A Practical Approach to Strengthen Vulnerable Downlinks via Superposition Coding

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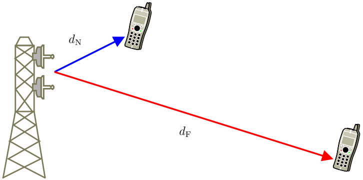
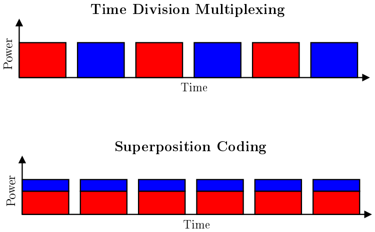
What is Superposition Coding?





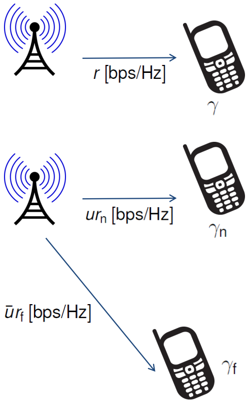
- BS sends information to *two* users N (near) and F (far) ↔ Communicating over a **Broadcast Channel** (BC)
- BS has full CSI: *Gaussian* BC [Cover06][1]
- BS has no CSI: *Fading* BC [Zhang09][2]
- Capacity achieved by **Superposition Coding** (SC) and **Successive Decoding** (SD)

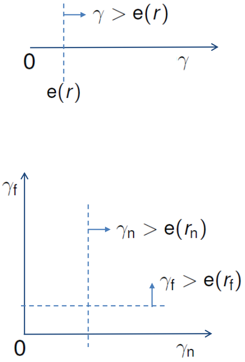
[1] T. Cover, and J. A. Thomas, Elements of Information Theory, 2nd ed., John Wiley & Sons, Inc., 2006.

[2] W. Zhang, S. Kotagiri, J. N. Laneman, On Downlink Transmission Without Transmit Channel State Information and With Outage Constraints," IEEE Trans. IT, Sept. 2009.

Orthogonal Coding on the BC

γ: the link SNR, $\mathsf{e}(x) \triangleq \exp(x) - 1$,
u (resp. $\bar{u} = 1 - u$): fraction of slots to N (resp. F).





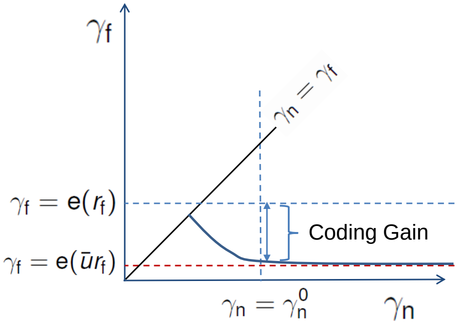
Min. link SNR independent of u!

SC as a Superior Multiuser Channel Code

Constraining $(ur_{\mathsf{n}}, \bar{u}r_{\mathsf{f}})$ to be feasible with SC, **minimum** far SNR

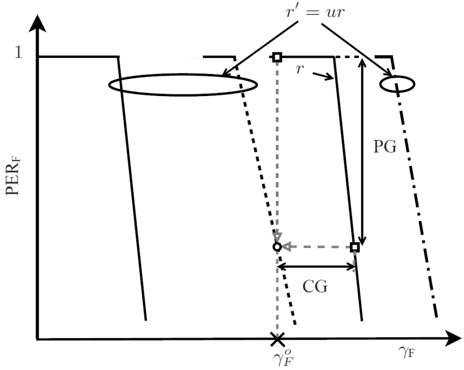
$$\gamma_{\mathsf{f}}^{*}(\gamma_{\mathsf{n}}; ur_{\mathsf{n}}, ur_{\mathsf{f}}) = \frac{\gamma_{\mathsf{n}}\mathsf{e}(\bar{u}r_{\mathsf{f}})}{\gamma_{\mathsf{n}} - \mathsf{e}(ur_{\mathsf{n}})(1 + \mathsf{e}(\bar{u}r_{\mathsf{f}}))}.$$

- Packets encoded **exactly** at $(ur_{\mathsf{n}}, \bar{u}r_{\mathsf{f}})$
- For each u, require $\alpha > \mathsf{e}(ur_{\mathsf{n}})/\gamma_{\mathsf{n}}$ with SC
- Coding gain (CG) increases with $\gamma_{\mathsf{n}} \Leftrightarrow$ pair F with high-SNR N!



Performance Gain (PG) in the Finite Blocklength Regime

- Non-zero decoding error probability or Packet Error Rate (PER) ϵ
- At PER $= \epsilon$, typical packet requires $\frac{1}{1-\epsilon}$ transmissions to reach F
- Easy to measure the Reliability Gain RG $= \frac{1-\epsilon_{\text{SC}}}{1-\epsilon_{\text{TD}}}$



SC with Finite Blocklength Channel Codes

- IT result **existential**, not constructive
- Need to understand how SC works with well-known codes
- Identify key practical issues that arise in its implementation

Definition (Code library)

A collection of $M < \infty$ encoder-decoder function pairs with spectral efficiencies (aka "rates") $r_1 < r_2 \cdots < r_M$

Definition: Packet Error Rate (PER)

The probability of codeword decoding error

Definition ($\epsilon-$feasible on a link)

A code with rate r is $\epsilon-$feasible on a link if the PER of a codeword encoded at r is no greater than ϵ

SC with a Finite Channel Code Library

Important special case: N close to BS, F at cell-edge.

- $r_n = r_M$, $\bar{u}r_{\mathsf{f}}$ is small (can set to r_1)
- Set $ur_M = r_k$, so that $u_k = r_k/r_M, r_f = r_1/\bar{u}_k,\ k \in \{1, \ldots, M\}$
- If library has codes $r_a < r_{\mathsf{f}} < r_b$, time-share between r_a and r_b

Compare SC using (r_k, r_1) with TD using $(r_M, r_1/u_k)$, for $k = 1, \ldots, M$.

The BICM Code Library

- Pairs powerful binary codes with well-known modulation techniques [Caire98][3]
- Combines the advantages of signal space coding with well-known binary codes
- Flexible and easy to implement
- Coding technique in DSL, Wi-Fi, WiMAX...

In our library:

- Modulations: BPSK, QPSK, 16-QAM
- Channel codes:
  - Standard const. length 7 rate-1/2 convolutional code with generator matrix [133,171]
  - Rates 2/3, 3/4, 5/6 punctured versions of mother code

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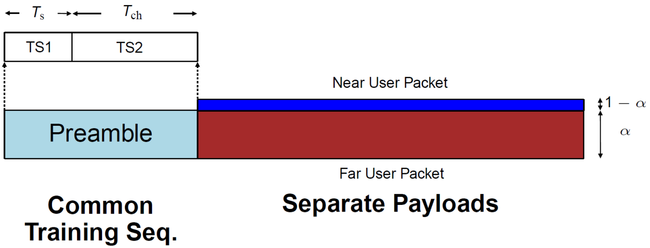
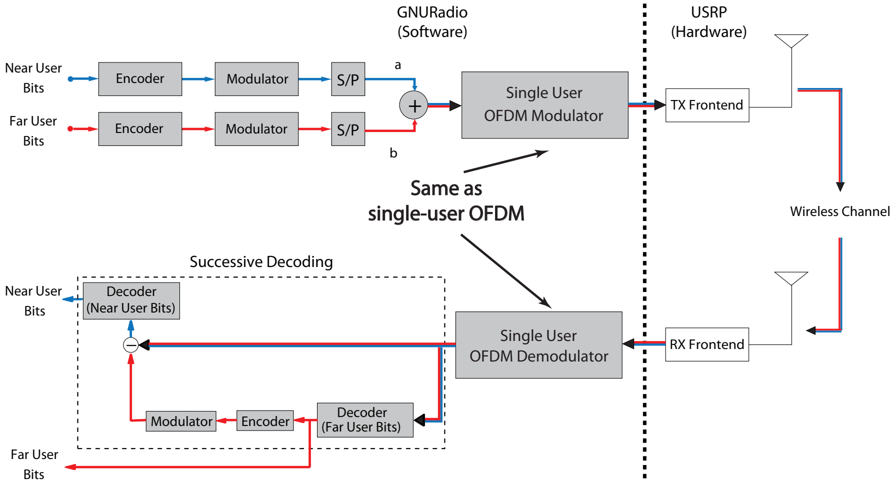
[3] G.Caire, G. Taricco and E.Biglieri, “Bit-Interleaved Coded Modulation”, IEEE Trans. IT, May 1998.

Frame Structure

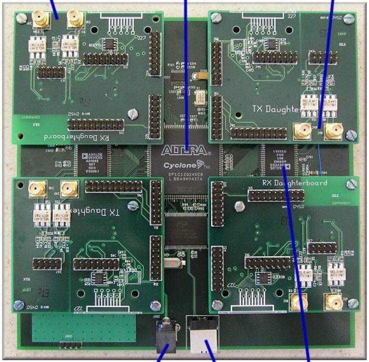


- TS1: Packet acquisition, timing and frequency sync. Duration $T_s = 48\mu s$
- TS2: Channel estimation. Duration $T_{ch} = 34\mu s$

Top-level Block Diagram



The USRP Board



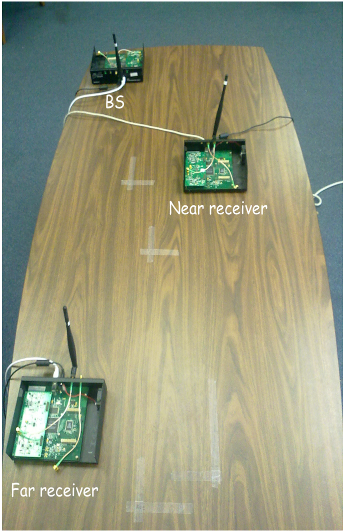
- Flexible
  - Multi-Protocol
  - Multi-Band
- Board has FPGA, DAC/ADC, RF Frontends
- USB 2.0 Interface with Linux PC
- Software-based DSP on GNURadio
  - Open Source
  - In-built USRP drivers

Setting up the BC

P : BS power, α: N's share

$$\gamma_{\mathsf{n}} \propto \alpha P \triangleq P_{\mathsf{n}}$$
$$\gamma_{\mathsf{f}} \propto \bar{\alpha} P \triangleq P_{\mathsf{f}}$$

Rate r is reliable $\leftrightarrow$ PER $\lessapprox 0.1$
For $k = 1, \ldots, M$:
SC Step:
Step 1: Set $P_{\mathsf{n}} = 0$ & $\uparrow P_{\mathsf{f}}$ s.t. r_1 is reliable
Step 2: $\uparrow P_{\mathsf{n}}$ s.t. r_k is reliable
Step 3: Keeping $P_{\mathsf{n}}/P_{\mathsf{f}}$ constant $\uparrow P_{\mathsf{f}}$ s.t. r_1 is reliable
TD Step: Find PER_{f} at BS power $P_{\mathsf{n}} + P_{\mathsf{f}}$ and rate r_1/u_k



Experimental Results

- $\bar{u}r_{\mathrm{f}} = 0.5$ [bps/Hz], SC always uses BPSK-1/2
- 16QAM-5/6 always feasible at N with full power
- SC adjusts N's power and code to provide the same rate as TD

	SC			**TD**		
u	γ_{f} (dB)	SIR (dB)	F PER	TD peak rate	F PER	RG
0.1	8.8	1	7%	Infeasible	N/A	N/A
0.2	7.4	1.95	6%	2.5	100%	∞
0.4	5.5	5	3%	1.25	75%	3.83
0.55	4.3	5	5%	1.11	38%	1.53
0.8	2.7	6	6%	0.63	37%	1.49
0.85	2.6	7.5	5%	0.59	29%	1.34

Conclusions

- **Experimentally** demonstrated a **practical** approach to exploit superposition codes
- **Specific decoding strategies** (e.g,. demodulate-and-decode) can render the Gaussian approximation for inter-user interference inaccurate
- **Signal superposition** opens up new possibilities for link-layer scheduling policies [Vizi11][4]

[4] P. Vizi, S. Vanka *et al.*, "Scheduling using Superposition Coding: Design and Software Radio Implementation", IEEE Radio and Wireless Week, Jan. 2011.