IMPACTS OF NARROWBAND INTERFERENCE ON OFDM-UWB RECEIVERS: ANALYSIS AND MITIGATION

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Presented By: S. M. Riazul Islam

INTRODUCTION

- The transmitted power level of UWB is limited to -41.3 dBm/MHz and can be spread over a huge BW 7.5 GHz.
- Enables the coexistence with other services such as GPS, IEEE 802.11 WLANs, IEEE 802.16 WiMax, etc.
- Due to their low Tx power and huge reception BW, UWB systems are subjected to NBIs.
- The scope of this paper is to analyze the impacts of NBI on the performance of an OFDM-UWB receiver.

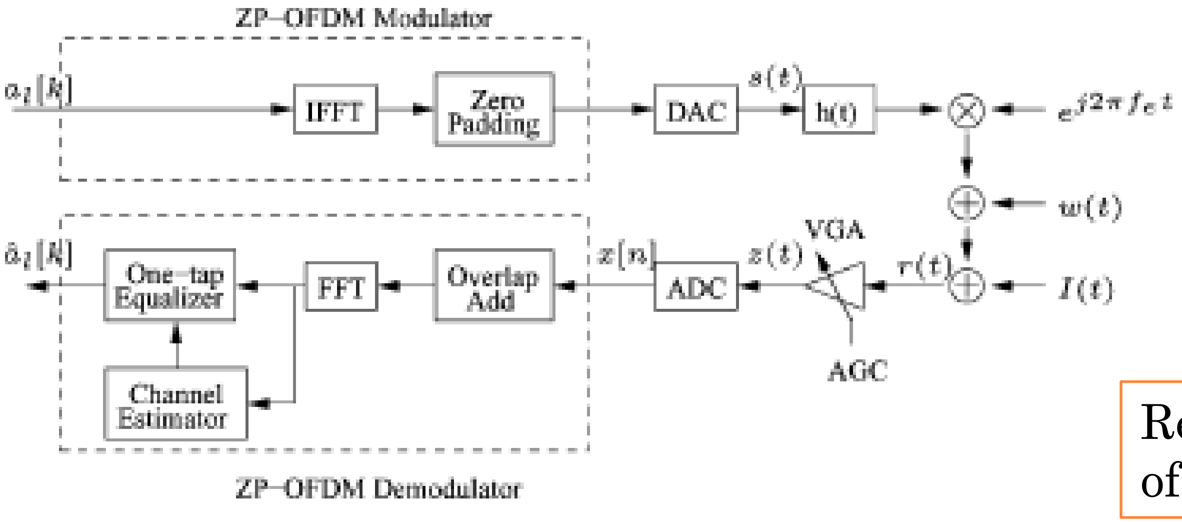
INTRODUCTION

- This doc presents an in-depth analysis of the impact of NBI on SINR loss at the O/P of ADC.

- Importance? SINR at the O/P of ADC serves as a good metric to evaluate the uncoded BER performance of an OFDM-UWB Rx.
- It is found that NBI increases the level of quantization noise.

- Solution? higher precision ADC. However, UWB receivers employs a flash data converter!
  - Proposed? Mixed interference mitigation scheme.

SIGNAL MODEL



Rectangular pulse of duration T_0

Subcarrier spacing

QPSK data

The transmitted signal

$$s(t) = \frac{1}{\sqrt{KT}} \sum_{l} \sum_{k \in C} a_l[k] e^{j2\pi k(t - lT_0)/T} g(t - lT_0)$$

Number of data subcarriers

Set of data subcarriers

SIGNAL MODEL

The power of the transmitted symbols is normalized to unity:

$$E[|a_l[k]|^2], E[|s(t)|^2] = 1$$

- A discrete-time implementation of s(t) that assumes the sampling period T_s=T/N is generated by means of N-point IFFT.

- According to CLT, s[n]:=s(nT_s) can be approximated as a complex Gaussian RV for sufficiently large number of subcarriers N>=20.

- In addition, OFDM modulation assumes a ZP of length $T_g=N_gT_s$ at the end of each symbol instead of CP.

- The above model is only fit for the conventional SB-OFDM systems. It is still applicable to the baseband of transceiver for both SB-OFDM and MB-OFDM.

SIGNAL MODEL

The received signal can be expressed by:

$$r(t) = e^{j2\pi f_\varepsilon t}\left[s(t) \otimes h(t)\right] + w(t) + I(t)$$

CFO

CIR

Thermal noise

NBI

The NBI is modeled by a linearly modulated signal of the form:

$$I(t) = A_i \sum_n b_n e^{j(2\pi f_i t + \Phi_i)} p(t - nT_i)$$

Modulated symbols of the interference

Rectangular pulse

Symbol period

IMPACTS OF NBI ON DATA CONVERTERS

- Due to the channel fading, the received signal r(t) presents a very large dynamic range.
- To improve the efficiency of the finite precision ADC, a VGA is used to normalize the power level to a desired level.
- The normalized signal z(t) is next sampled by ADC $z[n]=z(nT_s)$ and quantized into the digital signal x[n].

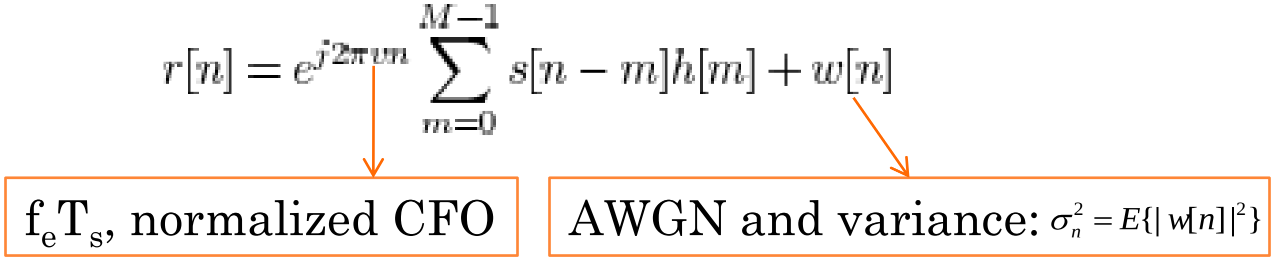
- For simplicity, a complex baseband model is used hereafter, and all signals are expressed in discrete time domain.

- Next the performance of ADC will be analyzed for two channel conditions: without and with NBI.

IMPACTS OF NBI ON DATA CONVERTERS

- A. NBI Free Channel

The received signal:



$$r[n] = e^{j2\pi \nu n} \sum_{m=0}^{M-1} s[n-m]h[m] + w[n]$$

$f_e T_s$, normalized CFO

AWGN and variance: $\sigma_n^2 = E\{|w[n]|^2\}$

Assume a quasi-static channel model with M paths and instantaneous channel power:

$$\overline{\sigma}_c^2 = \sum_{m=0}^{M-1} |h[n]|^2$$

Therefore, the instantaneous power r[n] is given by:

$$\sigma_r^2 = \overline{\sigma}_c^2 + \sigma_n^2$$

IMPACTS OF NBI ON DATA CONVERTERS

If σ_z^2 is denoted as the instantaneous power of VGA O/P z[n], i.e., $\sigma_z^2 = |z[n]|^2$
The VGA O/P becomes z[n]=G.r[n], where $G = \sqrt{\sigma_z^2 / \sigma_r^2}$.

If the maximum quantization level of ADC is 1, the PAPR of ADC can be defined as (?)

$$\Omega = \frac{1}{\sigma_z^2/2}.$$

To achieve a sampling speed as high as 528 *MHz* in OFDM-UWB Rx, a low-bit uniform ADC appears as the best solution. For a uniform b-bit ADC, the quantization step size:

$$\Delta = \frac{2}{2^b - 1}.$$

The power of the complex quantization noise q[n]:=x[n]-z[n]

$$\sigma_q^2 = 4 \sum_{i=0}^{2^{b-1}-2} \int_{i\Delta}^{(i+1)\Delta} (z-(i+1/2)\Delta)^2 p(z)dz$$

$$+4 \int_{1-\Delta/2}^{\infty} (z-1)^2 p(z)dz$$

pdf of I and Q components of z[n]

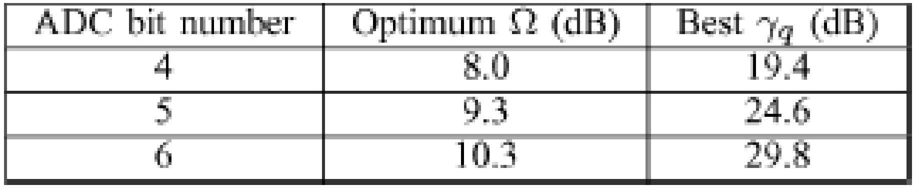
IMPACTS OF NBI ON DATA CONVERTERS

- Since both s[n] and w[n] can be interpreted as CGRVs, we can view z[n] as CGRV in AWGN channel.
- UWB MP channel is modeled by a multi-cluster quasi-static channel with large M (M>15). Although the paths within each cluster are correlated, the simulated histogram shows that the Gaussian approximation of z[n] still holds.
- Therefore, given b and σ_z^2 , one can easily calculate the quantization noise power σ_q^2.
- The signal-to-quantization-noise ratio: $\gamma_q = \frac{\sigma_z^2}{\sigma_q^2}$.
- For a given b, the optimum Ω can be found by solving

$$\partial\gamma_q/\partial\Omega = 0$$

IMPACTS OF NBI ON DATA CONVERTERS

- For a specific b-bit ADC, there is a optimum PAPR



ADC bit number	Optimum Ω (dB)	Best γ_q (dB)
4	8.0	19.4
5	9.3	24.6
6	10.3	29.8

- Higher precision ADCs lead to larger PAPR and higher Ω and higher γ_q
- For ADC O/P x[n], the SNR is given by,

$$\mathrm{SNR}_x = \frac{G^2\bar{\sigma}_c^2}{\sigma_q^2 + G^2\sigma_n^2}.$$

- Ignoring OLA and assuming perfect Synch

$$X[k] = \mathrm{FFT}\,(z[n] + q[n]) = G\,(a[k]H[k] + W[k]) + Q[k],$$

IMPACTS OF NBI ON DATA CONVERTERS

- According to CLT, Q[k] can be modeled as a GRV. Therefore, X[k] can be viewed as GRV, as well.
- After some direct manipulations,

$$\boxed{\mathrm{SNR}_x = \frac{\bar{\sigma}_c^2}{\left(\bar{\sigma}_c^2 + \sigma_n^2\right)/\gamma_q + \sigma_n^2}} \longrightarrow \boxed{A}$$

- This can be used to evaluate the uncoded BER of OFDM receiver.

IMPACTS OF NBI ON DATA CONVERTERS

- B. NBI Channel
- The received signal becomes

$$r[n] = e^{j2\pi v n} \sum_{m=0}^{M-1} s[n-m]h[m] + I[n] + w[n]$$

NBI with average power σ_i^2

- The ADC O/P is given by:

$$x[n] = G\left(e^{j2\pi v n} \sum_{m=0}^{M-1} s[n-m]h[m] + w[n] + I[n] \right) + q[n].$$

- SINR of x[n]:

$$\mathrm{SINR}_x = \frac{G^2 \bar{\sigma}_c^2}{\sigma_q^2 + G^2\left(\sigma_n^2 + \sigma_i^2\right)}$$

→ C

- And,

$$\mathrm{SINR}_x = \frac{\bar{\sigma}_c^2}{\left(\bar{\sigma}_c^2 + \sigma_n^2 + \sigma_i^2\right)/\gamma_q + \sigma_n^2 + \sigma_i^2}.$$

→ B

IMPACTS OF NBI ON DATA CONVERTERS

- Comparing (A) and (B), we find that NBI introduces two effects:

$$\mathrm{SNR}_x = \frac{\bar{\sigma}_c^2}{(\bar{\sigma}_c^2 + \sigma_n^2)/\gamma_q + \sigma_n^2} \rightarrow \boxed{A}$$

$$\mathrm{SINR}_x = \frac{\bar{\sigma}_c^2}{(\bar{\sigma}_c^2 + \sigma_n^2 + \sigma_i^2)/\gamma_q + \sigma_n^2 + \sigma_i^2}. \rightarrow \boxed{B}$$

1) The increase of received signal power leads to a smaller gain G for VGA, which causes the larger quantization noise:

$$\sigma_q^2/G^2 = (\bar{\sigma}_c^2 + \sigma_n^2 + \sigma_i^2)/\gamma_q \leftarrow \boxed{G = \sqrt{\sigma_z^2/\sigma_r^2}}$$

2) As to the third term of denominator in (B), interference directly affects the tone of Int($f_i T_s$) and its neighbor tones.

IMPACTS OF NBI ON DATA CONVERTERS

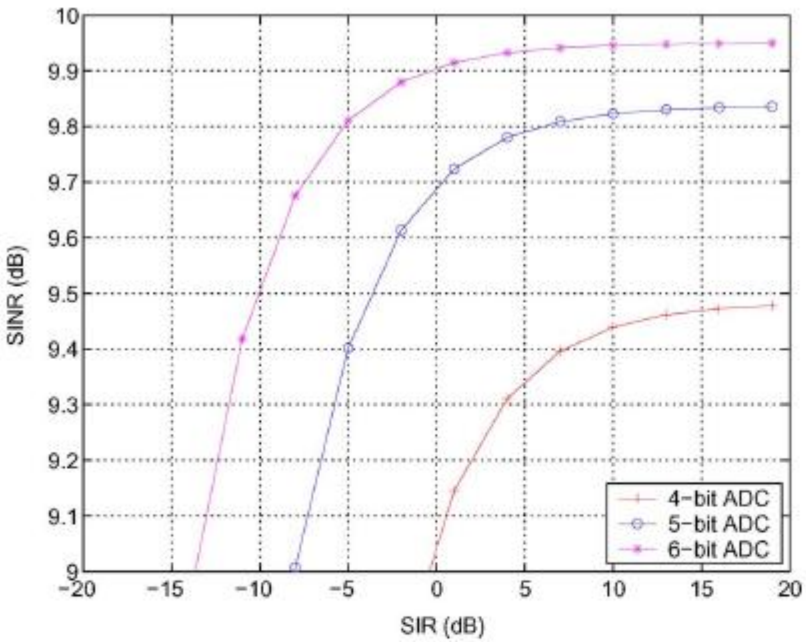
- We focus on the first effect of NBI, the enlarged quantization noise. Omitting the third term of denominator in (C),

$$\boxed{\mathrm{SINR}_x = \frac{\bar{\sigma}_c^2}{\left(\bar{\sigma}_c^2 + \sigma_n^2 + \sigma_i^2\right)/\gamma_q + \sigma_n^2}.}$$

→ D

- Assuming the same optimum value for γ_q as the one given by previous table and denoting $\boxed{\mathrm{SIR} = \bar{\sigma}_c^2/\sigma_i^2}$ as the SIR of r(t), we compare the SINR curves of ADC.

IMPACTS OF NBI ON DATA CONVERTERS



$\bar{\sigma}_c^2/\sigma_n^2 = 10\,\mathrm{dB}.$

Signal to thermal noise ratio

- As the NBI becomes stronger, the SINR of ADC is reduced.
- Ex. Reducing the SIR from 20 to 0 dB results in 0.5 *dB* SINR loss for the 4-bit ADC.

NBI SUPPRESSION

- When compared to the desired WB signal, the interference occupies a much smaller frequency band and presents a higher PSD.
- This motivates us to use transform-domain filtering techniques to suppress the NBI.
  - TD➔FD, find frequency location, frequency excision, remaining signal FD➔TD.

A. Digital NBI detection and mitigation

- Since the phase of the NBI is unknown, the NBI has to be detected noncoherently based on the absolute values of the received signal samples.
- The highest peak corresponds to the subcarrier affected by NBI

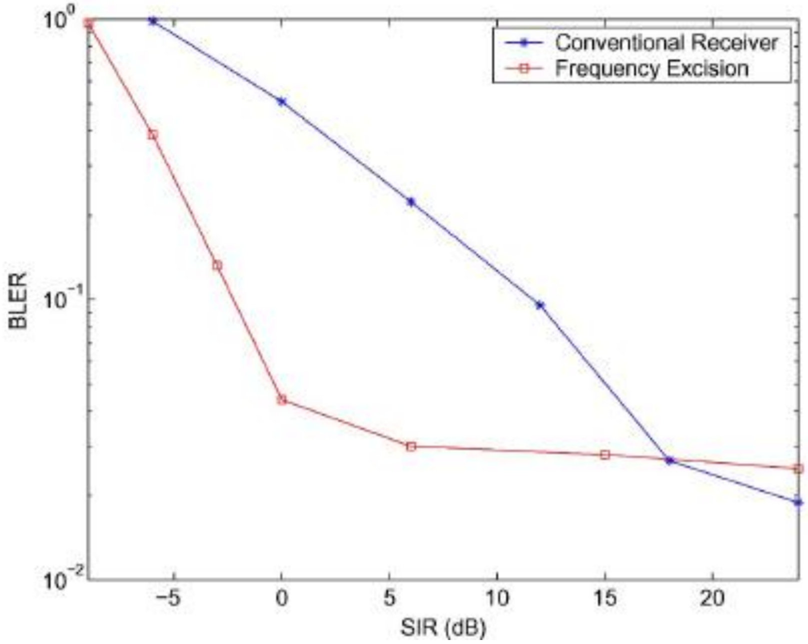
NBI SUPPRESSION

$| X[k] |^2$

- By comparing the magnitude-squared of the FFT bins with a threshold T_h, we can find the existence and location of NBI.
- Lost data caused by excision can be recovered by channel decoding techniques.
- Four adjacent subcarriers are also excised. (Why?)
- We observe the BLER plots

NBI SUPPRESSION

- Conventional means no frequency excision



$$\sigma_c^2/\sigma_n^2 = 6\,\mathrm{dB}.$$

- To achieve BLER=0.05, the conventional receiver requries SIR=15 *dB*. However, Rx with freq. excision needs 0 *dB*.

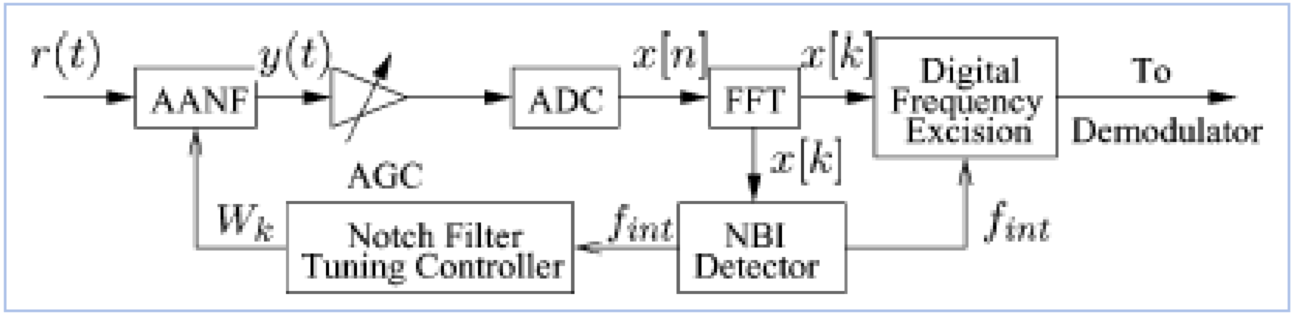
NBI SUPPRESSION

- As the SIR decrease, the BLER of Rx w. freq. excision increase very rapidly. (why?)
  - As NBI becomes stronger, normalized quantization noise σ_q^2/G^2 is increased, which leads to the SINR loss (D).
  - With the increasing power of NBI, spectral leakage becomes worse (more power of NBI will be leaked to the neighboring subcarriers).
- Possible solutions? Increasing the number of bits of ADC. Drawback➔ not affordable for practical UWB Rx.
  - Alternate? To suppress strong NBI, we need to find a low-complexity scheme.

NBI SUPPRESSION

B. Analog NBI Cancellation:

- Freq. excision method can not remedy the performance degradation when SIR< 0 *dB*.
  - The gain of the VGA is set according to the power of NBI, effectively increasing the quantization noise of the ADC.
  - Logical solution? Remove NBI before it enters the AGC and ADC.
- New suppression scheme: adaptive analog noise filter (AANF) with notch freq. f_0.

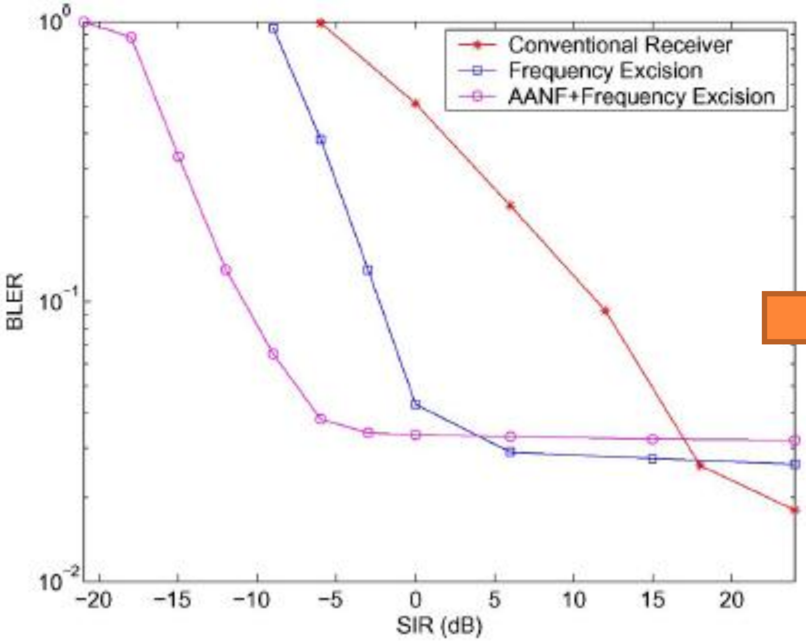


NBI SUPPRESSION

- For weak NBI level, freq. excision method is sufficient. However, for significant NBI, AANF needs to be activated.
- By controlling the notch frequency f_0, the contaminated freq. component is removed before it goes into AGC.
- To combat NBI adaptively, the AANF should designed to be tunable in the whole reception BW.
- For MB-OFDM, BW of one sub-band is 528 *MHz* spread from -264 to 264 *MHz*.

NBI SUPPRESSION

C. Performance of mixed NBI suppression scheme



For example, to achieve BLER=0.1,

1. the Rx with digital freq. excision needs SIR>-3 *dB*.

2. While mixed scheme can allow SIR as low as -12 *dB*.

- At SIR> 0 *dB*, there is a crossover (?)
  - Bypass AANF at SIR> 0 *dB*.

CONCLUSION

- An in-depth study to access the impact of NBI on the operation of ADC.
- Optimized designing of AGC can not remedy the performance loss at high NBI level.
- Most of the NBI have focused on purely digital cancellation
  - Not viable solution for MB-OFDM UWB systems
- **Mixed NBI suppression scheme is proposed**.

Thanks for your cooperation

Questions/Comments