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)

OSI Model			
	Data unit	**Layer**	**Function**
Host layers	Data	7. Application	Network process to application
		6. Presentation	Data representation, encryption and decryption
		5. Session	Interhost communication
	Segments	4. Transport	End-to-end connections and reliability, Flow control
Media layers	Packet	3. Network	Path determination and logical addressing
	Frame	2. Data Link	Physical addressing
	Bit	1. Physical	Media, signal and binary transmission

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

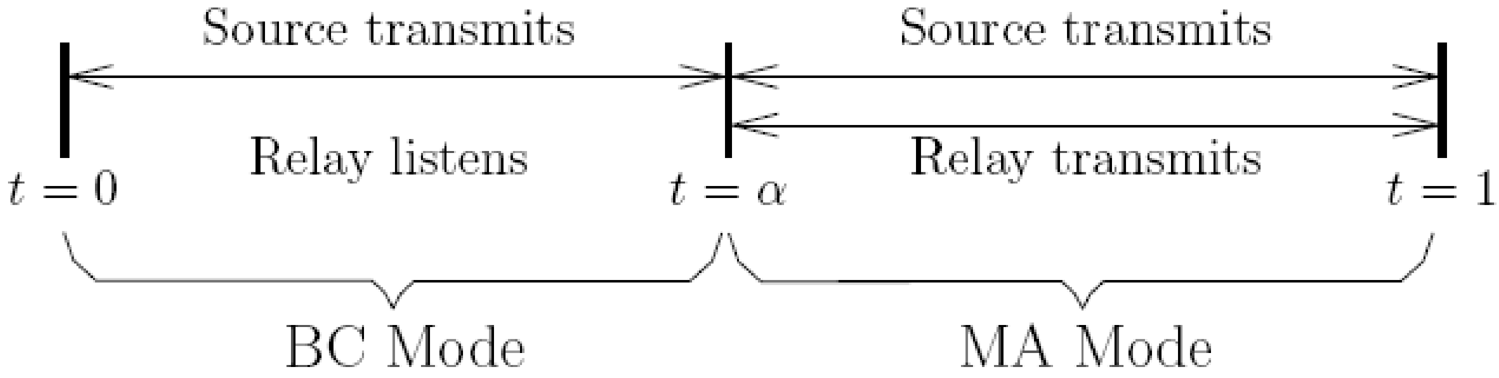
Overview of relays/cooperative communications

- 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, α ,between broadcast (BC) and multiple-access (MA) modes
- Power-sharing parameter, β, 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

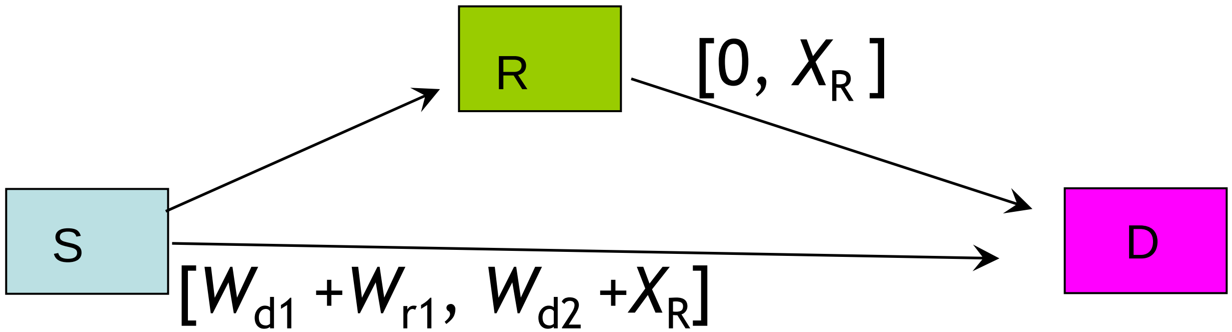
Compress-and-forward

- 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

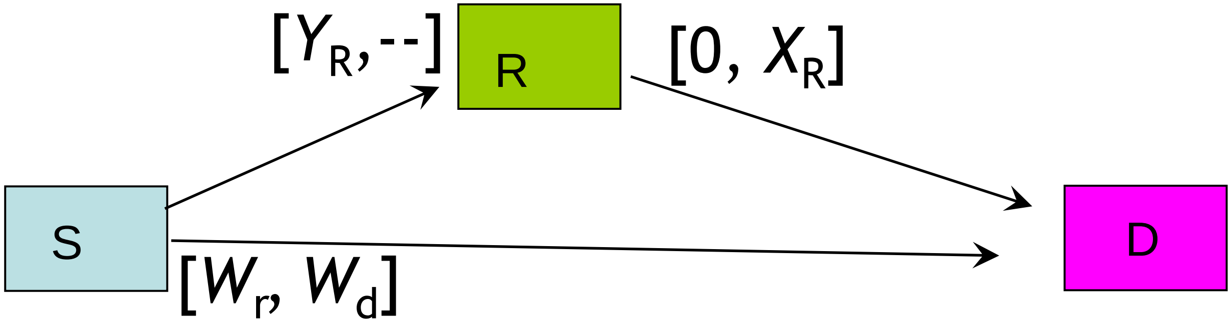
- Relay sends scaled version of received symbol
- Does not require a reliable s.-r. or r.-d. link

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)

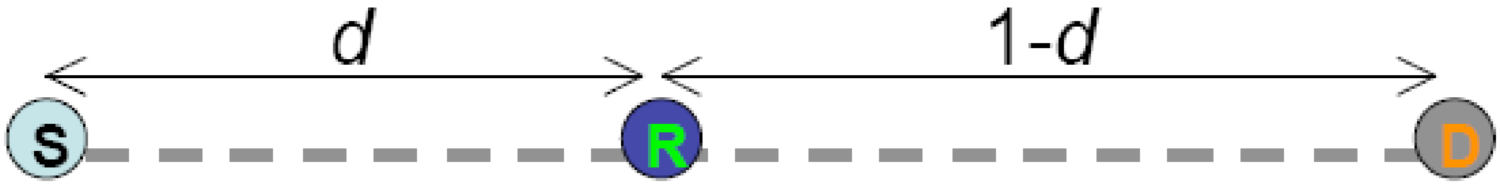


- Source message is delivered via W_r and W_d
  - Overall rate $R_{CF} = R_r + R_d$
- Relay sends quantized version of BC mode received symbol Y_R to destination as X_R
- Source sends W_d directly in MA mode
- Receiver decodes X_R assuming received W_d is noise
- Receiver estimates relay received symbol 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)

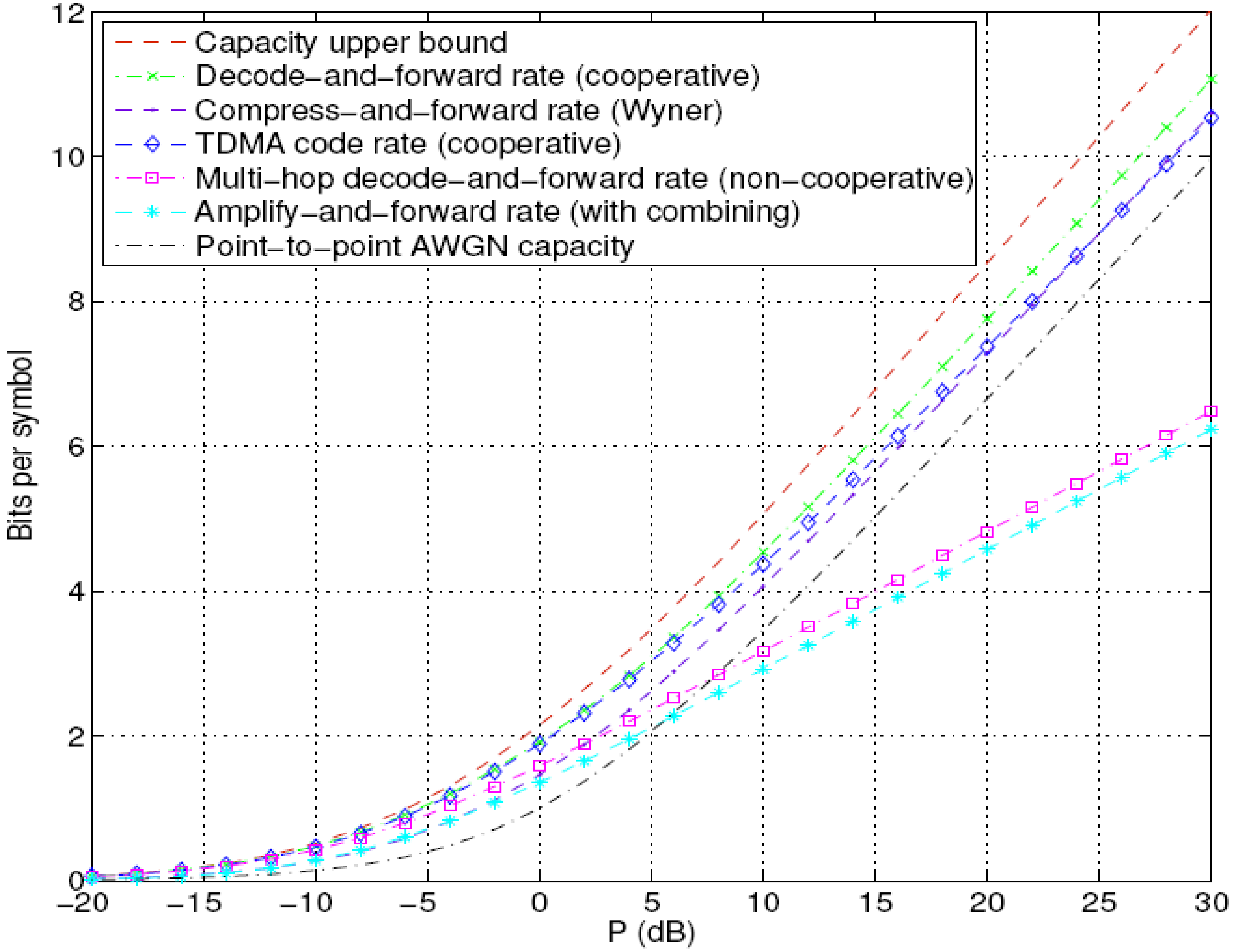
- Source is silent during MA mode
  - Time-division multiple access orthogonalization of source and relay signals
  - Receiver sees mixed SNR AWGN channel
- Application of rate-compatible codes
  - Consistent with ready-made rate-compatible codes
  - Optimized irregular codes are shown to approach the 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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