Implementation of an autocorrelation-based spectrum sensing algorithm in real-world channels with frequency offset

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Outline

- Background
- System Model
- Signals & Testbed
- Results
- Conclusion

Background

Spectrum sensing

- Cognitive radio (CR) – ability to adapt transmit and receive signal parameters to best suit (exploit) dynamic radio environment.

- Key aspects of CR transceiver design.
  - Determine **if** signals are present.
  - Distinguish **what** signals are present.

- **if** signals present -- Simple low complexity energy detectors.

- **what** signals present – More complex problem.

Background

Spectrum sensing

- **Multicycle cyclostationary detection.**
  - Can be applied iteratively to determine nature of signal that is present (blind).
  - Exploits the fact that multicarrier OFDM signals posses cyclical patterns on each sub-carrier frequency.
  - Performance appears not to be affected by hardware-based fractional frequency offset (FFO).
  - Main drawback is its high computational complexity.

Background

Spectrum sensing

- **Other techniques such as:**
  - Subspace-based analysis detection.
  - Distribution-based analysis detection.
  - Kullback-Leibler-based detection.
- Offer similar features and performance at expense of computational complexity.

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Background

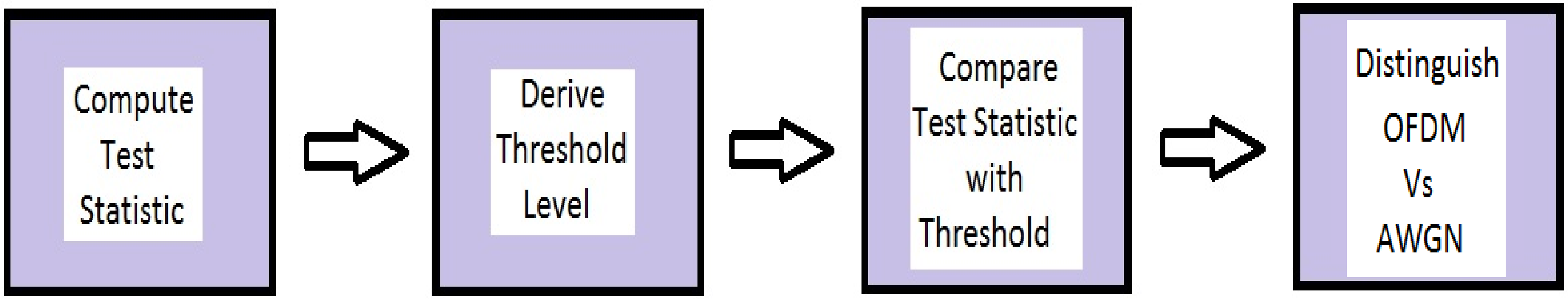
Spectrum sensing

- **Autocorrelation-based detection.**
  - Can be applied iteratively to determine nature of signal that is present (blind).
  - Exploits the fact that multicarrier OFDM signals posses cyclical prefix in time domain.
  - However performance **is affected** by hardware-based fractional frequency offset (FFO).
  - **Main advantage** is that it can exploit a process already present in OFDM receivers -- thus additional complexity is very low.

System Model

Autocorrelation-based detection

- **Autocorrelation-based sensing concept:**



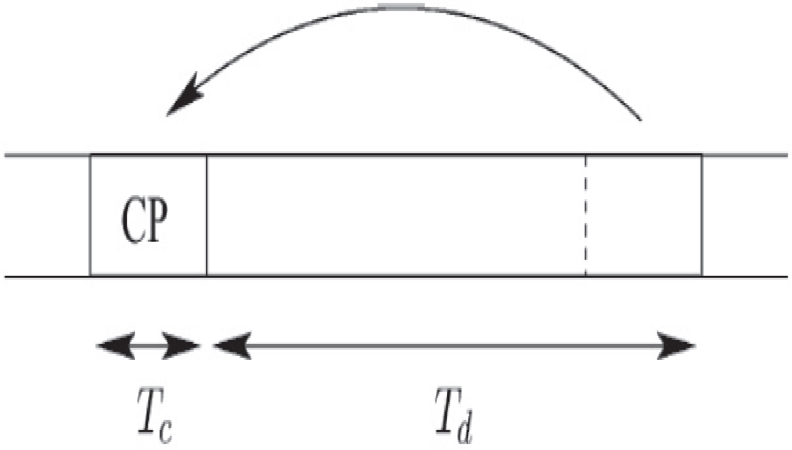
Compute Test Statistic → Derive Threshold Level → Compare Test Statistic with Threshold → Distinguish OFDM Vs AWGN

- A threshold is derived and a test statistic is then compared.
- Comparison determines presence of OFDM signal or AWGN, which have similar statistical properties.
- OFDM properties can be determined by appropriate iteration of this method.

System Model

Autocorrelation-based detection

- Consider OFDM block structure.
- T_d -- length of data samples or FFT size.
- T_c -- length of CP.
- CP offers cyclostationarity in time domain.

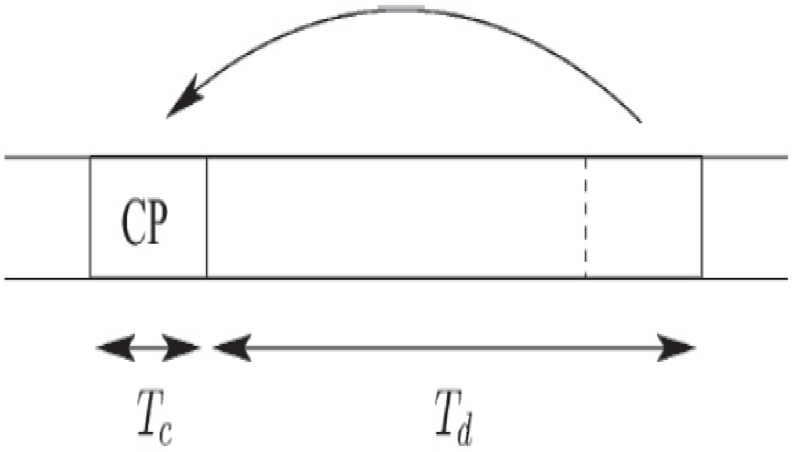


System Model

Autocorrelation-based detection

- Conventionally, at an OFDM receiver, an autocovariance is performed on the input time domain signal, $y(t)$:

$$\varphi = \mathbb{E}\{y(t)\, y^*(t+\Delta t)\}$$



- Δt -- the lag, set at T_d

- Angle of φ is used to correct for effect of fractional frequency offset (FFO) on modulation symbols.

System Model

Autocorrelation-based detection

- **Test statistic:** This can be computed from the maximum likelihood estimate (MLE) of the autocorrelation coefficient of the receive signal, which is:

$$\rho = \frac{\frac{1}{2M}\sum_{t=0}^{M-1}\Re\{\varphi\}}{\frac{1}{2M+T_d}\sum_{t=0}^{M+T_d-1}|y(t)|^2}$$

- M -- No. of input samples, $y(t)$ such that: $M > 2T_d + T_c$.

- Thus the test statistic, ρ, is merely a slightly modified autocovariance, φ .

System Model

Autocorrelation-based detection

- **Threshold:** If the samples, $y(t)$, contain only AWGN samples then ρ has a distribution according to:

$$\rho \sim \mathcal{N}_R\left(0, \frac{1}{2M}\right)$$

- $\sim \mathcal{N}_R$ -- Gaussian distribution over real numbers.

- From this, ρ has probability of exceeding a threshold, η_ρ :

$$\begin{aligned} P(\rho > \eta_\rho) &= \frac{1}{2}\operatorname{erfc}\left(\frac{\eta_\rho}{\sqrt{2}\sigma_r}\right) \\ &= \frac{1}{2}\operatorname{erfc}\left(\sqrt{M}\eta_\rho\right) \end{aligned}$$

- where $\operatorname{erfc}(\cdot)$ is the complementary error function.

System Model

Autocorrelation-based detection

- The term, $P\left(\rho > \eta_\rho\right)$, may be thought of as the probability of false alarm, P_{fa}, i.e. the probability of a false detection of an OFDM signal.
- P_{fa} is a trade-off between detection accuracy and good system performance at low SNR.
- Rearranging, the threshold, η_ρ , may then be computed as:

$$\eta_\rho = \frac{1}{\sqrt{M}} \operatorname{erfc}^{-1}\left(2P_{fa}\right)$$

- Thus: ρ > η_ρ -- OFDM
  < ρ --η_ρNGN

System Model

Autocorrelation-based detection

- **Appropriate iterations:** The algorithm can extract signal parameters.

- By replaying the algorithm assuming each time a different lag: Δt, i.e., T_d, until the threshold, η_ρ, is surpassed.

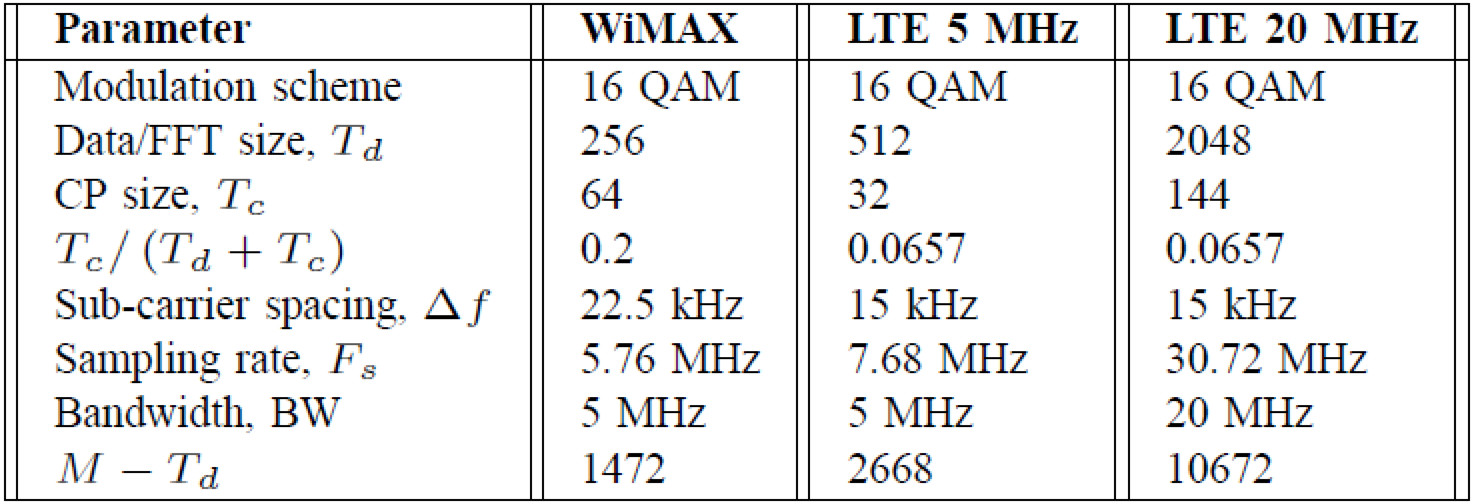
- It is then possible to infer the FFT size of the OFDM signal.

- Incorrect assumptions of T_d will return the same test statistic, ρ, as AWGN.

Signals & Testbed

OFDM signals

- **3 types of OFDM signals:**
  - WiMAX, LTE 5MHz & LTE 20 MHz.
  - Each has a different FFT size (T_d) and various other parameters as in Table.
  - Signals are derived from software simulators provided by Technical University of Vienna.

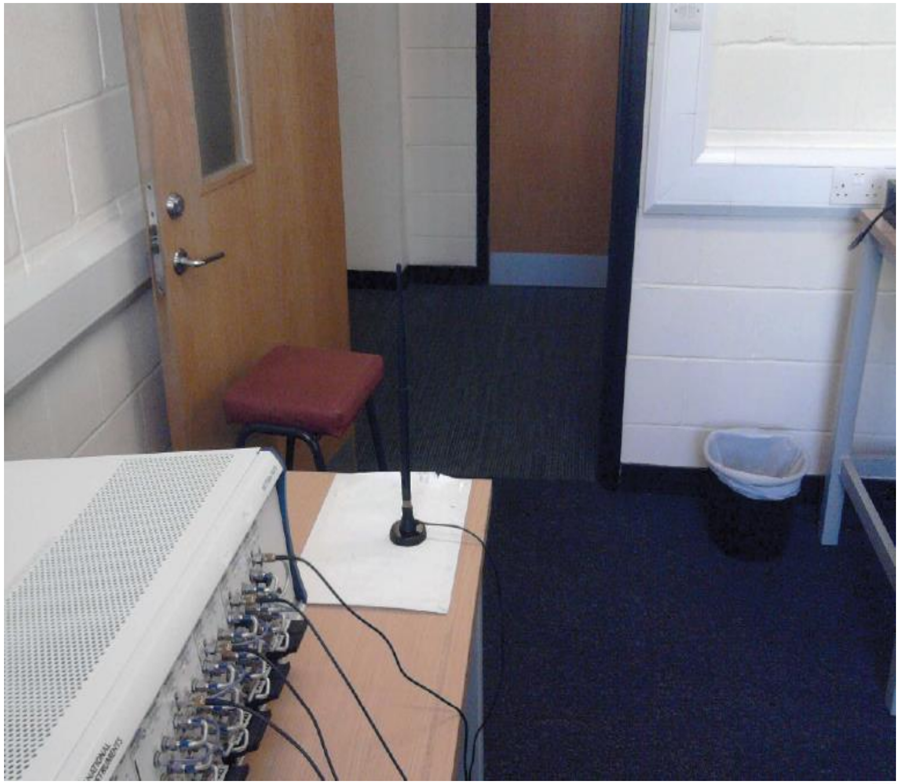


Parameter	WiMAX	LTE 5 MHz	LTE 20 MHz
Modulation scheme	16 QAM	16 QAM	16 QAM
Data/FFT size, T_d	256	512	2048
CP size, T_c	64	32	144
$T_c/\,(T_d + T_c)$	0.2	0.0657	0.0657
Sub-carrier spacing, Δf	22.5 kHz	15 kHz	15 kHz
Sampling rate, F_s	5.76 MHz	7.68 MHz	30.72 MHz
Bandwidth, BW	5 MHz	5 MHz	20 MHz
$M - T_d$	1472	2668	10672

Signals & Testbed

Testbed

- **Tx Chassis:**
- 4 Tx RF chains (only 1 used)
- Tx carrier frequency 2.45 GHz.
- 10 MHz local oscillator (LO) clock signal for internal synchronisation.
- Software controlled (Labview & Matlab) – installed on an internal PC controller board running Windows 7.
- Tx power varied to ensure Rx SNR -20 dB to 16 dB (3 dB step size).



Signals & Testbed

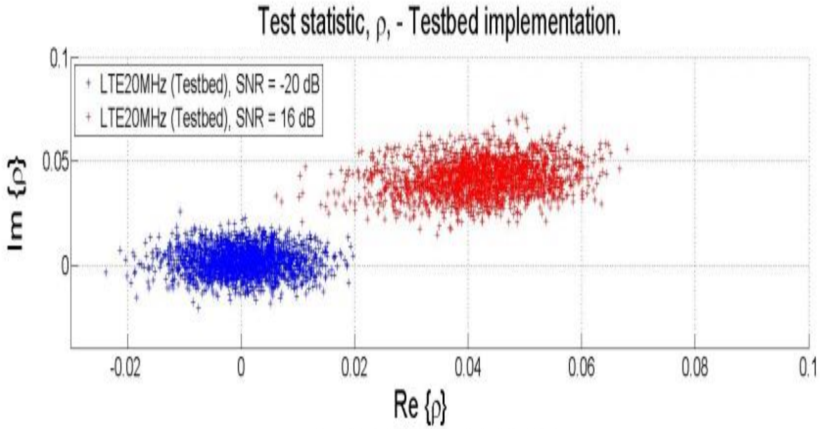
Testbed

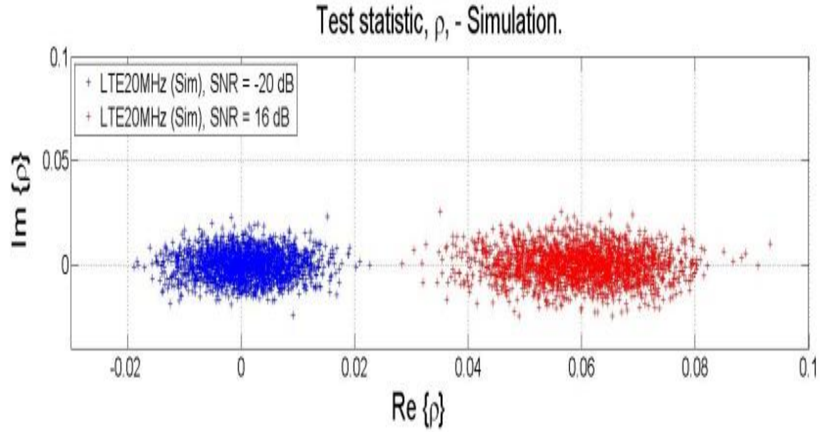
- **Rx Chassis:**
- 2 Rx RF chains (only 1 used)
- Downconversion from 2.45 GHz.
- 10 MHz local oscillator (LO).
- Software controlled (Labview & Matlab, Windows 7).
- Position of Rx in corridor beside lab. where Tx was.
- Non line-of-sight propagation.

Results

Test statistic

- 2000 calculations of ρ at SNR = -20 dB and 16 dB.
  - Testbed and Simulation.
- As SNR increases, mean of Re{ρ} increases in simulation.
- However for Testbed, mean of Re{ρ} **and** Im{ρ} increase.
- This is due to rotational effect of FFO.
  - Decreases in Re{ρ} and/or Im{ρ} are also possible, etc.





Results

Test statistic

- **FFO:** An issue to overcome that has received little attention in literature in the context of this algorithm.
  - Practical implementation issue rather overlooked in simulations.
  - Occurs due to Tx and Rx oscillator mismatches.
- **Statement of problem:** Given that ρ is proportional to $\Re\{\varphi\}$ and given that the possible values of φ may be stated as:

$$\varphi = \begin{cases} \sigma_x^2 + \sigma_n^2 & \Delta t = 0 \\ \sigma_x^2 \exp\{j2\pi\delta f\} & \Delta t = T_d \\ 0 & \text{otherwise} \end{cases}$$

For the case $\Delta t = T_d$, how to compensate appropriately for rotation due to FFO, δf?

Results

Test statistic

- As stated in a conventional OFDM receiver, the factor δf is calculated from the autocovariance.
  - A counter-rotation is then applied to modulation symbols to correct for effect of FFO.

- **However,** applying counter-rotations to φ (hence also to ρ) would change the statistics of ρ

- This negates the effectiveness of the threshold: η_ρ

Results

Test statistic

- **Proposed solution:**
  - Make N calculations of φ :

$$\varphi 1, \varphi 2, \ldots, \varphi N$$

  - Calculate their respective angles:

$$\theta_{\varphi(1)}, \theta_{\varphi(2)}, \ldots, \theta_{\varphi(N)}$$

  - Buffer & average to get: $\frac{1}{N}\sum_{n=1}^{N}\theta_{\varphi(n)}$, and hence new test statistic:

$$\rho = \frac{\frac{1}{2M}\sum_{t=0}^{M-1}\Re\left\{\varphi\exp\left\{-j\frac{1}{N}\sum_{n=1}^{N}\theta_{\varphi(n)}\right\}\right\}}{\frac{1}{2M+T_d}\sum_{t=0}^{M+T_d-1}|y(t)|^2}.$$

Results

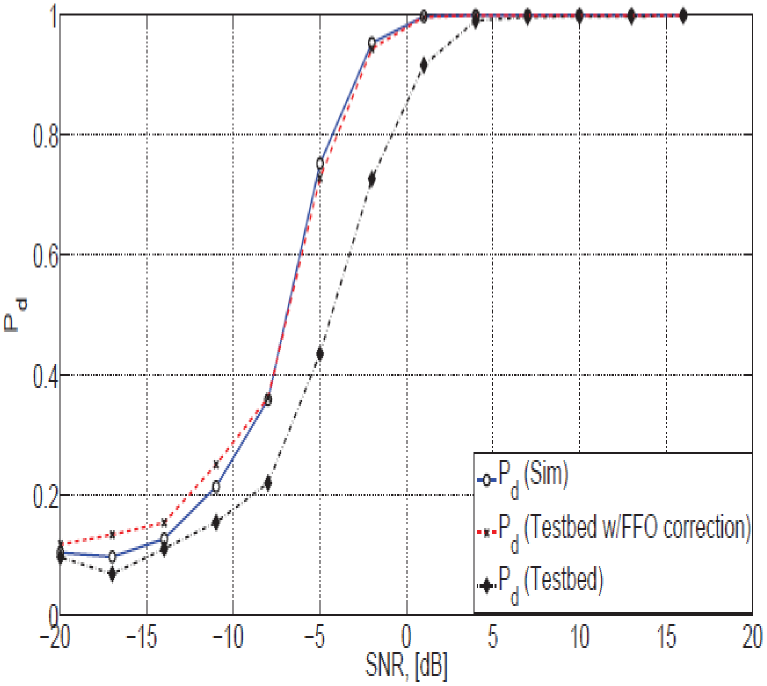
Calculation of results

- Make 2000 calculations of ρ and determine how many times η_ρ is exceeded -> ‘Probability of detection’, P_d .
- Set $P_{fa} = 0.1$.
- Compare Simulations **Vs**. Testbed **Vs**. Testbed w/FFO correction.

Results

Probability of detection

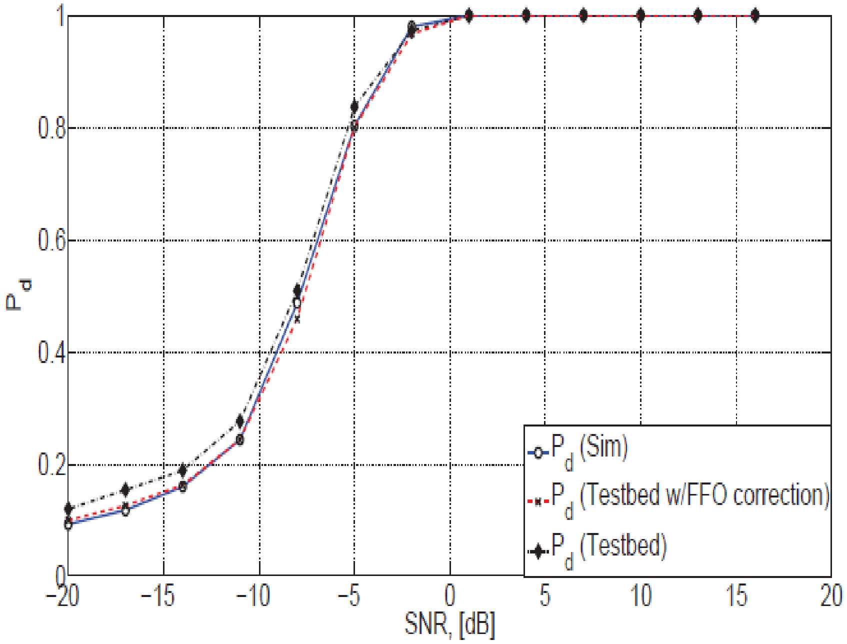
- LTE 20 MHz signal (T_d = 2048).
- Can clearly see a performance benefit with when FFO correction procedure is applied.
- **However** for smaller FFT sizes:
  - No requirement to apply FFO correction (**next slide**).



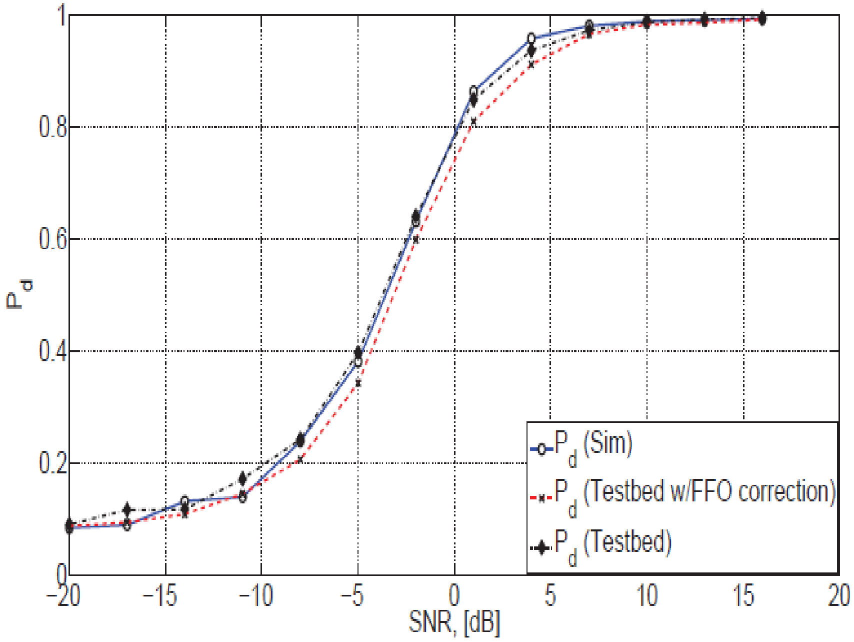
Results

Probability of detection

- WiMAX (T_d = 256).



- LTE 5 MHz (T_d = 512).



Conclusions

- A testbed implementation of an autocorrelation-based spectrum sensing algorithm.
  - A system model improvement to cope with effect of FFO.

- **Pros:**
  - Low complexity: Simple buffering of output of circuit already present in OFDM circuitry.
  - Good match with simulation results when improvement is applied.
  - Improvement need only be applied when FFT size is large (here: 2048).

- **Cons:**
  - Sensing time is increased (50 – fold).
  - Future work should consider effects of reducing sensing time on performance.

Thank you!