Adaptive massive MIMO for fast moving connected vehicles: *It will work with Predictor Antennas!*

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III. Performance Evaluation Methodology
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I. Motivation
The Problem of Channel Aging

The increased spectral efficiency of massive MIMO can reduce the cost of wireless access. The massive MIMO performance crucially relies on Channel State Information at transmitter (CSIT) side.
The Problem of Channel Aging

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The massive MIMO performance crucially relies on Channel State Information at transmitter (CSIT) side.

Here: Focus on the effect of **channel aging**, typically due to

- Mobility of the user (car), yielding a spatial displacement $\delta$
- Delay $\tau$ at the network side (e.g. CSI feedback delay in FDD, low channel training rates in TDD, processing delays at the base station)
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Channel Training in UL at time $t_0$
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Channel Training in UL at time $t_0$ Data Transmission in DL at time $t_0 + \tau$
The Impact of Channel Aging – A Quantitative Example

System-level Simulations

- 3GPP 38.901 Urban Micro TDD scenario,
- 57 cells, 200m ISD, on average 20 users per cell,
- 64 TXRUs, 41dBm Tx Pwr @10MHz BW, $f_c$=3.5GHz,
- Full-buffer users (best effort traffic) with x-pol. antennas (2 layers/user),
- SRS-based channel estimation in UL,
- Regularized zero-forcing (RZF) in DL for \{16,32\} layers,
- Perfect link adaptation (Shannon rates)

Significant performance losses (>43% @ 60kmph) due to channel aging
→ Channel prediction methods will help to maintain the massive MIMO gains at higher user speeds
→ Overhead due to frequent sounding can be easily compensated by higher cell spectral efficiency
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Potential Solution: Predictor Antennas

Illustration: Maximum Ratio Transmission (MRT) under heavy multi-path propagation
Potential Solution: Predictor Antennas

Without Prediction

With Prediction

Illustration: Maximum Ratio Transmission (MRT) under heavy multi-path propagation
Potential Solution: Predictor Antennas

Illustration: Maximum Ratio Transmission (MRT) under heavy multi-path propagation

Maximum speed supported by predictor antenna with

- Antenna distance $d \geq 0.5\lambda$
- Delay $\tau$ between measurement and BF

$$v \leq \frac{d}{\tau}$$

For $d = 3\lambda$, $\tau = 5\text{msec}$: $$v = \frac{d}{\tau} = \frac{0.42}{0.005} = 302 \text{ km/h}$$

For $d = 3\lambda$, $\tau = 3\text{msec}$: $$v = \frac{d}{\tau} = \frac{0.42}{0.003} = 503 \text{ km/h}$$

Requirements:

- Periodicity of UL channel sounding must be small enough to track the channel variations
- Antennas in line and with quasi-equal patterns
Previous Work*: Experimental Verification for SISO Links

Setup in Dresden

- 25-50 km/h user speed,
- OFDM (LTE numerology) at 2.53 GHz,
- Measuring SISO links in sub-urban area,
- Antenna distances $d=\{\lambda/4, \lambda/2, \lambda, 2\lambda, 3\lambda\}$

Result:
The Predictor Antenna is 10x more accurate than conventional prediction techniques.

Remaining question: How does it combine with massive MIMO beamforming?

*) SISO measurement results in [1][2].

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II. Measurement Setup
Measurement Setup

Network Side Setup:

- 64-element antenna array on rooftop of building at a height of 20m
  - Mechanical downtilt of 10 degree,
  - 4 rows with 16 (dual-polarized, but only one polarization direction was used) patch antennas,
  - Horizontal antenna spacing of \( \lambda/2 \), and a vertical separation of \( \lambda \),
  - 2.180 GHz carrier frequency.
Measurement Setup

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  - 2.180 GHz carrier frequency.

- Pilot signals in downlink
  - Time/frequency-orthogonal pilots (using LTE numerology) for all 64 antenna elements,
  - Pilot burst sent with a periodicity of 0.5msec,
  - For each antenna, 10MHz pilot comb with 180kHz spacing (i.e., 50 subbands over 10MHz).
Measurement Setup

Car Side Setup:

- Frequency synchronization of receiver via Pendulum GPS-12R Portable unit,
- R&S TSMW receiver + R&S IQR hard disk recorder,
- Two receive monopole antennas with distances $d = \{11, 15, 42\} \text{cm}$ mounted on metallic plate, installed upon the roof of the car.
Measurement Setup

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Measurement Procedure:
- Two non-line-of-sight routes have been chosen, without any traffic,
- Received pilot signal (at both monopole antennas) is continuously captured along each route over periods of 30s to 40s, with car speeds $v = \{15, 25\}$ kmph
- Channel estimation (per Tx antenna, subband and pilot burst) is performed offline (achieving NMSEs in the range of -20dB to -30dB without any time/freq.dom. averaging).
III. Performance Evaluation
Methodology
Analyzed Prediction Methods

Measured channel samples at time $n \in [1, N]$, and for frequency index $m \in [1, M]$. 

Car trajectory

Target Antenna

Predictor Antenna

$z_{n,k,m}$

Antenna Element $k \in [1, K]$
Analyzed Prediction Methods

Measured channel samples at time $n \in [1, N]$, and for frequency index $m \in [1, M]$

True Channel:
$$h_{n,k,m} = z_{n,k,m}$$
Analyzed Prediction Methods

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Predicted Channel from Predictor Antenna:
\[
h_{n,k,m}^{\text{pred}} = c_{g,k,m} z_{n-g,k,m}^{\prime}
\]
with predictor delay \( g = \text{Median}_{k,m} \left( \arg \max_l |c_{l,k,m}| \right) \)
and
\[
c_{l,k,m} = \frac{\sum_{n=N_0}^{N_0+N_1} z_{n,k,m} (z_{n-l,k,m}^{\prime})^*}{\sqrt{\sum_{n=N_0}^{N_0+N_1} |z_{n,k,m}|^2 \sum_{n=N_0}^{N_0+N_1} |z_{n,k,m}^{\prime}|^2}}
\]
(for \( N_1 = 1000 \))
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Measured channel samples at time \( n \in [1, N] \), and for frequency index \( m \in [1, M] \)

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and
\[ c_{l,k,m} = \frac{\sum_{n=0}^{N_1} z_{n,k,m} (z_{n-l,k,m}^{'})^*}{\sqrt{\sum_{n=0}^{N_1} |z_{n,k,m}|^2 \sum_{n=0}^{N_1} |z_{n-l,k,m}|^2}} \] (for \( N_1 = 1000 \))

Subsequently, we assume \( \tau = g \) (i.e., predictor antenna distance is matched to car speed, \( d = \delta \))
Received Power Loss for Maximum Ratio Transmission Beamforming

For timestep $n$, the received power at the data antenna (averaged over all subbands) is

$$r_{\text{ideal}}(n) = \frac{1}{M\alpha_n} \sum_{m=1}^{M} \left| \sum_{k=1}^{K} h_{n,k,m} \right|^2$$

with

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$$r_{\text{pred}}(n) = \frac{1}{M\alpha_n^{\text{pred}}} \left( \sum_{m=1}^{M} \left| \sum_{k=1}^{K} h_{n,k,m} (h_{n,k,m}^{\text{pred}})^* \right|^2 \right)^2$$

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**Power loss** w.r.t. ideal prediction: $r_{\text{norm}}(n) = \frac{r_{\text{pred}}(n)}{r_{\text{ideal}}(n)}$
Achievable Signal-to-Interference Ratio (SIR) for Zero-Forcing

Zero-forcing for two users with MIMO channel matrix (at time $n$, subband $m$) $\mathbf{H}^{(n,m)} \in \mathbb{C}^{2 \times K}$, where

- Predicted channel $h_{n,k,m}^{\text{pred}}$ is used for the first user,
- Circularly-shifted (in freq.dom) channel $h_{n,k,[(m+23)\text{mod } M]+1}^{\text{pred}}$ is used for a second “imaginary user”.
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Zero-Forcing precoder:

$$ \mathbf{P}^{(n,m)} = (\mathbf{H}^{(n,m,\text{pred})})^\dagger \left( \mathbf{H}^{(n,m,\text{pred})} (\mathbf{H}^{(n,m,\text{pred})})^\dagger \right)^{-1} \in \mathbb{C}^{K \times 2} $$

Effective (beamformed) channel matrix:

$$ \mathbf{G}^{(n,m)} = \mathbf{H}^{(n,m)} \mathbf{P}^{(n,m)} \in \mathbb{C}^{2 \times 2} $$

(Average) user SIR for time $n$, subband $m$:

$$ \text{SIR}(n, m) = \frac{1}{2} \left( \frac{|g_{1,1}^{(n,m)}|^2}{|g_{1,2}^{(n,m)}|^2} + \frac{|g_{2,2}^{(n,m)}|^2}{|g_{2,1}^{(n,m)}|^2} \right) $$
IV. Results
Illustration for Maximum Ratio Transmission Beamforming
**Received Power Loss for Maximum Ratio Transmission**

<table>
<thead>
<tr>
<th>N°</th>
<th>Direction on Route 2</th>
<th>V (km/h)</th>
<th>d (cm)</th>
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<tr>
<td>1</td>
<td>W-E</td>
<td>15</td>
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11 cm ~0.8\(\lambda\) and 42 cm ~3\(\lambda\)

**CDF of** \(r_{\text{norm}}(n)\) **for four drive-tests**

- #1 Predictor antenna
- #2 Predictor antenna
- #3 Predictor antenna
- #4 Predictor antenna
- #1 Outdated channel
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- #4 Outdated channel
Received Power Loss for Maximum Ratio Transmission

Drive-Tests

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11 cm ~0.8λ and 42 cm ~3λ

CDF of \( r_{\text{norm}}(n) \) for four drive-tests

Predictor antenna reduces the received power losses to less than 1dB!
Prediction horizons of 3λ (and possibly larger) are feasible!
SIR Gain from Predictor Antenna for Two-User Zero-Forcing

Drive-Tests

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CDF of SIR\((n, m)\) for four drive-tests

![CDF of SIR\((n, m)\) for four drive-tests](image-url)
SIR Gain from Predictor Antenna for Two-User Zero-Forcing

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11 cm \(\sim 0.8\lambda\) and 42 cm \(\sim 3\lambda\)

CDF of SIR\((n, m)\) for four drive-tests

Predictor antenna improves the SIR from typically around 5-15 dB to mostly between 20-30 dB.
Robustness of Our Simple Prediction Method

Predicted Channel from **Perturbated/Inaccurate** Predictor Antenna: 

$$h_{n,k,m}^{\text{pred}} = z'_{n-g,k,m}$$

with predictor delay 

$$g = \text{Median}_{k,m} \left( \arg \max_{l} \left| c_{l,k,m} \right| \right) + \epsilon$$

where $$\epsilon$$ is uniformly distributed [-5,5] (i.e., +/-2.5msec)
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Received power loss due to inaccurate prediction coefficient and delay is remarkably small!
V. Conclusions
V. Conclusions and Next Steps

First & successful experimental measurements for massive MIMO BF and Predictor Antenna:

- A prediction horizon of $3\lambda$ has been successfully tested (at 2.180 GHz).
- This enables the application of (MRT) beamforming for high velocities.
- Limited accuracy with the predictor is good enough for massive MIMO MRT.

Next steps:

1. Investigating prediction methods for the general case of $\tau \neq g$.
2. Running and evaluating a real-time prediction algorithm based on the Predictor Antenna concept, assuming a realistic time-frame structures in TDD systems (SRS periodicity).
3. Evaluate the hardware, software and system design factors that affect the performance of a predictor antenna system.

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<th>Latency $\tau$</th>
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Thank You!

Any Questions?
I. Introduction

• Do we really need to change anything?

• How many antennas do we need to put on connected cars?
I. Introduction

Not a problem for Operators today, due to low load of connected cars supportable for the network.
I. Introduction

A problem >2020 for Operators, due to high load of connected cars.

High data rate no longer supportable in a highly loaded network.
Prediction is useful whatever the ideal received BF gain.

Fig. 8. Time evolution of received ideal beamformed power by (17) (left) and the normalized received power by (10) (right), in Drive-Test 1.
Line-Of-Sight vs Non Line Of Sight

Probably LOS: high received power no huge gain due to Prediction

Fig. 9. Time evolution of received ideal beamformed power by (17) (left) and the normalized received power by (10) (right), in Drive-Test 3.
Fig. 11. The residual SIR, averaged for the two users and averaged over all subcarriers, along Drive 2, when applying zero forcing transmit beamforming using channels estimates from predictor antennas and outdated channel estimates.
Previous simulation studies on Wall of Speed for M-MIMO BF

Wall of speed for 256x1 MRT Beamforming, based on simulations

Cost in power

\[ v_{\text{wall}}(f) = \frac{C_{\text{wall}}}{f} \]

Values of \( C_{\text{wall}} \) determined by simulation in [1][2]

- Without BF
  - \( v_{\text{limit}} = 50 \text{km/h} \)
  - \( f_0 < 1.2 \text{GHz} \)
  - 2 antennas

- With BF
  - \( v_{\text{limit}} = 150 \text{ km/h} \)
  - \( f_0 < 1.2 \text{GHz} \)
  - 3 antennas


5G PPP Fantastic 5G Deliverable D2.3 (http://fantastic5g.com/wp-content/uploads/2017/08/FANTASTIC-5G_D2.3_final.pdf)