal space approach," *IEEE Trans. On Inform. Theory*, vol. 51, no. 2, pp. 523-536, Feb. 2005