Millimeter wave adaptive transmission using spatial scattering modulation

*Yacong Ding

Kyeong Jin Kim
Toshiaki Koike-Akino
Milutin Pajovic
Philip Orlik

* ECE Dept. of Univ. of California, San Diego. His work was done while he was with MERL.
Outline

• Motivation

• Contribution
  – Spatial modulation (SM)
  – Spatial scattering modulation (SSM)
    • Transmitter/signal/receiver
    • Simulation results
  – Adaptive SSM
    • Simulation results

• Conclusions
Motivation: Uplink mmWave System

- **hardware resource**
  - antenna array and phase shifter array in user equipment (UE) and base station (BS): we can form a very narrow and directional beam from both sides
  - a limited number of RF chains in UE due to hardware cost and power consumption: **a single RF chain in UE vs. a multiple number of RF chains in BS**

- **mmWave channel**
  - narrowband mmWave channel environment
  - line-of-sight (LOS) is entirely blocked
  - Only reflections from scattering clusters exist
  - Large path loss for nLOS over LOS: **sparsity in angular domain**

- **Question:** How to increase spectral efficiency considering mmWave channel characteristics and hardware resource especially in UE?
Spatial Modulation (SM): Overview

• Transmitter:
  – Activate a single antenna encoded by information bits
  – Two inputs are used due to available four antennas
  – In the example, \([b_2 : b_1] = [1 : 0]\)
  – Other antennas are in silent for one transmission epoch

• Receiver:
  – We need to detect which antenna was used for transmission, and actually transmitted symbols

• Problem in mmWave system:
  – Due to dense packing of antenna elements in the same aperture, transmissions from different antennas are indistinguishable
  – We still need to use a narrow and directional beamforming

Spatial Scattering Modulation (SSM)

- Extension SM, which uses the DoF in spatial transmit antenna domain
  - Use DoF in angular domain (AoD)
  - Due to use of a single RF chain
    - Each transmission epoch, UE steers only to a single direction (transmit antenna array points to one of the scattering clusters)
    - At least two scattering clusters are required
    - For $N_s$ scatters, $\lfloor \log_2 (N_s) \rfloor$ bits are encoded to specify a particular AoD or scattering cluster
  - Next $\log_2 (M)$ bits are used to select a point in the signal constellation with $M$ size
    These bits are transmitted via a transmit beam determined by selected AoD
  - If the receiver can detect the scattering cluster that used by UE, then $\lfloor \log_2 (N_s) \rfloor$ bits can be detected

Spatial Scattering Modulation (SSM): transmitter

Information data source

Symbol mapping

TF chain, $\{0,1\}$ $\{1,0\}$ $\{1,1\}$

Phase shifter

PA

Phase control

[log$_2$($N_s$)] bits

Switch

AoD table

$\lfloor \log_2(N_s) \rfloor$ bits

UE

[log$_2$($M$)] bits

$\lfloor \log_2(N_s) \rfloor$ + 1

$\lfloor \log_2(N_s) \rfloor$ + log$_2$(M) + 1

$\lfloor \log_2(N_s) \rfloor$ + 2 log$_2$(M)

$\lfloor \log_2(N_s) \rfloor$ + 1

$\lfloor \log_2(N_s) \rfloor$ + log$_2$(M)

$\lfloor \log_2(N_s) \rfloor$ + 2 log$_2$(M)

$\lfloor \log_2(N_s) \rfloor$ + log$_2$(M) + 1

$\lfloor \log_2(N_s) \rfloor$ + 1

$\lfloor \log_2(N_s) \rfloor$ + log$_2$(M)
Spatial Scattering Modulation (SSM): signal

- **Transmitter:**
  - $s$: modulation symbol, $p \in \{a_t(\theta^t_1), ..., a_t(\theta^t_{\log_2(N_s)})\}$, $a_t(\theta^t_i)$: ULA array manifold vectors

- **Channel:** a narrowband discrete channel model [3,4]
  - $H = \sum_{l=1}^{N_S} \beta^l a_r(\theta^r_l) a_t(\theta^t_l)^H$
    - $\beta^l$: gain of the $l$th scattering cluster
    - $a_t(\theta^t_i) = \frac{1}{\sqrt{N_t}} [1, e^{j2\pi \phi^t_i}, ..., e^{j2\pi \phi^t_i(N_t-1)}]^T$, $\phi^t_i = \frac{d_t}{\lambda} \sin(\theta^t_i)$
    - $a_r(\theta^r_i) = \frac{1}{\sqrt{N_r}} [1, e^{j2\pi \phi^r_i}, ..., e^{j2\pi \phi^r_i(N_r-1)}]^T$, $\phi^r_i = \frac{d_r}{\lambda} \sin(\theta^r_i)$
      - $d_t, d_r$: antenna spacing, $\lambda$: wave length of the propagation, $N_t, N_r$: antenna elements
    - Assume a large number of antenna elements in the UE and BS
      - $a_r(\theta^r_i) a_r(\theta^r_k)^H = \delta(l-k)$, $a_t(\theta^t_i) a_t(\theta^t_k)^H = \delta(l-k)$

- **Received signal**
  - $y = \sqrt{E} H p s + n = \sqrt{E} \sum_{l=1}^{N_S} \beta^l a_r(\theta^r_l) a_t(\theta^t_l)^H p s + n$
    - $= \sqrt{E} \beta^l a_r(\theta^r_l) s + n$

SSM: Receiver

$$y_c = \begin{bmatrix} r_1^H y \\ r_2^H y \\ \vdots \\ r_N^H y \end{bmatrix}$$

MLD: $$\{\hat{k}, \hat{s}\} = arg \min_{s,k \in \{1, \ldots, N_s\}} | y_c(k) - \mathbf{a}_r(\theta_k^r) \mathbf{H} \mathbf{a}_t(\theta_k^t)s|^2$$
Simulation results with SSM

- Number of antenna elements in UE and BS: 32
  - Number of RF chains: one for the UE and four for the BS
- Spectral efficiency: 4-bits/Hz
  - Modulation: QPSK for SSM vs. 16QAM for maximum and random beamforming (MBF/RBF) without SSM
- Scattering clusters:
  - $N_s = 4$, with gains $\beta_l \sim CN(0, \sigma^2_\beta)$
- Receiver:
  - Maximum likelihood detector

![Diagram of MBF, RBF, and SSM configurations]
Simulation results: Spectral efficiency: 4-bits/Hz

\[
N_s = 6
\]

\[
N_s = 12
\]

- SSM: 2-bit for encoding of the direction. 2-bit for QPSK modulation
- MBF/RBF: 4-bit for 16QAM
- Since \( N_s > N \), (# of RF chains), we choose \( N \) scattering clusters having the largest \( N \) gains
- When \( N_s \) is small, MBF works better in BER, however, as \( N_s \) increases, SSM works better. For \( N_s = 12 \), 2 dB gain can be achieved by SSM
Adaptive SSM

- Under available CSI in the system
  - choose one transmission scheme out of full-SSM (FSSM), partial-SSM (PSSM), and MBF which provides a best conditional BER (CBER)
    - a better CBER can be promised
  - FSSM vs. PSSM
    - FSSM uses $Q - \log_2(N_s)$ bits for modulation
    - PSSM uses $\log_2(N_s/2)$ bits in specifying a direction and $Q - \log_2(N_s/2)$ bits for modulation
Simulation setup

- Number of antenna elements in UE and BS: 32
  - Number of RF chains: one for UE and four for BS
- Spectral efficiency: 4-bits/Hz
  - Modulation: QPSK for FSSM / 8QAM for PSSM / 16QAM for MBF
- Scattering clusters:
  - $N_{Ts} = 4$, with gains $\beta_l \sim CN(0, \gamma_l)$, $\gamma_l = 10^{-0.1z_l}, z_l \sim N(0, \epsilon^2), \forall l$: lognormal distribution with a variance $\epsilon$
- Receiver:
  - Maximum likelihood detector
Simulation results: adaptive SSM

\[ \epsilon^2 = 1, N_{Ts} = 6/12 \]

- Analytical bounds and simulation results match well as the SNR increases
- MBF achieves better average BER performance comparing to FSSM and PSSM
- As \( N_{Ts} \) increases, performance gap between MBF and SSMs becomes smaller
- In all the SNR range, the ATS achieves the best performance of all
Simulation results: adaptive SSM: cont.

- Shows the impact of a large number of total scattering clusters \(N_{Ts}\) on the BER.
- Existence of a larger number of total scattering clusters is more beneficial to SSM (for both FSSM and PSSM).
- Adaptive SSM achieves the best BER performance in all the SNR range.
- \(N_{Ts} = 18\) provides adaptive SSM with 10 dB gain at \(1 \times 10^{-4}\) BER over \(N_{Ts} = 6\).
Simulation results: adaptive SSM: cont.

$\epsilon^2 = 1, N_{Ts} = 6/18$

Selection probability of each scheme

- When $N_{Ts} = 18$, although MBF can achieve better BER performance over SSM in average sense, there exist more transmission times that SSM achieves the smallest instantaneous BER.

- Even for $N_{Ts} = 6$, about 45% of time that the SSM schemes (FSSM and PSSM) can achieve better instantaneous BER at 25 dB SNR.

- SSM favors a larger number of clusters $N_{Ts}$.
Conclusions

• Have proposed a spatial scattering modulation scheme, which utilizes the sparsity in the angular domain of the mmWave channel to modulate additional information bits; also considered hardware resource in UE which uses a single RF chain

• Have derived the conditional BER (CBER) for considered schemes (MBF, FSSM, PSSM)

• Based on the derivation of the CBER, we have designed the adaptive SSM which chooses the transmission scheme that provides the best CBER at each transmission epoch

• Especially, adaptive SSM achieves better performance than non-adaptive transmission schemes as the total number of scattering clusters or SNR increases

Thank you