Interference Avoidance and Dispersive Channels. A New Look at Multicarrier Modulation

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Outline

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2. Communication over Dispersive Channels
3. Multicarrier Modulation and Multiuser Detection
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6. Conclusions and Future Work

Overview I

- Radios of yore: fixed structure
- Radios today/tomorrow: programable
- Future spectrum management?
  - Receivers/transmitters adjust transmission/reception methods to suit environment
  - Distributed (relax FCC requirements)
  - Can this possibly work efficiently?

Overview II

- Quality measure - SIR
- Improving SIR
  - power control
  - receiver optimization
  - codeword optimization through interference avoidance

Overview III

- IT WORKS!
  - FINE PRINT: for sychronous multiuser uplinks at a single receiver with perfect channel and interference information
  - Dispersive channels, imperfect information, downlinks, asynchronous operation, multireceiver, etc. ???
  - Direct application to dispersive channels?
  - Apply state of the art dispersive channel coding/equalization work?
- Main concern: dispersive channels
- Genesis of this work → frustration, ignorance and simple-mindedness
- Usefulness and practical issues → need feedback

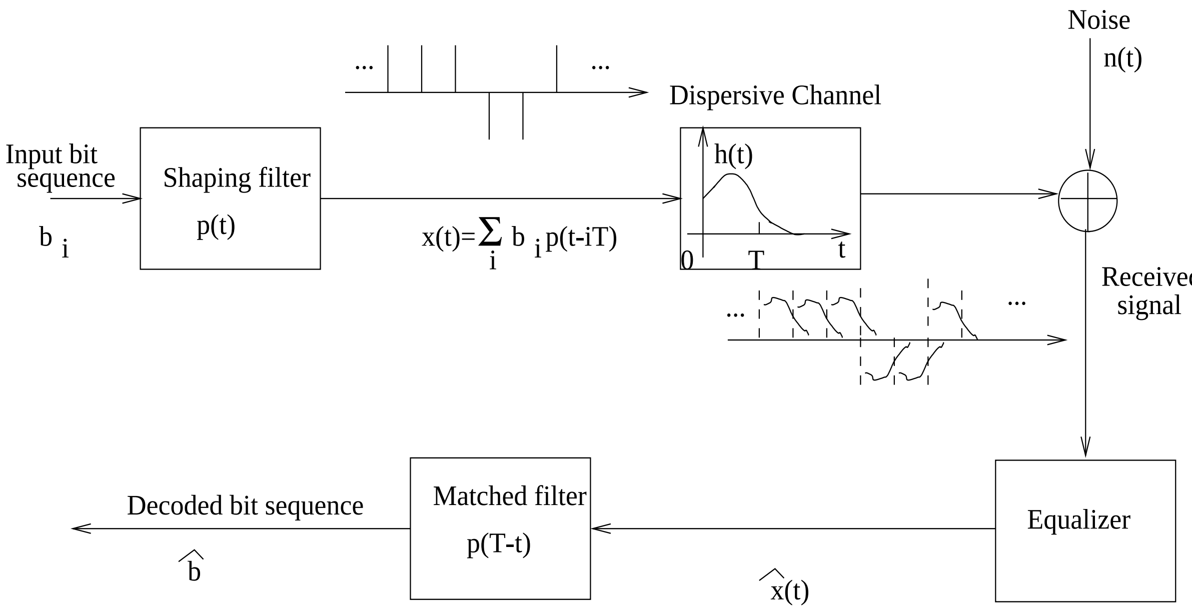
Communication over Dispersive Channels

- Main problem: ISI
- Equalization and coding used to combat ISI
- Multicarrier modulation
  - Partition channel into parallel, independent subchannels
  - Send data (coded) over the subchannels
  - Reconstruct at receiver (decision feedback, etc.)
- Multicarrier modulation based on channel eigenfunctions

Bit-Sequential Scenario

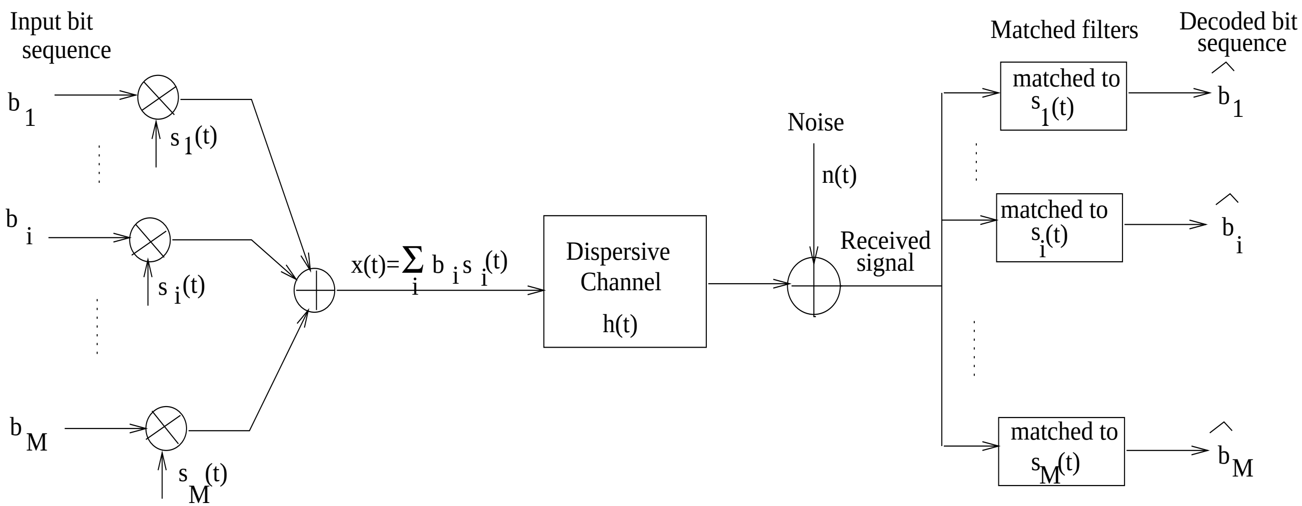
$$x(t) = \sum_k b_k p(t - kT)$$

b_k is the bit sent during interval k, T is the bit interval, $p(t)$ is the finite duration pulse used to convey the information over the channel

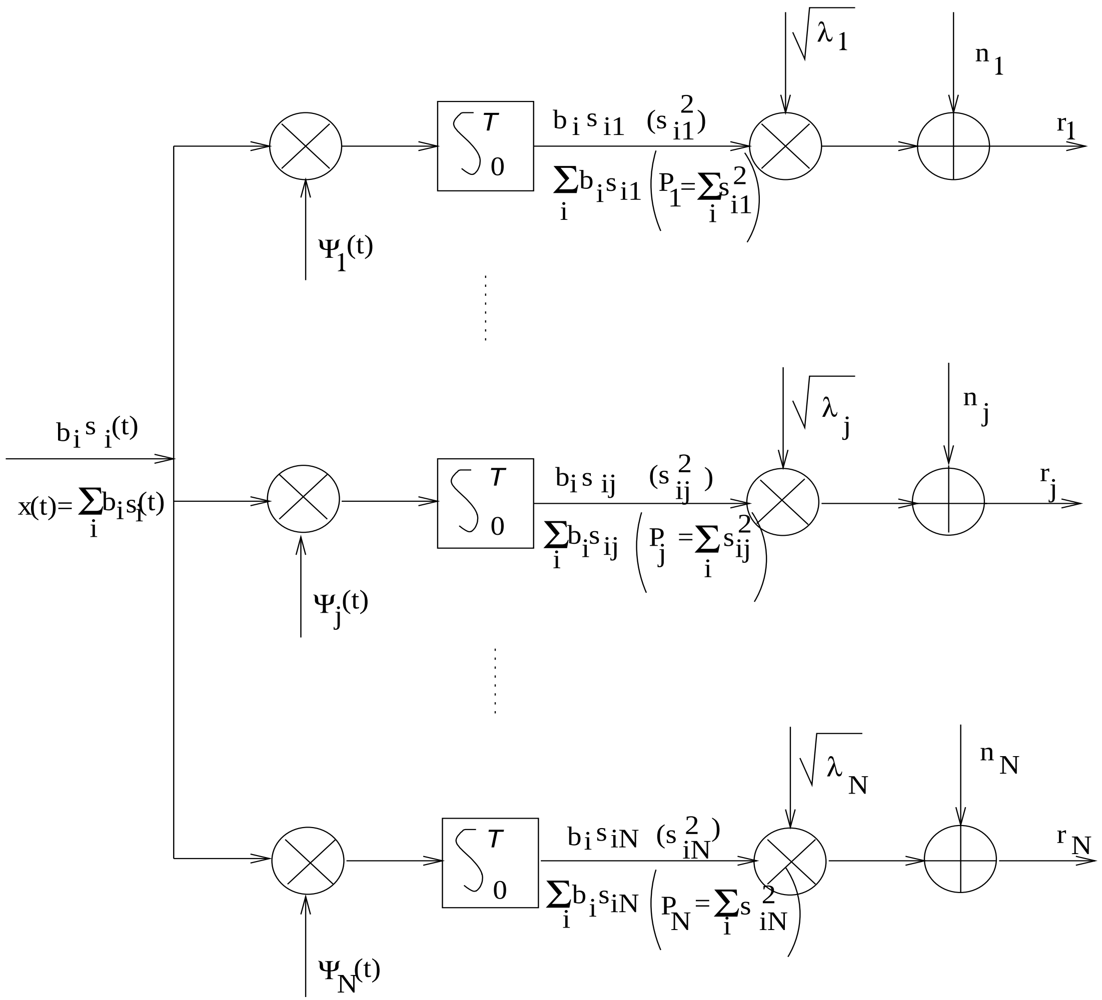


Our Version of Multicarrier Modulation

- Send bits in parallel using a distinct waveform $s_k(t)$ to convey each bit b_k, i.e. $x(t) = \sum_{k=1}^{M} b_k s_k(t)$
- Using a sufficiently long transmission interval ISI becomes irrelevant

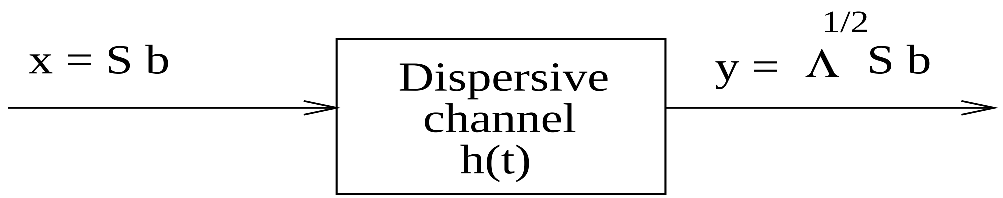


Modelling The Channel



Modelling The Channel – Basis Functions

- Need a set of orthonormal basis functions $\{\Psi_i(t)\}$ such that
  - can be used to represent channel inputs
  - channel responses to these functions are also orthogonal to allow simple representation of outputs
- Use channel eigenfunctions!



- Remark (due to Jianghong Luo): for FIR channels simple complex sinusoids are eigenfunctions

Channel Eigenfunctions

- Requirement

$$\int_0^{\mathcal{T}} \int_0^{\mathcal{T}} \Psi_i(\tau) h(t-\tau) d\tau \int_0^{\mathcal{T}} \Psi_j(\mu) h(t-\mu) d\mu dt = \lambda_i \delta_{ij}$$

- Define: $R_h(\tau - \mu) = \int_0^{\mathcal{T}} h(t-\tau)h(t-\mu)dt$ the channel autocorrelation function and rewrite as

$$\int_0^{\mathcal{T}} \int_0^{\mathcal{T}} \Psi_j(\mu) \Psi_i(\tau) R_h(\tau - \mu) d\tau d\mu = \lambda_i \delta_{ij}$$

- which is equivalent to

$$\int_0^{\mathcal{T}} \Psi_i(\mu) R_h(\tau - \mu) d\mu = \lambda_i \Psi_i(\tau)$$

Multiuser Detection

- Represent each waveform as $s_k(t) = \sum_{j=1}^{N} s_{kj} \Psi_j(t)$
- Define codeword matrix

$$\mathbf{S} = \begin{bmatrix} | & | & \dots & | \\ \mathbf{s}_1 & \mathbf{s}_2 & \dots & \mathbf{s}_M \\ | & | & \dots & | \end{bmatrix}$$

- Project received signal onto the basis functions

$$\mathbf{r} = \Lambda^{1/2}\mathbf{S}\mathbf{b} + \mathbf{n}$$

- Rewrite $\tilde{\mathbf{r}} = \Lambda^{-1/2}\mathbf{r} = \mathbf{S}\mathbf{b} + \tilde{\mathbf{n}}$
- Typical multiuser detection problem: the ensemble $b_k \mathbf{s}_k$ must be jointly decoded (subject to energy constraints)

Objectives

- Find an optimal set of waveforms $\{s_i(t)\}_{i=1}^{M}$, or equivalently the codewords $\{\mathbf{s}_i\}_{i=1}^{M}$, such that we get maximum SIR at the receiver for all bits.
- Remarks:
  - optimal codewords are WBE sequences with the property that the sequence set has minimum total squared correlation (TSC)
  - interference avoidance
    - minimizes TSC of received signal
    - yields a variant of WBE sequences tuned to channel noise and eigenvalues

Interference Avoidance

To obtain $\max$ **SIR, place all the signal energy where there is least interference**

Interference Avoidance – The Eigen-Algorithm

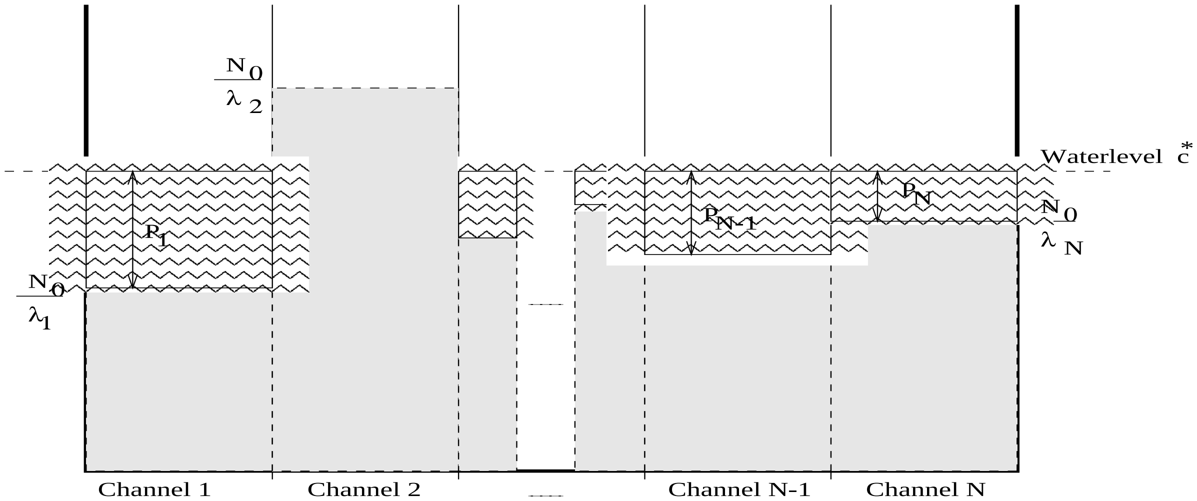
- START: initial set of signatures $\{s_k(t)\}_{k=1}^{M}$, with corresponding signature vectors $\{\mathbf{s}_k\}_{k=1}^{M}$
- For each bit k, calculate the interference generated by the other $M-1$ independent bits, described by the N-dimensional autocorrelation matrix $\mathbf{R}_k = \mathbf{S}\mathbf{S}^\top - \mathbf{s}_k\mathbf{s}_k^\top + N_0\Lambda^{-1}$.
- Find minimum eigenvalue μ_k^* of $\mathbf{R}_k$ and associated eigenvector $\mathbf{x}_k^*$, and replace $\mathbf{s}_k$ by $\mathbf{x}_k^*$.
- Repeat process iteratively for each bit signature until no improvement is obtained.

Minimizing TSC and Waterfilling

- minimize TSC subject to total power constraint $\sum_{j=1}^{N} P_j = M$ (M bits each with unit energy) with $P_j \geq 0,\ \forall j$ leads to the "water filling" distribution of powers
- Convergence of interference avoidance algorithm guarantees that minimum TSC can be reached

Waterfilling

$$P_j = \left(c^* - \frac{N_0}{\lambda_j}\right)^+, \quad \text{with } (x)^+ = \begin{cases} x \text{ if } x \geq 0 \\ 0 \text{ if } x < 0 \end{cases}$$



Turns out that minimizing TSC is same as maximizing sum capacity

Multiple Users

- Users share the same dispersive channel (so far)
  - application to non-wireless channels
  - first step towards the more general multiple channel problem (applicable to wireless channels)
- each of the L users has its own codeword ensemble matrix $\mathbf{S}_i$ and bit vectors $\mathbf{b}_i$ of dimension M, $\Rightarrow$ the received signal is

$$\mathbf{r} = \mathbf{n} + \Lambda^{1/2} \sum_{i=1}^{L} \mathbf{S}_i \mathbf{b}_i = \mathbf{n} + \Lambda^{1/2} \mathbf{S}' \mathbf{b}'$$

IA and Dispersive Channels: Conclusions

- Make ISI irrelevant by using a sufficiently long transmission interval
- Channel equalization and multiuser detection problems are then isomorphic
  - each bit is assigned a "CDMA" codeword
  - optimal codewords can be obtained through application of interference avoidance algorithms
  - with Gaussian signaling channel capacity could (theoretically) be achieved
- Trivial extension to multiple users sharing the same channel

Conclusions: Future Work on IA

1. Channel characteristic was assumed; how to do it adaptively?
2. Asynchronous operation
3. Multiple channels (currently under investigation)
4. Multiple Receivers
5. Multiple Antennas
6. Ultimately: is it worth all the trouble of adapting codewords?
    - Performance analysis