A New Communication Paradigm: Virtual Antennas for Distributed Broadband Communications via Cooperative Relaying

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Background

Envision of 4G
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- Very high speed → Gigabits
  3G: 2Mbps; 3.5G: 14.4Mbps
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### Envision of 4G

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- **Flat All-IP architecture**
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- Flat All-IP architecture

Fundamental challenge: signals transmitted over wireless attenuated in various forms
Signal attenuation

- Path loss
- Long term fading
- Short term fading
Signal attenuation

- Path loss
- Long term fading
- Short term fading

Pathloss and long term fading may be mitigated by power control
Signal attenuation

- Path loss
- Long term fading
- Short term fading

Short term fading can be mitigated by diversity techniques
Diversity

- Methods of combating the effects of fading by effectively receiving independent fading copies of the signal
Diversity

- Methods of combating the effects of fading by effectively receiving independent fading copies of the signal
- Spatial, temporal, and frequency
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Spatial Diversity

- Transmit diversity (MISO)
- Receive diversity (SIMO)
- Transmit and receive diversity (MIMO)
In spatial diversity techniques
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- E.g., wavelength = 0.33 m for 900 MHz signal
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- E.g., wavelength $= 0.33$ m for $900$ MHz signal
- Not feasible for mobile (handheld) devices
Virtual Antenna Array
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Forming a *Virtual* antenna array (VAA) by distributing antennas in the network [*Dohler’02*].
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A good alternative to MIMO without the need of collocated antennas
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A good alternative to MIMO without the need of collocated antennas

Another advantage is power saving; wireless signals attenuate exponentially fast as the distance increases
Two approaches to implement VAA
Implementation of VAA

Two approaches to implement VAA

- Connecting the VAA through coaxial cables or fibers
Implementation of VAA

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- Connecting the VAA through coaxial cables or fibers
- Connecting the VAA wirelessly
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The second approach, known as cooperative relaying, seems more interesting and will be the focus of this talk.
Diversity Gain

Using cooperative relays is expected to increase the diversity gain: a metric to evaluate the increase in the error rate slope as a function of SNR.
Cooperative Relaying Communication Concept

Phase I: Broadcast
Cooperative Relaying Communication Concept

Phase I: Broadcast

Phase 2: Cooperation
Cooperative Relaying Communication Concept

Phase I: Broadcast
Phase 2: Cooperation

Figure from: J. N. Laneman et al. ’03
Consider the following dual-hop communication system with one relay.
Relaying Methods

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Based on signal processing at relays
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Based on signal processing at relays
- Analog Relaying: Amplify-and-Forward
Consider the following dual-hop communication system with one relay

\[ y_R(t) = a_1 s(t) + n_1(t) \]
\[ y_D(t) = a_2 G y_R(t) + n_2(t) \]
\[ = a_2 G (a_1 s(t) + n_1(t)) + n_2(t) \]

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- Digital Relaying: Decode-and-Forward
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- Digital Relaying: Decode-and-Forward
Amplify-and-Forward

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  Resulting equivalent end-to-end SNR: $\gamma_{eq} = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2}$
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Comparison of Two Relay Gains

Comparison of the Two Choices of Relay Gain Using Monte Carlo Simulation

Outage Probability $P_{out}$ vs. Normalized SNR [dB]

- Relay Gain (Laneman)
- Relay Gain (Channel Inversion)
Diversity Gain due to A-F Collaboration

Effect of Collaborative Diversity on Average BER Performance

Average Bit Error Rate vs. Average SNR per bit for different values of $L$. The graph shows a clear trend of decreasing BER with increasing SNR, highlighting the effectiveness of collaborative diversity in improving the reliability of data transmission.
Decode-and-Forward

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- **Choice 2:** Set a *detection threshold*: optimal threshold is not obvious.
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Comparing to analog relaying, digital relaying is easy to implement and benefits from coding gain.
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Currently under discussion in 3GPP LTE-Advanced.
Extension to multiple relays

The above discussion focused on single-relay case, where the relay is fixed and dedicated for help.
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Consider the following dual-hop communication system with $n$ relay $\Rightarrow$ MISO channel.
Protocols to Cooperate

Broadcast (Phase 1)  Cooperation (Phase 2)

Source  $t_1$  $t_2$  $\cdots$  $t_p$

Relay 1  $T_1$

Relay 2  $T_2$

$\vdots$

Relay $n$  $t_q$

Broadcast (Phase 1)  Cooperation (Phase 2)

Source  $t_1$  $t_2$  $\cdots$  $t_p$

Relay 1  $T_1$  $T_2$  $\cdots$  $t_q$

Relay 2  $T_1$  $T_2$  $\cdots$  $t_q$

$\vdots$

Relay $n$  $T_1$  $T_2$  $\cdots$  $t_q$
The cooperative protocols can be designed to explore different degree of freedoms, e.g., *time, frequency, and code*
Multiplexing Gain

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For such a capacity, the data rate approaches to a constant for high SNR:

$$\lim_{\text{SNR} \to \infty} \frac{R(\text{SNR})}{\log(\text{SNR})} = r$$
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The multiplexing gain \( r \) is the rate increase over the single antenna AWGN channel capacity.
Recall that cooperative relaying increases diversity gain $d$, defined as

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Given $n$ transmission paths available, we can either maximize the transmission rate by sending independent information or maximize the reliability by sending identical information over all paths ⇒ Diversity-Multiplexing Tradeoff (DMF)
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The MR system can be modeled as a MISO channel with the DM gain bounded by

$$d(r) \leq (n + 1)(1 - r)$$
DMT for $n = 2$
Issues in MR case

- **Who** is Mr. helper? (relay selection)
  - SNR: avg., instant., harmonic mean [Bletsas’05]
  - Location-dependent [Zorzi’03]
  - Decision: destination, relay [Onat’08]
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  - Shadowing: burst errors occur
  - Save energy: sensor networks
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- **How** Mr. helper can help?
  - Power allocation to maximize received SNR [Li’07]
  - Receiver design for async. coop. [Wei’06]
Relaying Strategy

If relays always help (fixed relaying), the performance is poor in DF
Relaying Strategy

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Example: Single relay with very strong S-R channel but very weak R-D channel (Similar result can be expected for a week S-R channel)
Strategy I: only relays receiving correctly forward [Laneman’03]
Selection relaying

Strategy I: only relays receiving correctly forward \[\text{[Laneman’03]}\]

- Reduce to conventional MIMO with \(|D|\) transmit antennas, where \(D\) is the decoding set
Strategy I: only relays receiving correctly forward \cite{Laneman03}

- Reduce to conventional MIMO with $|\mathcal{D}|$ transmit antennas, where $\mathcal{D}$ is the decoding set

- Need relays to perform error detection even they cannot forward
Selection relaying

Strategy I: only relays receiving correctly forward \([\text{Laneman’03}]\)

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Strategy II: Check branch quality by comparing it with a threshold
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- Need relays to perform error detection even they cannot forward

**Strategy II:** Check branch quality by comparing it with a threshold
- Similar to “selection combining” in MIMO
- Fixed threshold is simple but not optimal; need to adaptively determine the threshold
Given a decoding set $\mathcal{D}$, use $|\mathcal{D}|$ orthogonal channels for diversity combining
Selection Strategy I

Given a decoding set $\mathcal{D}$, use $|\mathcal{D}|$ orthogonal channels for diversity combining $\Rightarrow$ Need special channel codes to avoid multiplexing loss
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- Select $R^* = \arg \max_{r \in \mathcal{D}} \min\{|a_{s,r}|^2, |a_{r,d}|^2\}$
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DMT Comparison

- Ideal
- Opportunistic Relaying
- Space-time coding
- Repetition coding
- Non-cooperative
Delay in OR

![Graph showing average delay (ms) vs. ASNR (dB) for different numbers of relays (One relay, Two relays, Three relays, Four relays, Five relays).]
Delay in OR

![Graph showing delay variance (ms) vs. ASNR (dB) for one relay, two relays, three relays, four relays, and five relays.](image-url)
Selection Strategy II

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- Selection that minimizes e2e BER: clear benefit from exploring $\gamma_{sd}$, but marginal from $\gamma_{rd}$ [Onat’08].
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- Selection that minimizes e2e BER: clear benefit from exploring $\gamma_{sd}$, but marginal from $\gamma_{rd}$ [Onat’08]
- Above results do not consider diversity combining: conventional MRC combiner fails to obtain full diversity in multi-relay case
Further Reading

A. Nosratinia et al.
*Cooperative Communication in Wireless Networks.*

F. A. Onat et al.
*Threshold Selection for SNR-based Selective Digital Relaying in Cooperative Wireless Networks.*

S. W. Peters et al.
*The Future of WiMAX: Multihop Relaying with IEEE 802.16j.*
The END. Thank you!

Questions?