UWB signaling and channel modeling: Some open issues

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outline

- UWB channel systems challenges
- UWB channel modeling using information theoretic arguments
  - Subspace Analysis Using Akaike Information theoretic Criteria (AIC)
  - Model selection using AIC
  - UWB Channel entropy analysis
  - UWB channel spatial dynamics analysis
- UWB systems capacity and signaling
  - Duty-cycled DSSS
  - Channel Division Multiple Access Technique: ChDMA
- Conclusions

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Motivations

- Third generation wireless systems and beyond (3G and 4G systems).
- Compatibility with existing systems.
- UWB capacity issues.
- UWB Applications:
  - Cable replacement
  - Location Based Services
  - Cognitive Radio...

Ultra Wideband Communications Challenges

- Telatar & Tse (00) show that: With spread spectrum signals over multipath channels, the data rate is inversely proportional to the number of channel paths.
  - Direct sequence spread spectrum with no duty cycle has zero throughput in the limit, if the number of channel paths increases with bandwidth.
  - The channel uncertainty versus the bandwidth has to be assessed.

Subspace Analysis using Information Theoretic Criteria

Wax and Kailath (1985) presented a new approach for estimating the number of signals in multichannel time-series and frequency-series, based on AIC (*Akaike Information Criterion*) and MDL (*Minimum Description Length*).

Let $\mathbf{h(t)} = [h_1(t), h_2(t), ..., h_N(t)]$.

Consider a set of candidate covariance matrices, $R^{(k)}$, with rank k

$$\mathbf{R^k} = \sum_{i=1}^{k} \left(\lambda_i - \sigma^2\right) \psi_i \psi_i^H + \sigma^2 \mathbf{I}$$

where λ_i is the i^{th} eigenvalue, ψ_i is the i^{th} eigenvector and σ^2 is the noise variance.

Information Theoretic Criteria (1)

Akaike proposed to select the model which gives the minimum AIC, defined by:

$$AIC = -2.log(\mathbf{f}(\mathbf{h}|\hat{\theta^k})) + 2.k$$

Both Schwartz's and Rissanen's approaches yield to the same criterion, given by:

$$MDL = -log(\mathbf{f}(\mathbf{h}|\hat{\theta^k})) + (1/2)k.log(N)$$

where the $\hat{\theta^k}$ is the maximum likelihood estimate of the parameter vector θ^k and k is the number of freely adjustable parameters in θ^k. With $\theta^k = \left(\lambda_1, ..., \lambda_k, \sigma^2, \psi_1, ...\psi_k\right)$.

Information Theoretic Criteria (2)

- The AIC is

$$AIC(k) = -2log\left(\frac{\prod_{i=k+1}^{p}\lambda_i(\mathbf{h})^{\frac{1}{(p-k)}}}{\frac{1}{p-k}\sum_{i=k+1}^{p}\lambda_i(\mathbf{h})}\right)^{N(p-k)} + 2k(2p-k) \quad (1)$$

- The MDL function is given as follows:

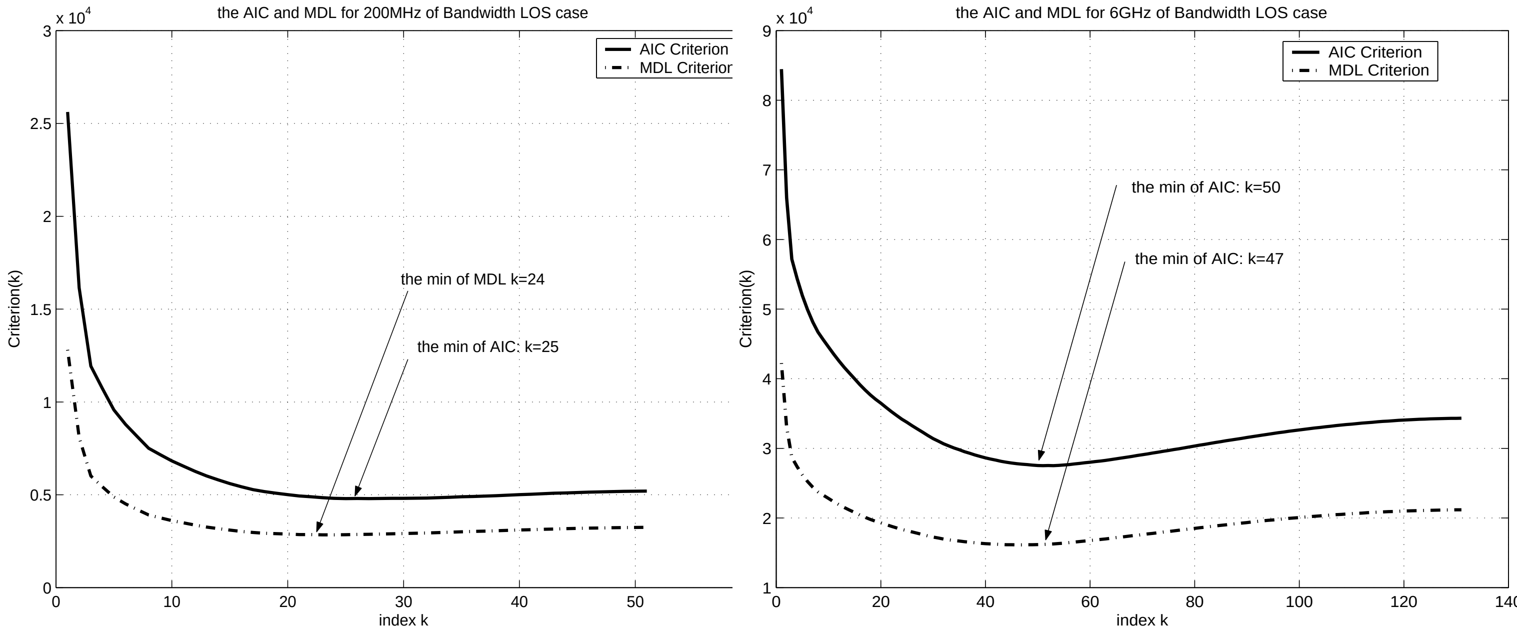
$$MDL(k) = -log\left(\frac{\prod_{i=k+1}^{p}\lambda_i(\mathbf{h})^{\frac{1}{(p-k)}}}{\frac{1}{p-k}\sum_{i=k+1}^{p}\lambda_i(\mathbf{h})}\right)^{N(p-k)} + log(N)\frac{k(2p-k+1)}{4} \quad (2)$$

Estimation of the degrees of freedom

The number of degrees of freedom, mainly the number of significant eigenvalues, is determined as the value of $k \in \{0, 1, ..., p - 1\}$ which minimizes the value of (1) or (2).
In this work, the number of DoF represents the number of unitary dimension independent channels that constitute an UWB channel.

Results

DoF estimation results



200 MHz 6 GHz

Figure 1: The number of UWB channel DoF for LOS setting.

- The number of DoF doesn t scale linearly with the bandwidth

Model selection using AIC (1)

Schuster and Bolcskei (06) used Akaike's Information-Theoretic Criteria to determine suitable distributions for UWB channel impulse response taps.

Denote the unknown cumulative distribution function (CDF) of the operating model by F, and the set of all CDFs by $\mathcal{M}$. A parametric candidate family $\mathcal{G}^j = \left\{ G^j_{\Theta^j} \left| \Theta^j \in \mathcal{T}^j \right. \right\}$ is the subset of $\mathcal{M}$, with individual CDFs G^j_{Θ} parametrized by the U -dimensional vector $\Theta^j \in \mathcal{T}^j$, with $\mathcal{T}^j \subset R^U$

The goal of the model selection procedure is to choose the distribution that minimizes the discrepancy among all members of the candidate set.

Model selection using AIC (2)

AIC is an approximately unbiased estimator of the expected Kullback-Liebler (KL) distance:

$$AIC_j = -2 \sum_{n=1}^{N} \log g^j_{\widehat{\Theta}}(x_n) + 2U$$

with:

$$\widehat{\Theta}^j = arg \cdot max_{\Theta^j \in \mathcal{T}^j} \frac{1}{N} \sum_{n=1}^{N} \log g^j_{\Theta}(x_n)$$

The Akaike weights are given by:

$$\omega_j = \frac{e^{-\frac{1}{2} D_j}}{\sum_{i=1}^{J} e^{-\frac{1}{2} D_i}}$$

with $D_j = AIC_j - min_i AIC_i$ and $i \in J$

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Model selection using AIC: Results

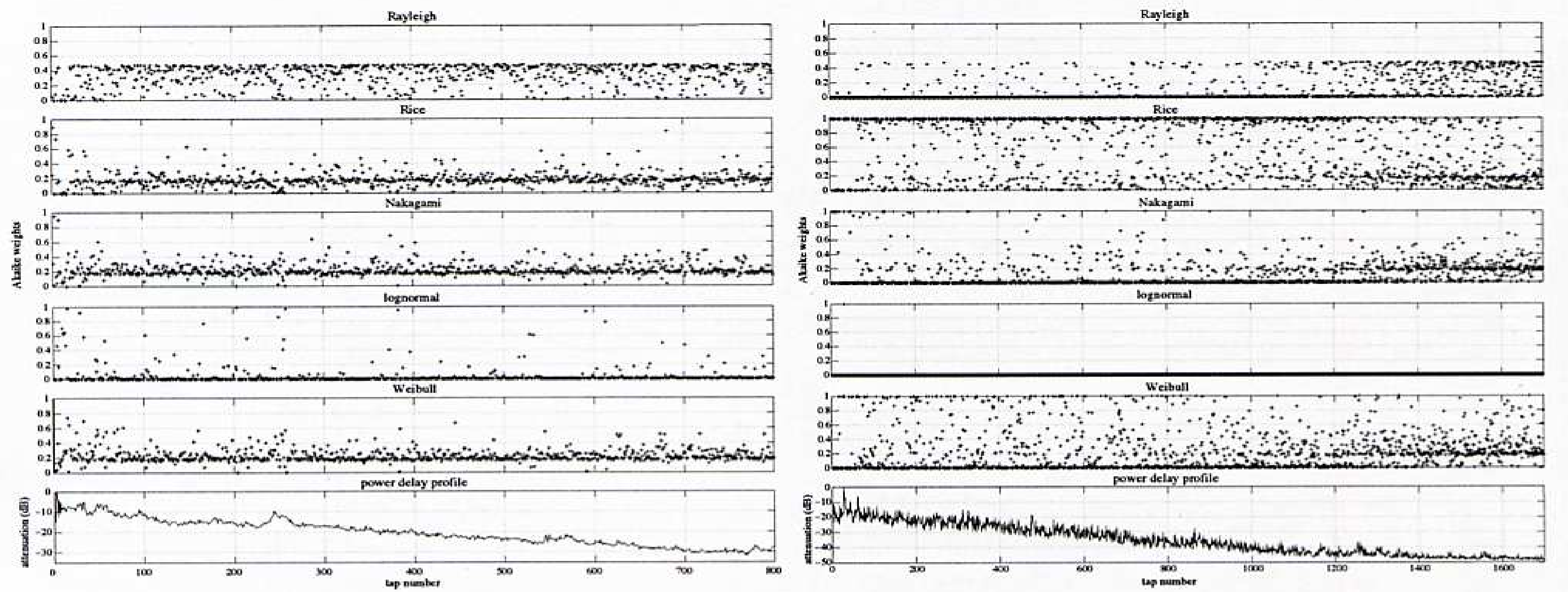

Fig. 1. PDP and Akaike weights for Measurement Campaign I

Fig. 2. PDP and Akaike weights for Measurement Campaign II

- Model selection using AIC show that Rayleigh, Rice and Weibull distributions exibit a good fit to the measurement data

Maximum entropy approach to UWB channel modeling(1)

Idea: Given a set of measurements, we try to find the best process model under some constraints.

Entropy rate of a Gaussian process The entropy rate of a stationary Gaussian stochastic process can be expressed as

$$h(\chi) = \frac{1}{2} log 2\pi e + \frac{1}{4\pi} \int_{-\pi}^{\pi} log S(\lambda) d\lambda \qquad (3)$$

Maximum entropy approach to UWB channel modeling(2)

Burg's Maximum Entropy Theorem:

The maximum entropy rate stochastic process X_i satisfying the constraints

$$E[X_i X_{i+k}^*] = \alpha_k, \quad k = 0, 1, ..., p, \quad for\ all\ i, \tag{4}$$

is the p^{th} order Gauss-Markov process of the form

$$X_i = -\sum_{k=1}^{p} a_k X_{i-k} + Z_i \tag{5}$$

where the Z_i are i.i.d.$\sim N(0, \sigma^2)$ and $a_1, a_2, ..., a_p, \sigma^2$ are chosen to satisfy eqn.(4)

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Maximum entropy approach to UWB channel modeling(3)

AR process coefficients estimation

$$R(0) = -\sum_{k=1}^{p} a_k R_{-k} + \sigma^2 \quad (6)$$

and

$$R(l) = -\sum_{k=1}^{p} a_k R_{l-k}, \quad l = 1, 2, ...p. \quad (7)$$

These equations exactly resemble the Yule-Walker equations. There are $p+1$ equations in the $p+1$ unknowns $a_1, a_2, ..., a_p, \sigma^2$.Therefore we can solve for the parameters of the processes from the covariances using fast algorithms such as the Levinson and the Durbin recursion.

Maximum entropy approach to UWB channel modeling(4)

Spectrum estimation After the coefficients $a_1, a_2, ..., a_p$ have been calculated from the covariances, the spectrum of the maximum entropy process is seen to be

$$S(l) = \frac{\sigma^2}{|1 + \sum_{k=1}^{p} a_k e^{-ikl}|^2} \tag{8}$$

This is the maximum entropy spectral density subject to the constraints $R(0), R(1), R(2), ..., R(p)$.

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Results

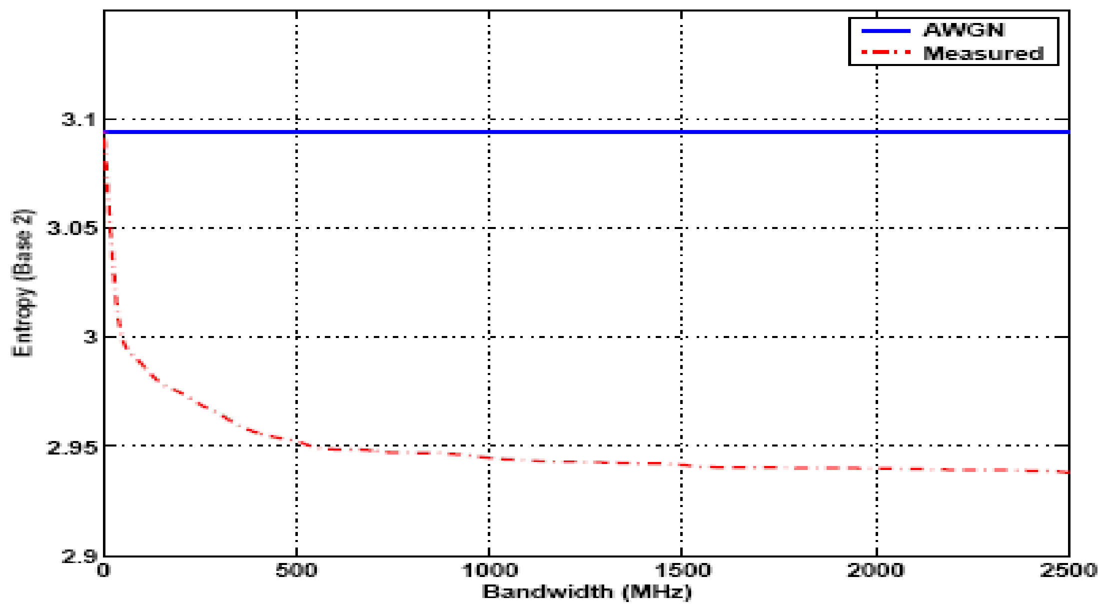


Figure 2: Entropy variation with respect to the bandwidth.

- Maximum entropy analysis shows that the channel information doesn't increase so much with increasing the bandwidth

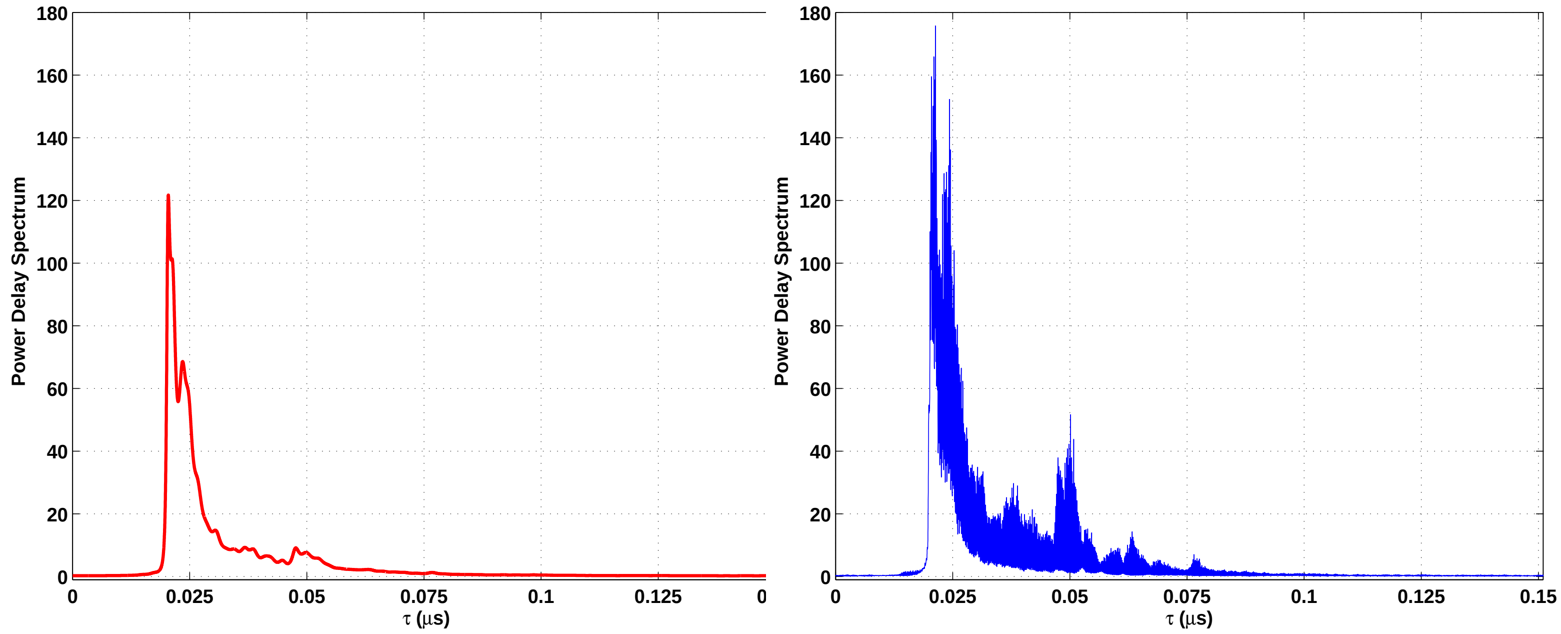


Figure 3: Estimated Power Delay Spectrum with 500Mhz Bandwidth and 6GHz Bandwidth

- The PDP shape can be reproduced with a limited AR model order.

UWB channel spatial dynamics

The investigation described in this work focuses on the apparent size of the visibility areas of UWB channel multipath components. We show that the visibility areas tend to shrink as the carrier frequency or the bandwidth increases.

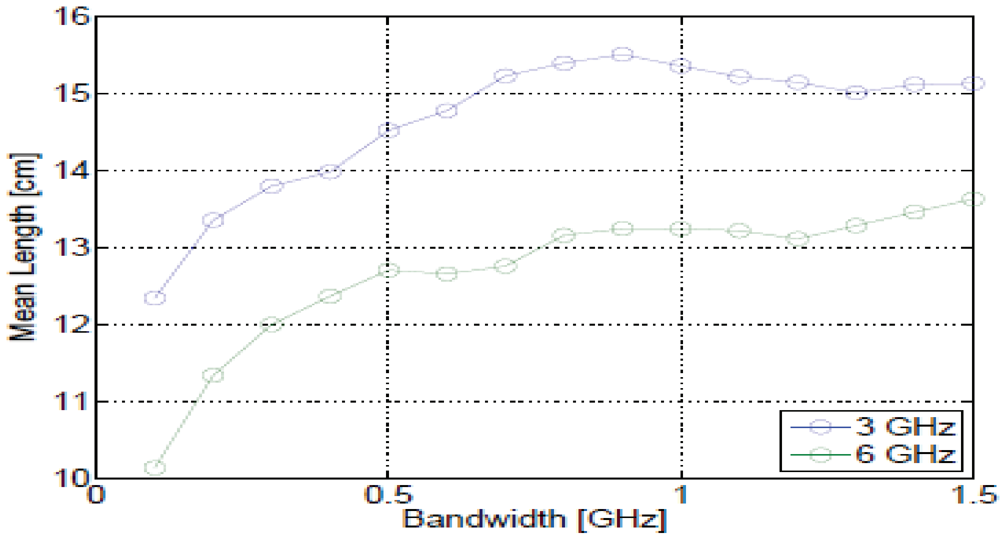


Figure 4: The mean apparent length of multipath components at the carrier 3 GHz and 6 GHz

Ultra Wideband Systems Capacity and Signaling(1)

- Golay (49) showed that AWGN capacity, with non fading channels, can be approached by on-off keying (pulse position modulation) with very low duty cycle.
- Kennedy(69) proved this for flat fading channels using FSK signals with duty cycle transmissions.
- Telatar & Tse (00) extended the proof for multipath channels with any number of paths.

Summary: FSK with duty cycle achieves AWGN capacity for any number of paths.

UWB systems capacity and signaling (2)

- Médard & Gallager (02) show that direct sequence spread spectrum with no duty cycle, approaches zero data rate in the limit of infinite bandwidth and with a high number of paths.
- Telatar & Tse (00) show that: With spread spectrum signals over multipath channels, the data rate is inversely proportional to the number of channel paths.
  - **Summary:** Direct sequence spread spectrum with no duty cycle has zero throughput in the limit, if the number of channel paths increases with bandwidth.
  - **Why?** The data rate is penalized when the receiver has to estimate the channel.
  - **Question?** How to perform multiple access in the infinite bandwidth case.

UWB systems capacity and signaling (3)

- Due to the channel uncertainty that communication systems faces, a necessary condition for a communication system to achieve the AWGN channel capacity in the limit of infinite bandwidth is that the channel estimation in the limit is perfect and this requires [Porat & Tse]:

$$SNR_{est} = \frac{2PT_c}{N_0 \theta L} \to \infty \tag{9}$$

Where L is the number of independent resolvalbe paths, T_c is the coherence time and θ is the duty cycle parameter.

UWB systems capacity and signaling (4)

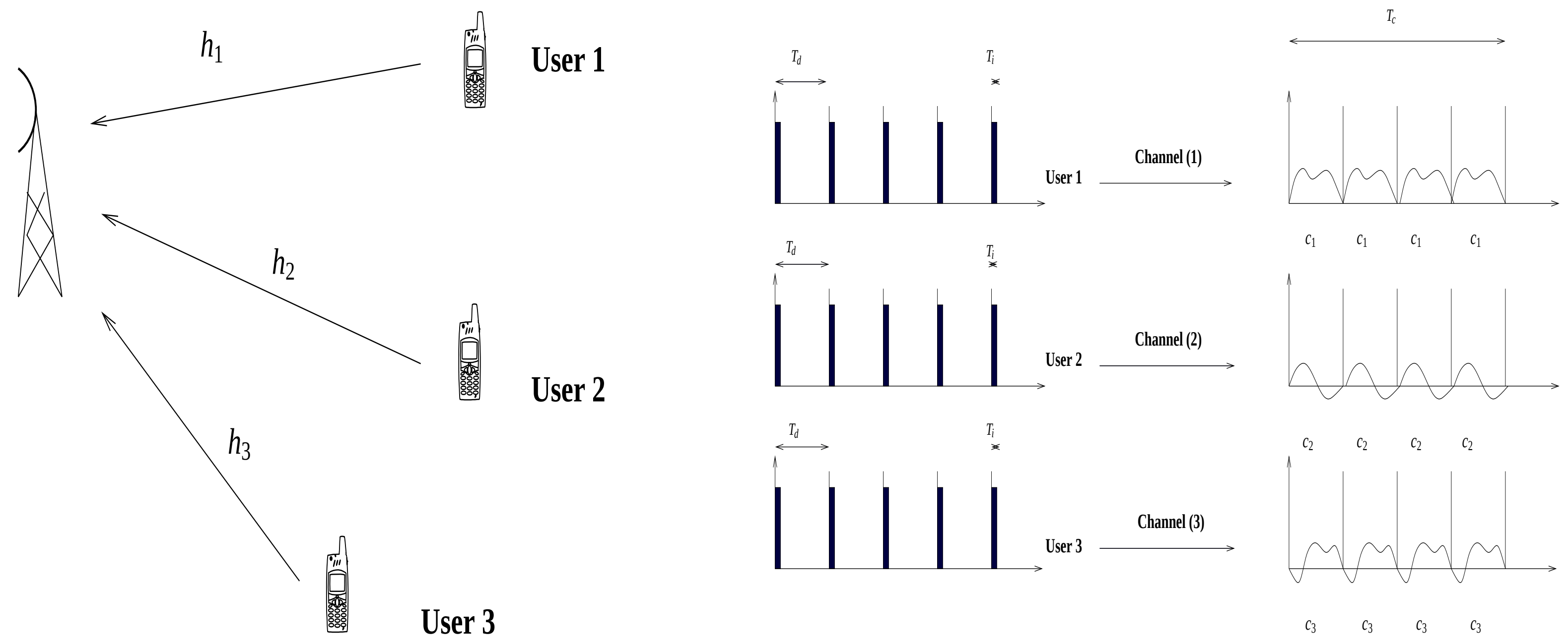
- Porrat, Tse & Nacu (06) showed that duty-cycled DSSS systems achieve the wideband capacity as long as the number of independently faded resolvable paths increases sub-linearly with the bandwidth while duty-cycled PPM signaling achieves the wideband capacity only if the number of paths increases sub-logarithmically.

Why? Because PPM is an orthogonal Modulation, so the rate increases only logarithmically with the bandwidth whereas the rate of DSSS systems increases linearly.

UWB systems capacity and signaling:ChDMA principle

Idea

- ChDMA address the problem of multiple access in decentralized networks (ad-hoc UWB) and non-cooperative transmissions.



- Each user sends a very modulating peaky signal every T_d (In UWB, T_d is typically about $15ns$ whereas T_c about $100\mu s$)
- Channels can act as codes if they have enough independent entries (similar to CDMA).
- The system uses very low duty cycles and is flexible from an ad-network perspective (no code allocation).

Channel Division Multiple Access: Channel Model (1)

We consider a time invariant channel $c^{(k)}$ of user k given by:

$$c^{(k)}(\tau) = \sum_{l=1}^{L^{(k)}} \lambda_l^{(k)} \delta(\tau - \tau_l^{(k)}), \qquad (10)$$

where λ_l and τ_l represent respectively the gain and the delay of the l-th multipath.

- All users are in the same environment, operating at the same bandwidth.
- The number of paths is the same ($L^{(k)} = L$).

Channel Model (2)

Furthermore, because of the pulse signal $\mathbf{g}$ employed for the transmission of the symbols on the environment, the channel $h^{(k)}(\tau)$ of the k-th user is given by

$$h^{(k)}(\tau) = \sum_{l=1}^{L} \lambda_l^{(k)} g(\tau - \tau_l^{(k)}), \qquad (11)$$

where g is the transmit filter.
The discrete channel matrix $\mathbf{H}$ is given by the concatenation of the discrete channel vector of each user as shown in the following:

$$\mathbf{H} = [h^{(1)} h^{(2)} \ldots h^{(K)}]. \qquad (12)$$

where the channel vector length is given by the ratio between the temporal resolution (T_r) and the symbol period (T_s).

ChDMA Capacity Assessment (1)

In the case of Gaussian independent entries, since

$$\mathbb{E}(\mathbf{y}\mathbf{y}^H) = \sigma^2\mathbf{I}_N + \mathbf{H}\mathbf{H}^H$$
$$\mathbb{E}(\mathbf{n}\mathbf{n}^H) = \sigma^2\mathbf{I}_N$$

The mutual information per dimension (known as spectral efficiency), with optimum receiver, is:

$$\gamma = \frac{1}{N}\left(\log_2 \det(\mathbf{I}_N + \frac{1}{\sigma^2}\mathbf{H}\mathbf{H}^H)\right)$$

ChDMA Capacity Assessment (2)

- For the matched filter (MF) and the MMSE receivers:

$$\gamma = \frac{1}{N}\sum_{i=1}^{K}\log_2\left(1 + SINR_i\right)$$

with:

$$\mathrm{SINR}_{MF_i} = \frac{\mid \mathbf{h}_i^H \mathbf{h}_i \mid^2}{\sigma^2(\mathbf{h}_i^H \mathbf{h}_i) + \sum_{j=1, j\neq i}^{K} \mid \mathbf{h}_i^H \mathbf{h}_j \mid^2} \quad (13)$$

$$\mathrm{SINR}_{MMSE_i} = \mathbf{h}_i^H(\tilde{\mathbf{H}}_i\tilde{\mathbf{H}}_i^H + \sigma^2\mathbf{I})^{-1}\mathbf{h}_i, \quad (14)$$

where $\tilde{\mathbf{H}}_i$ is $N \times (K-1)$ matrix which contains all time response vectors $\mathbf{h}_j$ for all $j \neq i$.

- With BPSK signaling, the mutual information becomes:

$$\gamma = \frac{1}{N} \sum_{i=1}^{K} 1 - \int_{-\infty}^{+\infty} \frac{e^{-\frac{v^2}{2}}}{\sqrt{2\pi}} \log_2 \left(1 + e^{-2\mathrm{SINR}_i - 2\sqrt{\mathrm{SINR}_i} v} \right) dv, \quad (15)$$

where $SINR_i$ for MF and MMSE receivers are already defined before.

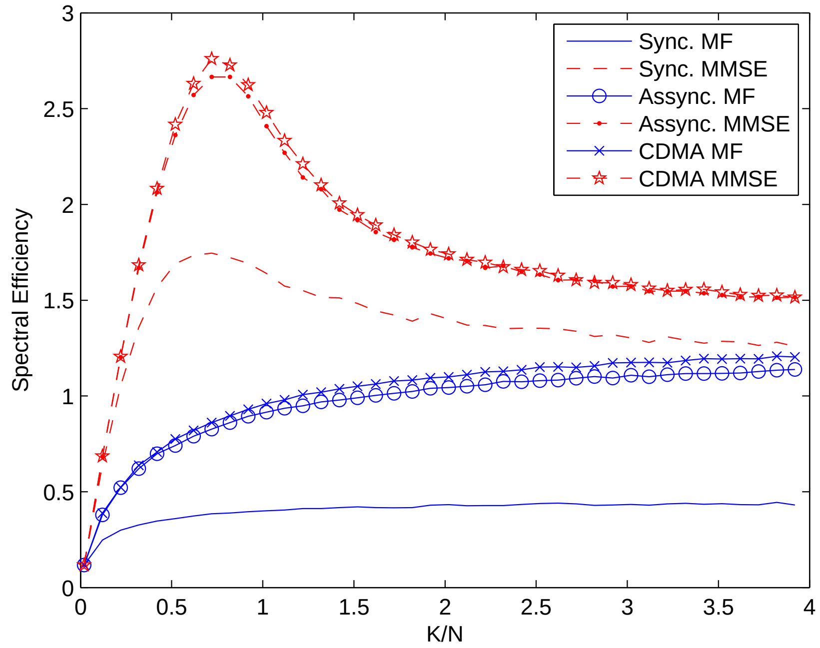
How many users can simultaneously communicate?

For $K \to \infty$ (and supposing the non-zero eigenvalues equal to λ_i with $1 \leq i \leq L$):

$$\frac{B}{N} \log_2 \det \left(\mathbf{I}_N + \frac{P}{N_0 B} \mathbf{H}\mathbf{H}^H \right) = \frac{B}{N} \sum_{i=1}^{L} \log_2 (1 + \frac{P\lambda_i}{N_0 B})$$

- there is a limit in the number of users since the system depends only on L.
- The number L has already been characterized before as the number of degrees of freedom of the wideband channel.
- The values of λ_i (linked to the energy of the channel) also matter in the infinite bandwidth regime

Capacity Assessments: CDMA versus ChDMA at 10dB



- The CDMA-based case has been simulated in an ideal AWGN channel
- With asynchronism, the CDMA gain is not very significative with respect to ChDMA for the MMSE and Optimal receiver and may be reduced or becomes even worst in frequency selective fad˙

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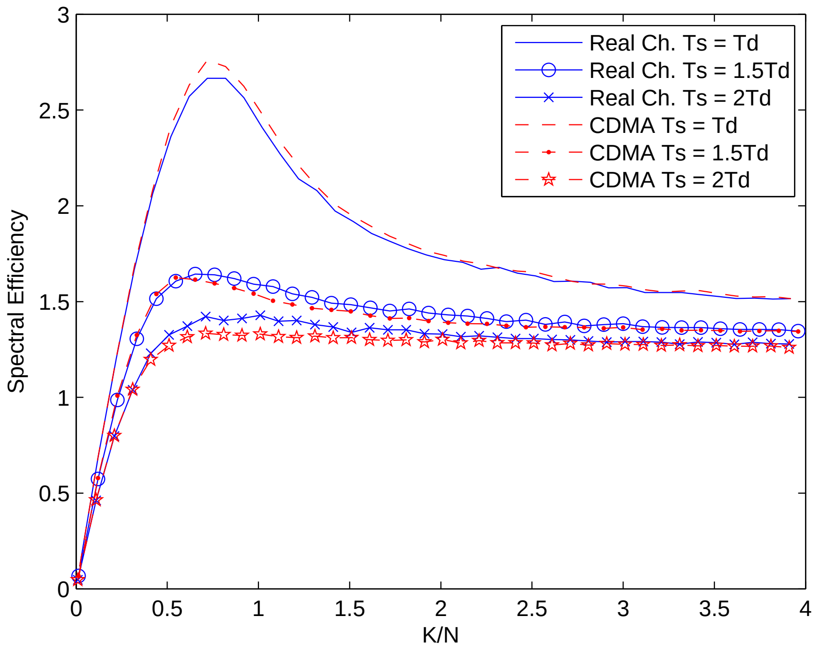
Capacity Assessments: Symbol period effect with asynchro



- The Optimum results, for both CDMA and ChDMA, are with T_s equal to channel delay spread.
- With BPSK signaling, the results are the same.

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ChDMA versus Duty-Cycled DSSS

- Peaky modulation
- Spread spectrum like signaling due to UWB channel high temporal resolution
- Location dependent signatures: No code allocation, security issues, decentralized architecture...

Conclusions

- Information Theoretic Arguments are used to address UWB channel diversity, modeling and entropy
- New UWB channel spatial dynamics analysis that shows frequency and bandwidh dependence
- A New Multiple Access Scheme has been devised which is flexible with no constraint in terms of code acquisition
- Initial results for ChDMA show very good separation capability and interference reduction due to the wideband nature of the channel especially for the asynchronous mode

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THANK YOU!

Questions?