Stagnation in Physical Layer Research
– an Industry Perspective

NAE-NATF Event, 23.11.2013, Chantilly, France
Wireless Broadband Session

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One reason why I am here today...

Is the PHY Layer Dead?

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Abstract

This paper originates from a panel with the above title, held at IEEE VTC Spring 2009, in which the authors took part. The enthusiastic response it received prompted us to discuss for a wider audience whether research at the physical layer (PHY) is still relevant to the field of wireless communications. Using cellular systems as the axis of our exposition, we exemplify areas where PHY research has indeed hit a performance wall...

...
WHAT is the Physical Layer?

internet

"gateway"

medium access (MAC)

bit transmission (PHY)

Operating system

WLAN/UWB network card

medium access (MAC)

bit transmission (PHY)

channel

Access point (WLAN/UWB Base station)

transport (TCP)

network (IP)

driver

Application (webbrowser)
The Physical Layer: How it works

Source

- source coding
- bits
- channel coding
- modulation
  - symbols

channel coding

additive white Gaussian Noise (AWGN)

Sink

- source decoding
- channel decoding
- demodulation
  - Y

I(X;Y)
Physical Layer: The Spectral Resources

- **Wired cable**: available ca. 1GHz bandwidth, i.e., can carry Mb/s..Gb/s
- **Wireless**
  - Wireless access, ca. 1GHz bandwidth, Mb/s..Gb/s
  - Point-to-point: several GHz bandwidth
- **Optical**: 200THz bandwidth
Wireless Network Structure

1. Wireless Access (Mb/s)

2. Backhaul (Gb/s)

3. Optical core network (Tb/s)

- Physical layers involved in wireless broadband
- Cellular concept: spatially reuse spectrum
Outline

- Wireless Perspective
- Optical Perspective
- Summary
The Theoretical Frontier... How to get there?

high rate

$E_b/N_0$ in dB

spectral efficiency bits/Hz per symbol
L-value for QAM and various bit-labelings

L-value of bit 1, $L_A(x_k) = 0$, $P_{\text{apriori}}[x_k=-1] = 0.5$

http://www.inue.uni-stuttgart.de/lehre/demo.html
...to SOFT Detection.

L-value for QAM and various bit-labelings

L-value of bit 1, \( L_A(x_k) = 0 \), \( P_{apriori}[x_k = -1] = 0.5 \)

\[
\begin{array}{cccc}
1100 & 1000 & 0100 & 0000 \\
1011 & 0111 & 1111 & 1010 \\
1001 & 0110 & 0011 & 1110 \\
0001 & 1101 & 0010 & 0101 \\
\end{array}
\]

\( E_s/N_0 \) [dB]

\begin{align*}
0 & \quad P_{apriori}[x_k = +1] \\
0.5 & \\
\end{align*}

- **Number of Bits/Symbol**: 4
- **Labeling Options**:
  - Gray-labeling
  - anti Gray
  - natural
  - random
  - keep current random label

\( \text{range L-value colormap} \)

Plot L-value for bit: 1

**Update**

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Source code
From ONE-SHOT to ITERATIVE/JOINT processing

Source $X_2$ → outer encoder → $Y_2$ → inner encoder → inner decoder → $A_1$ → demodulator → $E_1$ → inner decoder → $A_2$ → outer decoder → $E_2$ → sink

$X$ → AWGN → $Y$ → $I(X;Y)$

- **inner encoder**
- **inner decoder**
- **outer encoder**
- **outer decoder**
- **source**
- **sink**
- **modulator**
- **demodulator**

**Soft, Iterative**

- **a priori knowledge**
- **extrinsic (new) knowledge**
Soft, iterative Processing: We did it!
The next frontier...

- Advances in theory and implementation
  - Posed hardware challenge over the past decade
  - But today: solved
  - Single link (point-to-point) Shannon limit pretty much achieved

- What was NEXT?
  - Multi-antenna processing
  - Investment in detection algorithms
  - up to 8 antennas in widespread use (since about 2005)
Pushing the frontier through multiple antennas

\[ C_{AWGN} \]

Increase vs. of antennas

Spectral efficiency bit/s/Hz per symbol vs. \( E_b/N_0 \) in dB
The new frontier: Scaling it up... and precoding

• What about using hundreds of antennas?
  - to further increase data rate per cubic meter
  - interference mitigation through precoding

• First prototypes built, channel measurements done

• Challenges
  - Channel modelling
  - Exploit channel reciprocity to avoid training
  - Transmit/receiver calibration
  - wiring, connectivity... how to integrate with facade

Large antenna arrays

• Scalable prototype at Bell Labs (Oct. 2013), design target 1024 antennas
Conventional Deployment

- Few base station antennas
- Concept of cells, sectors, for frequency reuse, interference mitigation
• Distributed, massive number of antennas
• Interference mitigation through matrix precoding at basestation
• Increase data rate per cubic meter by factor 20..50
Requires new basestation architecture (1/3)

- Initial base station deployment (GSM, 1990s):
  - long RF cables
  - Several dBs in power loss
Requires new basestation architecture (2/3)

- Introduction of Remote Radio Heads, 2000s
  - short RF cables
  - Digital interface
Requires new basestation architecture (3/3)

- “Silicon Antenna”: add highly integrated chip to antenna
  - Very short RF cables; amplifiers right at antenna
  - Novel distributed algorithms
- Investment in Mixed-Signal ASICs: high volume, low-cost
Outline

- System Overview and Wireless Perspective
- Optical Perspective
- Summary
Spectral Overview

- Wireless, GHz
- Optical: 200THz, vast bandwidth resources
  - backhaul/core network must not become the bottleneck
- What are the limits?
Innovations over the past decade
Chromatic Dispersion

6GBaud-Signal after 50km

- fiber length in km: 50
- symbol rate in Gbd: 6
- $D_C$ in ps/km/nm: 17
- rectangular
- raised cosine $\alpha = 0.5$
- raised cosine $\alpha = 1$

http://www.inue.uni-stuttgart.de/lehre/demo.html
100GBaud-Signal after 50km

- Fiber length in km: 50
- Symbol rate in GBd: 100
- $D_C$ in ps/km/nm: 17
- Rectangular
- Raised cosine $\alpha = 0.5$
- Raised cosine $\alpha = 1$

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Source code
State of the Art

• Prior to coherent detection in optics
  - Dispersion compensation in „analog“ (special compensating fiber)

• With advent of coherent detection (around 2005...)
  - Digital compensation
  - Other linear/non-linear impairments can be mitigated

• Heavy investment in silicon chips (ASICs)!

• Also, special error detecting/correcting codes needed
  - Very low bit error rates in optical: $10^{-15}$  (wireless access: $10^{-4}$)
  - New kid on the block: „Spatially coupled codes“

• Optics... a communication engineer‘s dream

Physical layer can be proprietary, no standardization needed!
Peak Power Limited; Next Frontier: Space?

From 2 to 100s of Spatial Modes

**Single-mode fibers**
- One spatial mode but support two modes (two polarization states)
- Used for distances > 1km

**Multimode fibers**
- Can support a few or many spatial modes
- For short reach (~ 100 meters)

**Multicore fibers**
- Can exhibit coupling or not between cores
- Coupled-core fibers support “supermodes”
Summary and Outlook

• Wireless access
  - Point-to-point links: theoretical limits achieved ✓
  - Cellular infrastructure goes „massive, and consumer electronics“

• Optical backhaul/core
  - Coherent detection state of the art, 400Gb/s per 100GHz bandwidth ✓
  - Room for further improvements: signal processing (ASICs) and coding ✓
  - Next frontier: Multicore fibers and associated algorithms, technology