Cyclostationary Signature Detection in Multipath Rayleigh Fading Environments

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***Abstract*—Cognitive radio-based Open Spectrum systems offer a solution to the issue of spectrum scarcity by allowing wireless networks to dynamically access spectrum while coordinating to co-exist and avoid the creation of harmful interference. However, before a practical open spectrum system may be implemented, a number of significant technical and policy challenges must be overcome. One such technical challenge is the distributed coordination of operating frequencies and bandwidths between co-existing systems.**

Cyclostationary signatures have been shown to be a powerful tool in overcoming this challenge. A cyclostationary signature is a unique identifier or watermark which may be embedded in the physical properties of a communications signal. Such signatures may be used to aid peer devices in performing a number of critical tasks, including signal detection, classification and frequency acquisition.

A key limitation of cyclostationary signatures when implemented in orthogonal frequency division multiplex (OFDM)-based systems is the sensitivity exhibited in time-variant multipath Rayleigh fading environments. Although OFDM-based systems offer robust performance under multipath conditions, detection of cyclostationary signatures can be severely degraded. As signature detection is adversely affected, the ability of Open Spectrum Systems to coordinate and coexist is seriously undermined.

This paper therefore presents techniques for effectively overcoming the issue of multipath Rayleigh fading in the detection of cyclostationary signatures for Open Spectrum systems. Approaches for the generation and detection of signatures in OFDM-based waveforms are outlined and improvements in detection performance are illustrated using simulation results.

I. Introduction

One of the key challenges currently facing wireless system designers and telecommunications policy makers alike is the issue of spectrum scarcity. The spectrum allocation tables of the Federal Communications Commission (FCC) in the US clearly illustrate the lack of unallocated spectrum available for the deployment of new systems and services. At the same time, however, an increasing number of reports [1] suggest that though spectrum may be exhaustively allocated, an overwhelming proportion is only very sparingly utilized. Prompted by this apparent lack of efficiency, policy makers and researchers have in recent years begun to explore the possibility of wireless systems capable of automatically and efficiently allocating and utilizing spectrum. Broadly termed *Open Spectrum* systems [2], these approaches threaten a paradigm shift in the manner in which spectrum is managed and used to facilitate the transfer of information.

Although Open Spectrum systems promise the possibility of ubiquitous, cost-effective wireless access, there remain some significant technical and policy challenges to be overcome before they may be successfully realized. Regarding policy, these include the transition from a command and control to a more market driven approach to spectrum management and the introduction of distributed yet minimally restrictive spectrum sharing protocols. Additionally, suitable mechanisms are required for handling congestion, enforcing conformance and protecting privacy and security. In terms of the technical challenges, some outstanding issues are the reliable detection of unutilized spectrum or white space, the distributed coordination and coexistence of heterogeneous systems and the development of highly adaptive and frequency agile yet robust radio platforms.

Distributed coordination of heterogeneous cognitive networks is a key challenge as it is this mechanism which must replace one of the major traditional roles of the spectrum regulator. Through the allocation of exclusive-usage licenses, the regulator effectively mitigates the issue of harmful interference between neighboring wireless systems. In Open Spectrum systems, networks must self-organize to adjust operating frequencies and bandwidths to avoid conflicts.

One suggested approach for facilitating the levels of coordination required is the use of a common control channel over which systems could negotiate access to available spectrum. However, the common control channel approach has a number of significant drawbacks. The first of these is the assumption of continuously available spectrum on which to host the control channel. Opportunistic spectrum use involves secondary systems which are capable of occupying spectrum *white space* i.e. frequency bands which are allocated to a primary system but which are not in use at a given time or place. These spectrum white spaces must then be vacated as soon as the primary system requires them. In this context, dedicated spectrum for a control channel may not be available and an alternative mechanism for coordination is required.

Secondly, in order to access the common control channel, all Open Spectrum systems must agree upon and support a predefined set of waveforms, parameters, frame structures and access protocols to be used. By employing a less restrictive and complex mechanism for coordination, it may be possible to permit a greater range of wireless system types to take part and access the available spectrum.

The novel use of cyclostationary signatures to facilitate distributed coordination in Open Spectrum systems was first introduced by the authors in [3]. It was shown that signatures may be easily embedded in OFDM-based waveforms, detected using low-complexity structures and used to perform signal classification and acquisition.

Although cyclostationary signatures provide a valuable solution to the issue of distributed coordination, there is one significant drawback associated with their usage. This is their sensitivity to multipath Rayleigh fading.

Among the key advantages of OFDM-based systems is their robustness in multipath fading environments. OFDM effectively converts a high data rate serial stream to a number of closely spaced, parallel, low-rate streams. As a result, OFDM symbols typically have a long duration in comparison to single carrier transmission schemes and hence a reduced sensitivity to inter-symbol interference (ISI). In addition, a cyclic prefix (CP) is added to each symbol transmitted. This serves to collect multipath signal components arriving within the duration of the CP and allows them to be used to constructively contribute to the received symbol.

In order to take advantage of a cyclic prefix to overcome the effects of multipath fading, symbol timing estimation is required. However, in the context of distributed coordination, this information is not available and the received signal can be significantly distorted by ISI. Accordingly, signatures become more difficult to detect and coordination may become impossible.

This paper therefore presents approaches for effectively overcoming multipath sensitivity in the detection of cyclostationary signatures. Techniques are outlined for the generation and detection of signatures in OFDM-based waveforms and detection performance under conditions of time-variant multipath Rayleigh fading is examined using simulation results.

Section II discusses cyclostationary signatures as a novel solution to the issue of distributed coordination in Open Spectrum systems. Section III presents and examines simulation results used to assess the performance of cyclostationary signatures when employed in time-variant multipath environments. Simulation results are discussed in Section IV and the paper is concluded in Section V.

II. Cyclostationary Signatures

Cyclostationary signal analysis provides a powerful tool in the detection and classification of many of the wireless communications signals in use today. Cyclostationary features may arise as a result of coupling stationary message signals with periodic signals such as sine wave carriers, pulse trains or spreading codes or operations such as sampling, multiplexing or coding. These features manifest themselves as specific

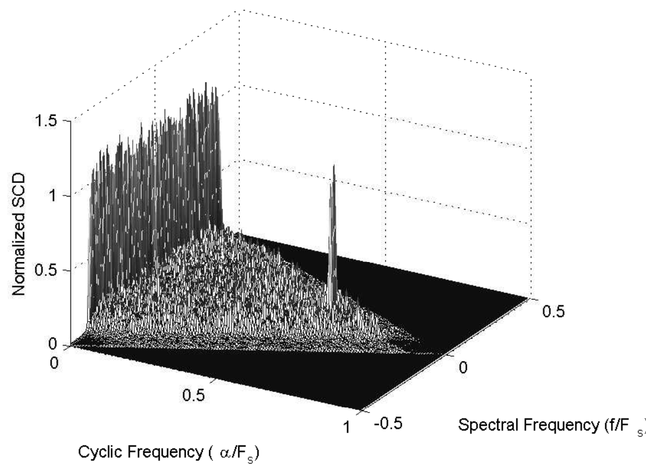

Fig. 1. Normalized spectral correlation density (SCD) for a signal containing an embedded cyclostationary signature. The signature can be seen at cyclic frequency $\alpha = 0.6F_s$ and the signal carrier frequency, f_0

correlation patterns in the spectrum of the signal and may be detected and analyzed using appropriate transformations.

While cyclostationary features may arise due to the inherent processes used to generate a signal, it has been shown that they may also be artificially created and intentionally embedded in signals to facilitate detection and analysis. Such cyclostationary features are termed *Cyclostationary Signatures*.

Although it has been shown that optimal detection may be performed using cyclostationary signal analysis [4], the real power of the technique lies in the additional information which may be obtained about signals which are analyzed. Different waveforms typically contain different features relating to the processes used in their generation. By detecting these different features, it has been shown that waveforms may be effectively classified and identified. Additionally, it is often possible to derive useful information about the characteristics of a waveform from the detected features. These uses of cyclostationary features in the analysis of communication signals have been extensively examined by Gardner *et al.* [5], [6].

An important advantage of cyclostationary signal analysis when considering distributed coordination lies in the ability to analyze a signal without the need for phase-related information. This allows information to be obtained without the overhead of frequency acquisition and phase synchronization associated with alternative coherent approaches.

A. Signature Generation

OFDM provides a number of significant advantages for Open Spectrum systems. The ability to directly manipulate the spectral shape of an OFDM signal has been identified as a key property in enabling interference avoidance [7] and bandwidth matching [8]. In addition, the use of a Fourier transform at the OFDM receiver permits valuable information about the communications channel to be obtained.

Second order cyclostationary features manifest themselves as specific correlation patterns in the spectrum of the signal in question. Therefore, by artificially creating such correlation patterns, it is possible to intentionally embed a cyclostationary feature. In the case of OFDM, this is made possible through spectrum sculpting by controlling the symbols used to modulate individual subcarriers.

An OFDM signal may be expressed as a time-varying signal $x(t)$,

$$x(t) = \sum_{k=1}^{K} X_k[n] \mathrm{e}^{j2\pi k \Delta f t}, \tag{1}$$

where K represents the number of subcarriers used and Δf is the subcarrier frequency spacing. Here, $X_k[n]$ represents the n-th transmitted symbol on the k-th subcarrier and $n = t/T_0$, where T_0 is the OFDM symbol duration.

Thus, a signature is generated through the mapping of OFDM subcarrier symbols as

$$X_k[n] = X_{k+\Delta k}[n], \qquad k \in Q, \tag{2}$$

where Q is the set of subcarrier values to be mapped and Δk is the number of subcarrier spaces between mapped symbols.

Figure 1 illustrates a signature generated in this manner using a normalized spectral correlation density (SCD). The feature generated can be clearly identified at cyclic frequency $\alpha = 0.6F_s$ and the signal carrier frequency, f_0. In this case F_s represents the sample rate of the signal.

B. Cyclostationary Signatures in Open Spectrum Systems

In Section I, the challenge of distributed coordination for Open Spectrum access was discussed. In order to dynamically utilize spectrum whilst avoiding the creation of harmful interference, Open Spectrum system nodes must be capable of carrying out a number of key tasks. These include

- Detection of neighboring nodes in frequency and space
- Classification of detected systems
- Rendezvous and frequency acquisition

Cyclostationary signatures provide a mechanism for effectively accomplishing each of these tasks. It has been shown that cyclostationary features may be used to detect signals at low signal-to-noise ratios (SNRs) [4]. An important strength of signal detection using cyclostationary features is the ability to improve detection performance by increasing the length of the observation time used. In the context of reconfigurable, software-defined radios, this allows the SNR performance of the detector to be dynamically adjusted (within certain limits) as required. By embedding a predefined signature or watermark in a transmitted signal, an Open Spectrum node enables neighboring nodes to detect its presence and react accordingly.

In addition to facilitating signal detection, cyclostationary signatures may be used to differentiate between the signals of neighboring systems in an Open Spectrum frequency band. In generating an embedded signature through carrier mapping, the cyclic frequency, α at which the signature occurs is determined by the spacing between the carrier sets, Δk. By choosing a unique value of Δk to be used by nodes of a given system, designers may permit signals generated within that system to be classified by any receiving device. In the case where a number of Open Spectrum systems operate in a common frequency band, these unique signatures may be used to differentiate between nodes of neighboring systems and to identify the spectrum resources currently in use by each.

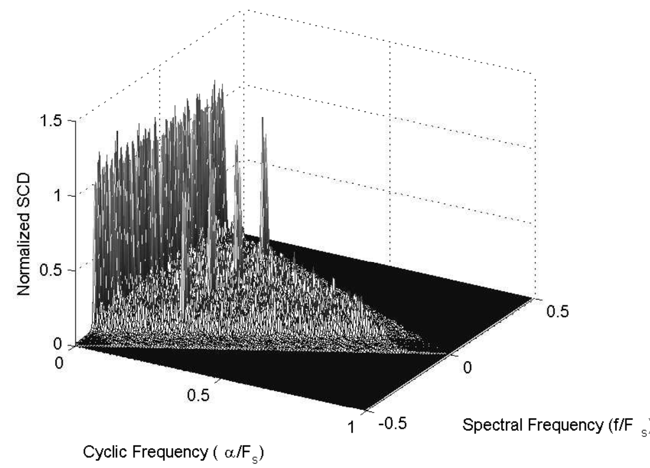

Fig. 2. Normalized SCD for a signal containing a robust cyclostationary signature. The signature is generated using multiple OFDM subcarrier mappings and can be seen at cyclic frequency $\alpha = 0.2F_s$

The third task of rendezvous and frequency acquisition is a challenge which arises due to the uniquely flexible nature of Open Spectrum systems. In a conventional wireless system, operating frequencies are typically predefined or may be determined using fixed frequency control channels. In Open Spectrum systems this may not be the case as operating frequencies depend upon the spectrum resources available at a given time and place. Therefore, upon commencing operation, an Open Spectrum-enabled node must be capable of identifying those frequencies currently in use by its peer nodes and thus achieving synchronization. The uses of cyclostationary signatures for detection and classification of signals have already been discussed, however, signatures may also play a role in the acquisition of the signals of peer devices in an Open Spectrum network.

Figure 1 illustrates a single cyclostationary signature generated using OFDM subcarrier mapping. The signature occurs at the carrier frequency of the signal, f_0. Therefore, upon detection of such a signature, it's location on the frequency plane may be used for coarse signal carrier estimation. When used together with a fine frequency tracking approach such as that outlined in [9], frequency acquisition and synchronization can be acheived.

C. Signature Detection

In order to realize each of the benefits of cyclostationary signatures outlined above, a suitable signature detector is required. A signature generated using OFDM subcarrier mapping occurs at only a single cyclic frequency, α_{sig}, therefore the cyclic cross spectrum of the signal at that cyclic frequency may used for detection.

It has been shown that the time-smoothed cyclic periodogram, $\hat{S}$, is a consistent, asymptotically unbiased and complex normally distributed estimator of the cyclic cross spectrum [10] where

$$\hat{S}_x^{\alpha}[m] = \frac{1}{L}\sum_{l=0}^{L-1} X_l[m]X_l^*[m-\alpha]W[m] \quad (3)$$

and where $X_l[m]$ is the discrete Fourier transform of the received signal $x[n]$,

$$X_l[m] = \sum_{n=0}^{N-1} x[n]\mathrm{e}^{\frac{-j2\pi nm}{N}}. \quad (4)$$

Here $W[m]$ denotes a smoothing spectral window. Estimates are averaged over L windows of length N, where N is the duration of a single OFDM symbol.

A key advantage of this detector design lies in the use of the Fourier transform. As an OFDM receiver already uses a Fourier transform, it may be possible to incorporate signature detection using a time-smoothed cyclic cross periodogram within existing receiver designs.

Using a flexible radio platform, it is possible to parameterize the cyclic frequency of the detector and thus permit it to be used to detect signatures occurring at any cyclic frequency of interest. In this way a highly flexible general signature detector may be realized.

D. Overcoming Multipath Fading

Cyclostationary signatures offer a highly flexible tool for overcoming the issue of distributed coordination in Open Spectrum systems. However, a significant limitation of cyclostationary signatures is their sensitivity to time-variant multipath Rayleigh fading. Distortion of a single signature generated using OFDM subcarrier mapping can severely compromise detection and impact the performance of an entire system.

In order to overcome this limitation, it is necessary to increase the robustness of a generated signature. One approach for achieving this is the use of multiple OFDM subcarrier mappings to increase the number of features which are generated in the signal. Use of a single mapping in order to generate a signature was discussed in Section II-A. In order to generate multiple features, this approach may be extended such that $Q \in Q_1, Q_2 ...$, where Q is the set of subcarrier indices to be mapped. Figure 2 illustrates the SCD of a signal containing such a signature. The presence of four independent features may be seen at cyclic frequency, $\alpha = 0.2F_s$.

An advantage of this approach is that, as the signature is still present at just one cyclic frequency, the detector design outlined in Section II-C may also be used to detect this type of signature.

Although the use of multiple subcarrier mappings effectively increases the robustness of the resulting signature, this comes at the cost of increased overhead due to the increased number of subcarriers which must be used to carry mapped

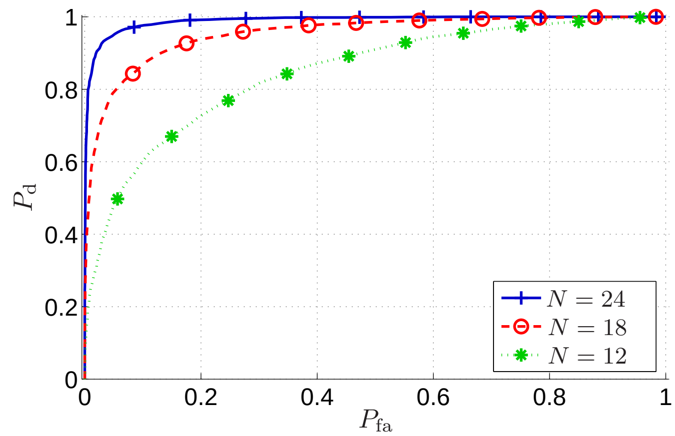

Fig. 3. ROC for detection window lengths equivalent to N OFDM symbols. An AWGN channel with SNR$= 5\,\mathrm{dB}$ was used.

data symbols. This tradeoff between system overhead and signature robustness is further examined in Section IV.

III. Simulations

To evaluate the reliability of cyclostationary signature detection under various conditions, a number of Monte Carlo simulations were carried out. Empirical receiver operating characteristics (ROCs) were computed by randomly generating OFDM symbols and inserting cyclostationary signatures only in some of them. Subcarriers were modulated using quadrature phase shift keying (QPSK), and sets of three carriers were mapped for signature generation (see Section II-A). The data was propagated through a channel model and noise with an SNR of $5\,\mathrm{dB}$ was added. Detection was then carried out using a signal recorded for a duration of N OFDM symbols. Finally, probabilities of detection and false alarm, P_d and P_fa, were estimated by averaging 10,000 runs. In the following the simulation results are illustrated for a simple additive white Gaussian noise (AWGN) channel and for a time variant multipath channel.

A. AWGN Channel

Initially, detector performance was examined using a simple AWGN channel and a range of different signal observation durations. A single cyclostationary signature using three carriers was inserted into the symbols, as described in Section II-A. The ROCs in Figure 3 show that the performance of the signature detector improves significantly when longer signal observation times are used, with good performance for a duration equivalent to $N = 24$ OFDM symbols. However, while these results were computed using a simple AWGN channel, detector performance is expected to deteriorate when more realistic time variant multipath channels are utilized.

B. Time Variant Multipath Channel

In order to simulate a time-variant multipath channel, the COST 207 bad urban model [11] was adopted. A total of six Rayleigh-fading paths with their respective powers

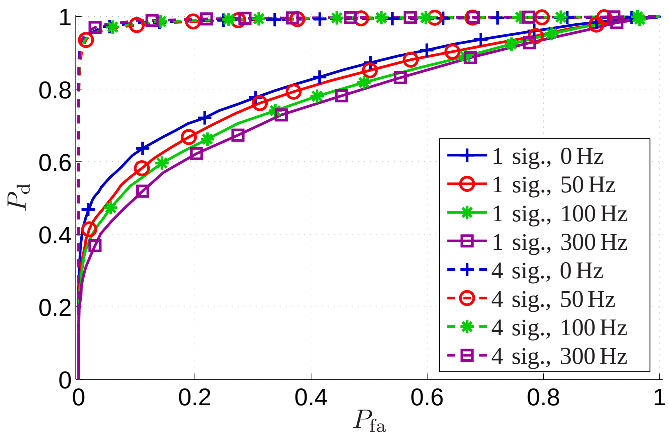

Fig. 4. Effects of time variance (Doppler spread) on the ROC with single-feature and multi-feature cyclostationary signatures. The COST 207 bad urban multipath Rayleigh-fading channel [11] was used, with the maximum Doppler frequencies indicated (SNR= 5 dB, $N = 60$).

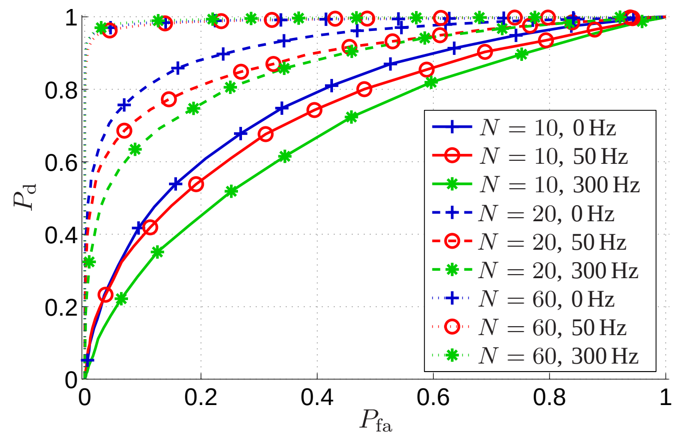

Fig. 5. Effects of the detection window length (equivalent to N OFDM symbols) with different Doppler spreads. Four cyclostationary signatures were generated. A COST 207 bad urban multipath Rayleigh-fading channel was used, with the maximum Doppler frequencies indicated (SNR= 5 dB).

and delays for a carrier frequency of 900 MHz are given in Table I. Additionally, the maximum Doppler frequency for all paths was specified, with the classic 'U shaped' spectral distribution [12]. The signature detection performance was estimated for Doppler frequencies between 0 and 300 Hz, *i.e.*, for maximum movement speeds up to 100 m/s.

TABLE I
COST 207 Bad Urban Channel Model

Path Number	Delay (μs)	Power (dB)
1	0.0	-2.5
2	0.3	0
3	1.0	-3.0
4	1.6	-5.0
5	5.0	-2.0
6	6.6	-4.0

Firstly, the effect of different maximum Doppler frequencies on the detection performance of cyclostationary signatures was examined. As with simulations discussed in Section III-A, signal observation times of $N = 60$ OFDM symbols were used by the detector to achieve high reliability. The solid lines in Figure 4 show the resulting ROCs. It can be seen that multipath fading affects detector performance significantly. Indeed, single signature ROC performance using $N = 60$ under multipath conditions is worse than the equivalent AWGN channel using $N = 12$ (see Figure 3). Additionally, as the Doppler frequency increases, the detection performance deteriorates.

However, as the dashed lines in Figure 4 indicate, if a multi-feature signature containing four features is generated, the detection performance improves considerably. The Doppler frequency has almost no effect on the detection statistics. Thus, using multi-feature signatures significantly improves detection robustness under multipath time variant channel conditions.

Secondly, the effects of using different signal observation times at the detector were examined. As shown in Figure 5, the detection performance improves and the effect of the Doppler spread decreases with N. Thus, as was the case under conditions of AWGN fading, increased signal observation durations result in improved detector performance.

IV. Discussion

Simulations have shown that the detection of cyclostationary signatures can be seriously compromised by time-variant multipath Rayleigh fading. However, this sensitivity may be effectively overcome through the use of more robust signatures containing multiple, independent features. In addition, it has been shown that the use of multi-feature signatures provides robustness against the effects of Doppler spread and that detection performance can be improved considerably through use of increased observation durations.

The performance improvements which may be realized using multi-feature signatures come at the cost of increased overhead. Multi-feature signatures are generated through the use of multiple sets of OFDM subcarrier mappings, resulting in fewer subcarriers which may used to carry independent data. The tradeoff is illustrated in Table II, where the overhead associated with the single-feature and multi-feature signature types used in simulations are compared. The system overhead here is given for the case of 256-subcarrier OFDM, where 55 guard subcarriers and 8 pilot subcarriers are used.

TABLE II
Signature Overhead

Signature Type	Redundant Carriers	Overhead
Single	3	1.56 %
Multiple	12	6.25 %

Although the use of multi-feature signatures provides improved detection performance under multipath channel conditions, these improvements do not come at the cost of increased detector complexity. As the signature features reside at the same cyclic frequency, they may be easily detected using an unchanged detector structure. However, slightly more complex approaches are required in order to perform frequency acquisition using multi-feature signatures.

V. Conclusions

This paper has presented techniques for the creation and detection of cyclostationary signatures in OFDM-based waveforms. The uses of signatures in facilitating distributed coordination in Open Spectrum systems have been discussed. Simulation results have been used to illustrate the sensitivity of cyclostationary signatures to time-variant multipath fading and it has been shown that this sensitivity may be overcome through the use of more robust multi-feature signatures. In addition it has been shown that signature detection performance may be improved through the use of increased signal observation times.

Future work in the area of cyclostationary signatures for Open Spectrum systems will involve the implementation of a signature-enabled OFDM transceiver system upon the CTVR Plastic Project platform [13] for cognitive radio experimentation. This implementation will be used to explore the use of cyclostationary signatures in achieving distributed coordination between heterogeneous cogntive networks. In addition, detector performance will be further examined through simulations using a greater range of multipath channel models.

VI. Acknowledgments

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