Selected PHY topics from 4G wireless standards

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Introduction

• Pre-history: Ma-bell, Bell Labs R&D
• 1983 divestiture
• 1996 Lucent Technologies is formed
  – Equipment arm of ATT
  – Bell Labs goes with Lucent
• 2001 telecomm bubble is burst
• 2006 Alcatel-Lucent
• 2007 LGS Innovations is a wholly owned subsidiary of ALU (with congressional oversight) that does government facing R&D
Outline

• Overview of a protocol stack
• Overview of 4G standards
• Overview of PHY layer techniques of 4G systems
• Focus on two interesting PHY topics
  – Hybrid-ARQ
  – Cooperative relay coding
The OSI reference model (protocol stack)

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Functions and services performed by the Physical Layer

- Establishment and termination of a connection to a communications medium
- Participation in the process whereby the communication resources are effectively shared among multiple users
  - Contention resolution and flow control
- Modulation, or conversion between the representation of digital data in user equipment and the corresponding signals transmitted over a communications channel
  - Particularly signals operating over the physical cabling (such as copper and optical fiber) or over a radio link
Overview of 4G systems

- **LTE/3GPP, LTE-Advanced**
  - December 2009 TeliaSonera opens first available LTE service in Stockholm and Oslo
  - AT&T U.S. announces its rollout of LTE service for 2011

- **WiMax/IEEE 802.16**
  - “WiMax Mobile” modestly deployed worldwide
  - Harmonization with Europe and South Korea standards
  - Release 2 in 2011

- **UMB/3GPP2**
  - Qualcomm now favoring LTE
Overview of 4G PHY technology

• High data-rates for peak rate users
  – ~100 Mbps (Mega-bits-per-second) downlink
  – ~50 Mbps simultaneous uplink
  – How?

• Orthogonal Frequency Division Multiplexing (OFDM): de facto channelization technique

• Adaptive rate and power control techniques
  – Use of feedback to address time-varying radio propagation and interference environments

• Quadrature Amplitude Modulation (QAM): spectrally efficient digital modulation techniques—more bits per symbol
Overview of 4G PHY (continued)

- High-end Error Correcting Codes (ECCs) can efficiently correct errors introduced by the physical (radio) channel
  - We can “approach the capacity”
- Multi-antenna techniques: MIMO, beamforming
  - Increase the Signal-to-Noise Ratio (SNR) and/or number of parallel channels
- Cooperative communications
  - Multi-base station (macro-diversity)
  - Femto cells/Pico cells
  - Relays, cooperative terminals
Selected PHY topics

- **Hybrid-ARQ**
  - ACK/NACK feedback
  - Incremental redundancy, receiver combing
  - Rate-compatible codes

- **Cooperative relay coding**
  - Three terminal channels
  - More capacity (bits per second per Hz)
  - Optimize power emission behavior of network
Overview of H-ARQ

• Main idea: Minimize the energy per bit using re-transmissions
  – Mitigate uncertainty regarding the channel fading state using ACK/NACK style feedback

• ARQ (Automatic repeat request)
  – Error-control using ACKs

• Hybrid-ARQ (Type-II)
  – Re-transmissions contain incremental redundancy (more coded bits)
  – *Rate-compatible codes*: re-transmissions are segments of a larger code word
Overview of relays/cooperative communications

• Multi-terminal communication channel with sender, receiver, and cooperative terminals
• Cooperative communication protocols achieve rates beyond the non-cooperative (point-to-point) channel
• Rich history in the research literature and in practice
• Modern coding techniques approach the capacity of relay channels
  – Various levels of complexity/performance
  – Application of rate-compatible codes
Cooperative relay codes

- Relay protocols applicable to 4G systems and beyond
- Cooperative coding strategies are known to approach the capacity
  - Joint source and relay code book design (aka cooperative coding/ cooperative diversity)
- Specialization to the half-duplex case
  - Relay does not simultaneously receive and transmit in the same frequency band (TDD/FDD diplexing)
  - Avoids tx/rx “self-interference” problems
- Complexity considerations
  - Encoder/decoder complexity
  - Complexity of optimization/construction
  - Protocol/MAC complexity
- We discuss a practical cooperative coding strategy termed the TDMA relay code
  - Significant gains are demonstrated with the practical code
Half-duplex relay model

- Time-sharing parameter, $\alpha$, between broadcast (BC) and multiple-access (MA) modes
- Power-sharing parameter, $\beta$, between BC and MA modes:
  - $P_{BC} = \beta P$
  - $P_{MA} = (1-\beta)P$
  - for total system power, $P$
Strategy 1: Decode-and-forward

- Relay decodes the source message and sends additional coded bits
  - Reliable source-relay link
- Baseline approach: independent (non-cooperative) coding on each link (multi-hop)
- Cooperative decode-and-forward
  - Relay encoder is cooperative with the source encoder
  - Distributed beamforming, dirty-paper coding, rate-compatible coding
Other strategies

*Compress-and-forward*
- Relay sends quantized version of the received symbol
- Reliable relay-destination link
- Gaussian quantization of relay received symbol
- Wyner quantization with decoder side-info

*Amplify-and-forward*
- Relay sends scaled version of received symbol
- Does not require a reliable s.-r. or r.-d. link
Decode-and-forward ach. rate (detail)

- Source message is delivered via $W_r = [W_{r1}, X_R]$ (relay codeword) and $W_d = [W_{d1}, W_{d2}]$ (direct codeword)
  - Overall rate $R_{DF} = R_r + R_d$
- In BC mode source sends both $W_{d1}$ (for dest.) and $W_{r1}$ (for relay)
- Relay decodes $W_{r1}$ treating received $W_{d1}$ as noise and encodes cooperative code symbol $X_R$ for MA mode tx
- In MA mode, source sends both $W_{d2}$ and relay symbol $X_R$
  - Relay symbol $X_R$ from source and relay arrive phase coherent at receiver
- Receiver decodes $W_r$ assuming received $W_d$ is noise
- $W_d$ is decoded after subtracting contribution due to $W_r$
Compress-and-forward ach. rate (detail)

Source message is delivered via $W_r$ and $W_d$
- Overall rate $R_{CF} = R_r + R_d$

Relay sends quantized version of BC mode received symbol $Y_R$ to destination as $X_R$

Source sends $W_d$ directly in MA mode

Receiver decodes $X_R$ assuming received $W_d$ is noise

Receiver estimates relay received symbol from $X_R$ and combines with direct (BC mode) received symbol to decode message $W_r$

Message $W_d$ is decoded after subtracting contribution due to relay symbol
TDMA relay code design (proposed)

- Source is silent during MA mode
  - Time-division multiple access orthogonalization of source and relay signals
  - Receiver sees mixed SNR AWGN channel
- Application of rate-compatible codes
  - Consistent with ready-made rate-compatible codes
  - Optimized irregular codes are shown to approach the capacity
- Practical cooperative coding strategy
  - No requirement of phase-synchronous reception of source and relay symbols
  - No need for successive interference decoding
Channel model

- Relay position is modeled as co-linear with source and destination
- Path loss model:
  - Channel gain attenuates as $d^{-p}$
  - with path loss exponent $p$, $2 < p < 4$
- Our numerical evaluations assume $d=1/2$ and $p=3
Capacity numerical example
Observations

• The decode-and-forward achievable rate is shown to approach the max-flow min-cut capacity upper bound for the distance-half geometry
  – Phase coherent reception of the source and relay symbols
  – Successive interference decoding at receiver
• Decode-and-forward achievable rate dominates the alternative strategies
• Reduced-complexity code (TDMA relay code)
  – Source does not transmit MA mode symbol
  – Rate-compatible code structure
  – Minimal loss to best code
Conclusions

- 4G systems utilize a laundry list of impressive PHY technologies to provide next gen levels of performance
  - Question: is then wireless solved? What of 5G and beyond?
- A close look at a cooperative coding for relays
  - Cooperative codes are an active research subject
  - First cooperative relay to be included in a cellular standard
- Future study on relays/cooperative comm
  - De-centralized networks/sensor networks/large networks
  - Application of rate less codes in the context of cooperation?
  - Distributed interference planning/scheduling
- References
  - N. Jacobsen, *Practical cooperative coding for half-duplex relay channels*, CISS March 2009
  - N. Jacobsen and R. Soni, *Design of rate-compatible irregular LDPC codes based on edge growth and parity splitting*, VTC Fall 2007
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