MITSUBISHI ELECTRIC RESEARCH LABORATORIES
Cambridge, Massachusetts

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

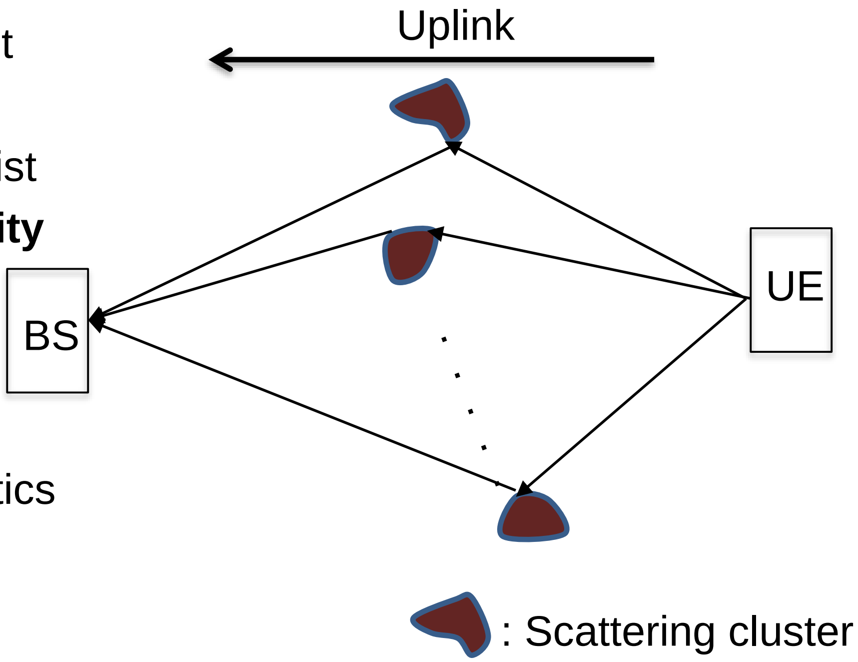
- Motivation

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

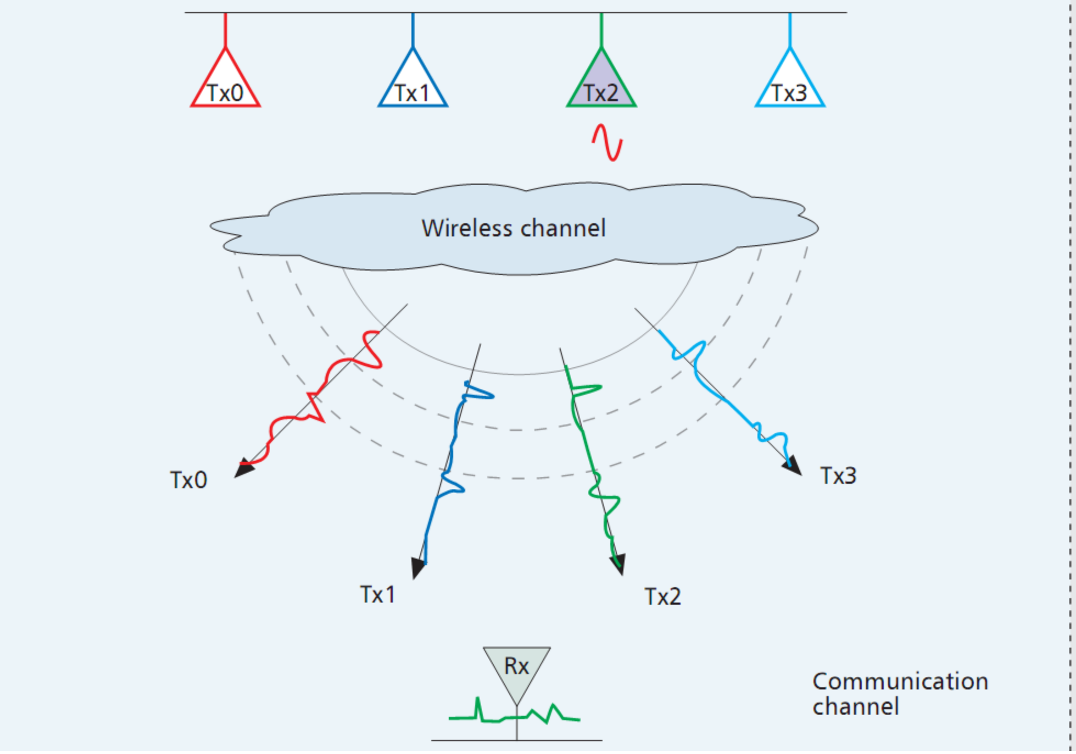
- Conclusions

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



[1] M. D. Renzo, et al, “Spatial Modulation for Multiple-Antenna Wireless Systems: A Survey”, IEEE Commu. Mag. Dec. 2011

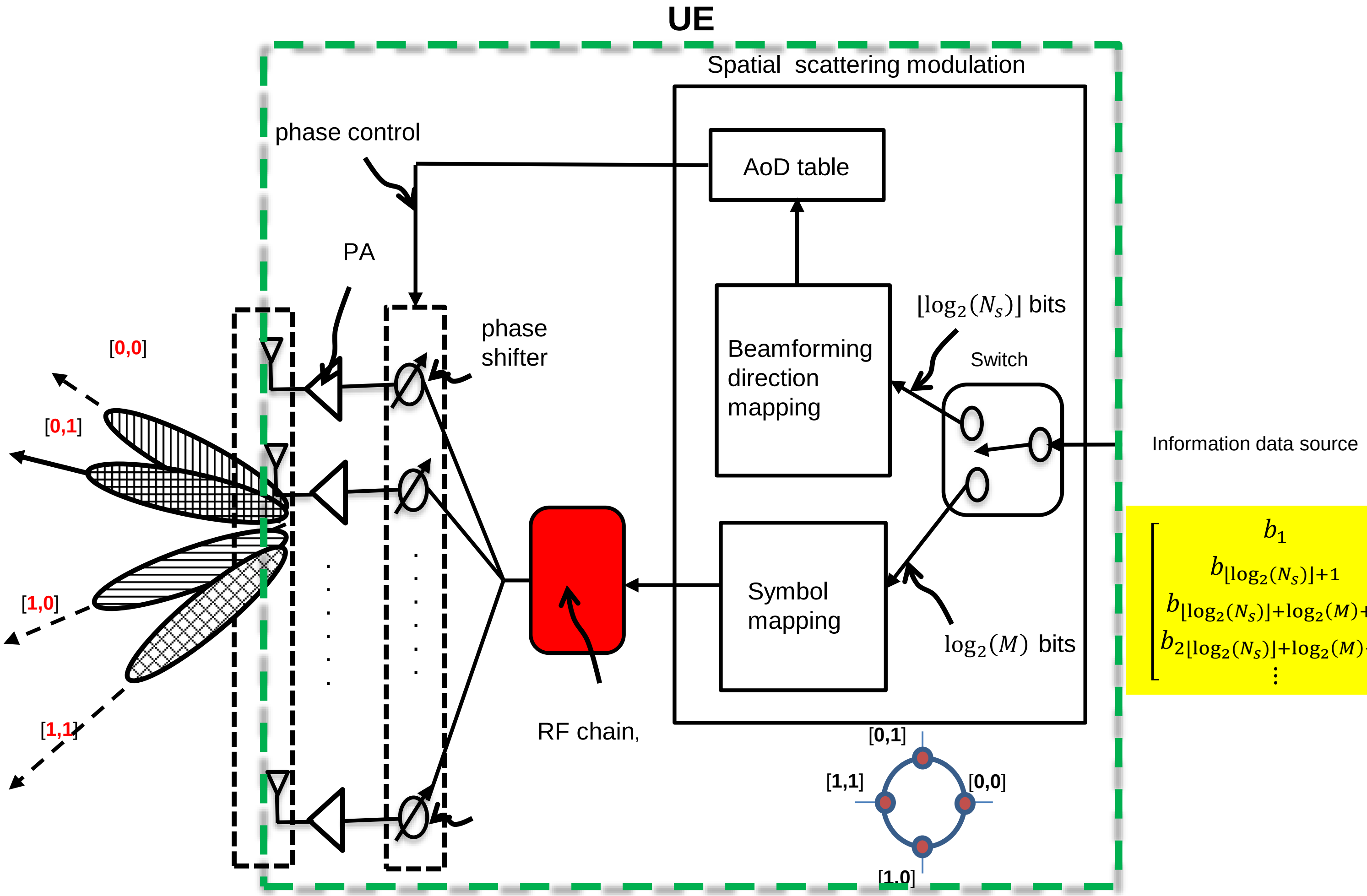
- Transmitter:
  - Activate a single antenna encoded by information bits
  - Two inputs are used due to available four antennas
  - In the example, $[b_2 : b_1] = [1 : 0]$
  - Other antennas are in silent for one transmission epoch
- Receiver:
  - We need to detect which antenna was used for transmission, 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

[2] Y. Ding, et al, “Spatial Scattering Modulation for Uplink Millimeter-Wave Systems", IEEE Communications Letters, 2017

Spatial Scattering Modulation (SSM): transmitter



$$\begin{bmatrix} b_1 & \cdots & b_{\lfloor \log_2(N_s) \rfloor} \\ b_{\lfloor \log_2(N_s) \rfloor+1} & \cdots & b_{\lfloor \log_2(N_s) \rfloor+\log_2(M)} \\ b_{\lfloor \log_2(N_s) \rfloor+\log_2(M)+1} & \cdots & b_{2\lfloor \log_2(N_s) \rfloor+\log_2(M)} \\ b_{2\lfloor \log_2(N_s) \rfloor+\log_2(M)+1} & \cdots & b_{2\lfloor \log_2(N_s) \rfloor+2\log_2(M)} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

Spatial Scattering Modulation (SSM): signal

- Transmitter:
  - s: modulation symbol, $\boldsymbol{p} \in \{\mathbf{a}_{\mathrm{t}}\left(\theta_1^t\right), \ldots, \mathbf{a}_{\mathrm{t}}\left(\theta^t_{\lfloor \log_2(N_s) \rfloor}\right)\}$, $\mathbf{a}_{\mathrm{t}}(\theta_l^t)$: ULA array manifold vectors
- Channel: a narrowband discrete channel model [3,4]
  - $\boldsymbol{H} = \sum_{l=1}^{N_S} \beta_l \, \mathbf{a}_{\mathrm{r}}(\theta_l^r) \, \mathbf{a}_{\mathrm{t}}(\theta_l^t)^H$
    - β_l: gain of the lth scattering cluster
    - $\mathbf{a}_{\mathrm{t}}(\theta_l^t) = \frac{1}{\sqrt{N_t}}\left[1, e^{j2\pi\phi_l^t}, \cdots, \; e^{j2\pi\phi_l^t(N_t-1)}\right]^T, \phi_l^t = \frac{\mathrm{d_t}}{\lambda}\sin(\theta_l^t)$
    - $\mathbf{a}_{\mathrm{r}}(\theta_l^r) = \frac{1}{\sqrt{N_r}}\left[1, e^{j2\pi\phi_l^r}, \cdots, \; e^{j2\pi\phi_l^r(N_r-1)}\right]^T, \phi_l^r = \frac{\mathrm{d_r}}{\lambda}\sin(\theta_l^r)$
      - d_t, d_r: antenna spacing, λ: wave length of the propagation, N_t, N_r: antenna elements
  - Assume a large number of antenna elements in the UE and BS
    - $\mathbf{a}_{\mathrm{r}}(\theta_l^r) \, \mathbf{a}_{\mathrm{r}}(\theta_k^r)^H = \delta(l-k), \quad \mathbf{a}_{\mathrm{t}}(\theta_l^t) \, \mathbf{a}_{\mathrm{t}}(\theta_k^t)^H = \delta(l-k)$

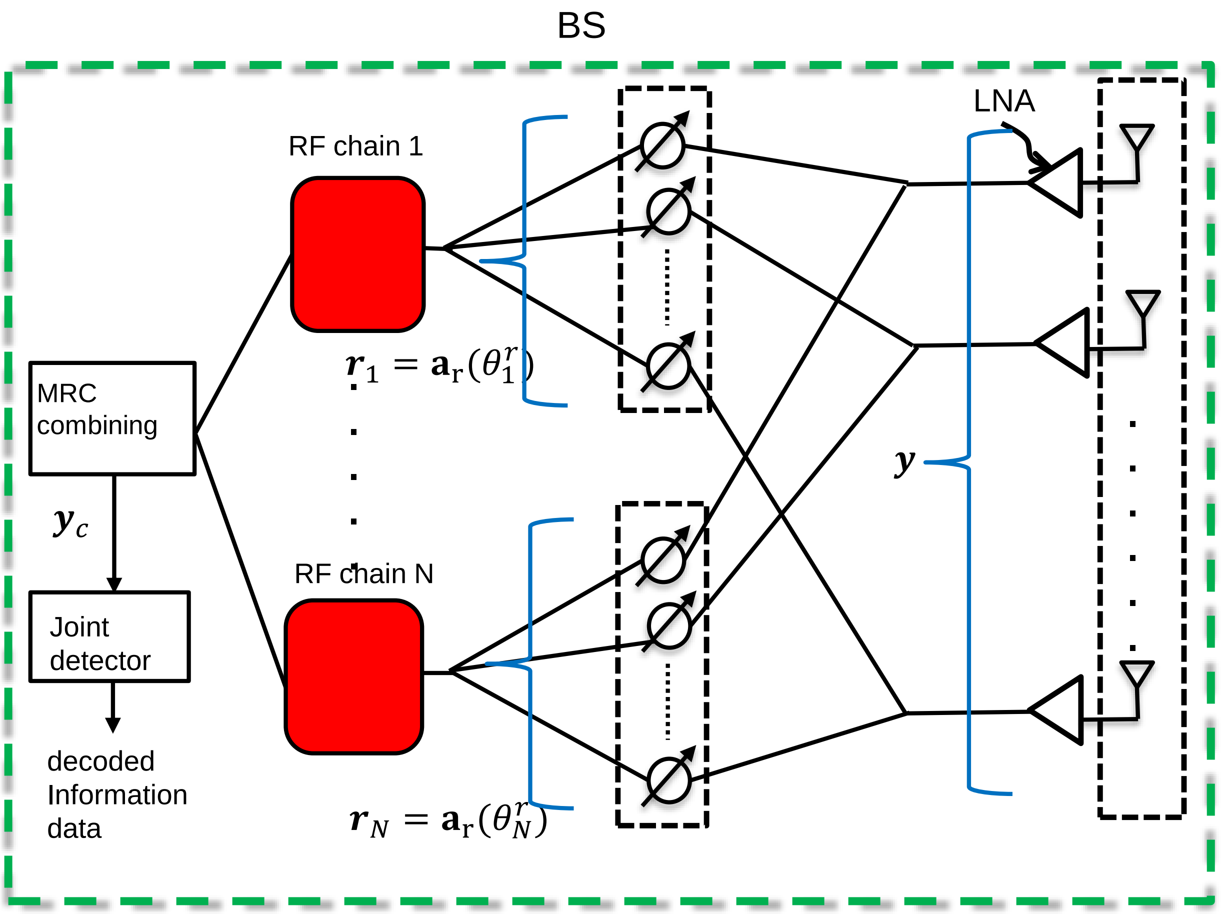
- Received signal
  - $$\boldsymbol{y} = \sqrt{E}\boldsymbol{H}\boldsymbol{p}s + \boldsymbol{n} = \sqrt{E}\sum_{l=1}^{N_S} \beta_l \, \mathbf{a}_{\mathrm{r}}(\theta_l^r) \, \mathbf{a}_{\mathrm{t}}(\theta_l^t)^H \boldsymbol{p}s + \boldsymbol{n}$$
    $$= \sqrt{E}\beta_{l'}\mathbf{a}_{\mathrm{r}}(\theta_{l'}^r) \; s + \boldsymbol{n}$$

[3] A. M. Sayeed, “Deconstructing multiantenna fading channels,”T-SP, vol. 50, no. 10, pp. 2563–2579, 2002

[4] O. El Ayach, et al, “Spatially sparse precoding in millimeter wave MIMO systems,”*T-WC, vol. 13, no. 3, pp. 1499– 1513, 2014*

SSM: Receiver

$$\boldsymbol{y}_c = \begin{bmatrix} \boldsymbol{r}_1^{\mathrm{H}}\mathbf{y} \\ \boldsymbol{r}_2^{\mathrm{H}}\mathbf{y} \\ \vdots \\ \boldsymbol{r}_N^{\mathrm{H}}\mathbf{y} \end{bmatrix}$$



BS

LNA

RF chain 1

$\boldsymbol{r}_1 = \mathbf{a}_{\mathrm{r}}(\theta_1^r)$

MRC combining

$\boldsymbol{y}_c$

Joint detector

decoded Information data

RF chain N

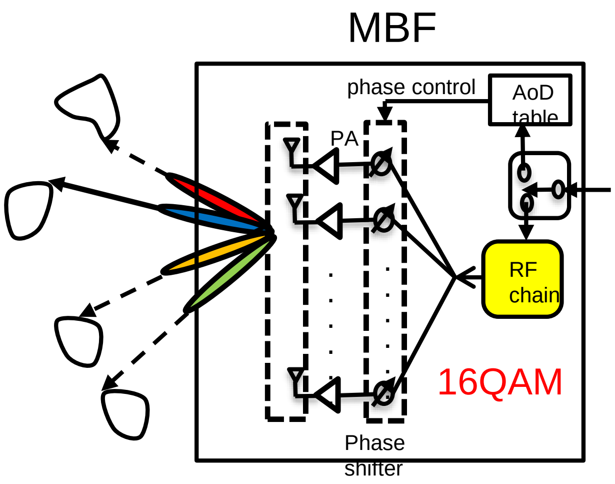
$\boldsymbol{r}_N = \mathbf{a}_{\mathrm{r}}(\theta_N^r)$

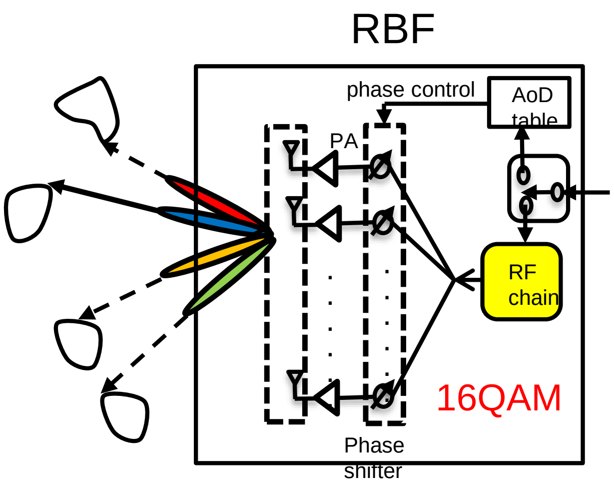
$\boldsymbol{y}$

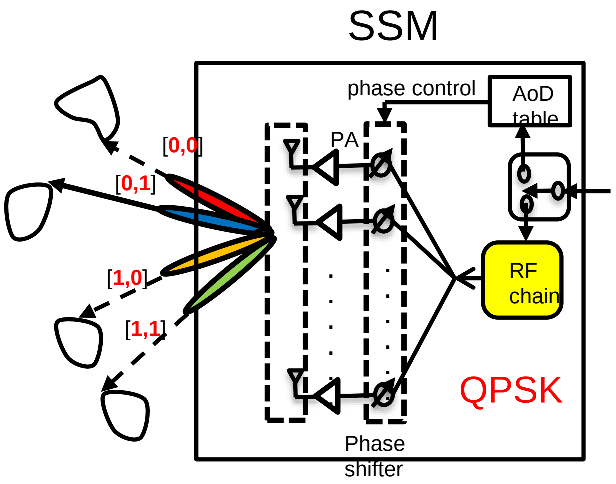
$$\text{MLD: } \{\hat{k}, \hat{s}\} = arg \min_{s,k\in\{1,\ldots,N_s\}} |\, \boldsymbol{y}_c(k) - \boldsymbol{a}_r(\theta_k^r)^H \sqrt{E}\boldsymbol{H}\boldsymbol{a}_t(\theta_k^t)s|^2$$

Simulation results with SSM

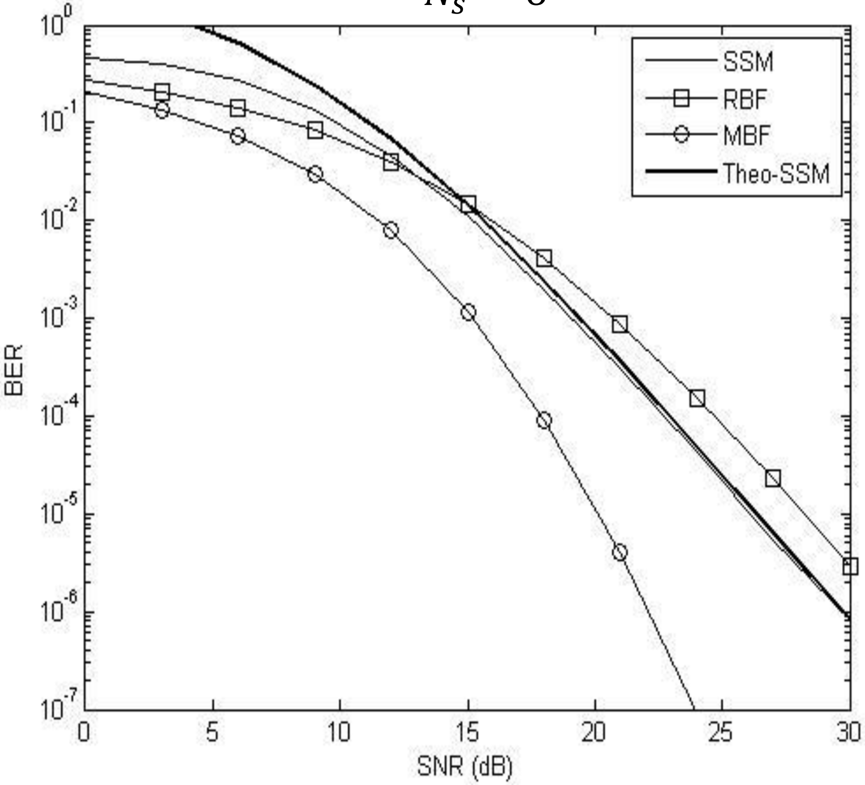
- Number of antenna elements in UE and BS: 32
  - Number of RF chains: one for the UE and four for the BS
- Spectral efficiency: 4-bits/Hz
  - Modulation: QPSK for SSM vs. 16QAM for maximum and random beamforming (MBF/RBF) without SSM
- Scattering clusters :
  - $N_s = 4$, with gains $\beta_l \sim CN(0,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

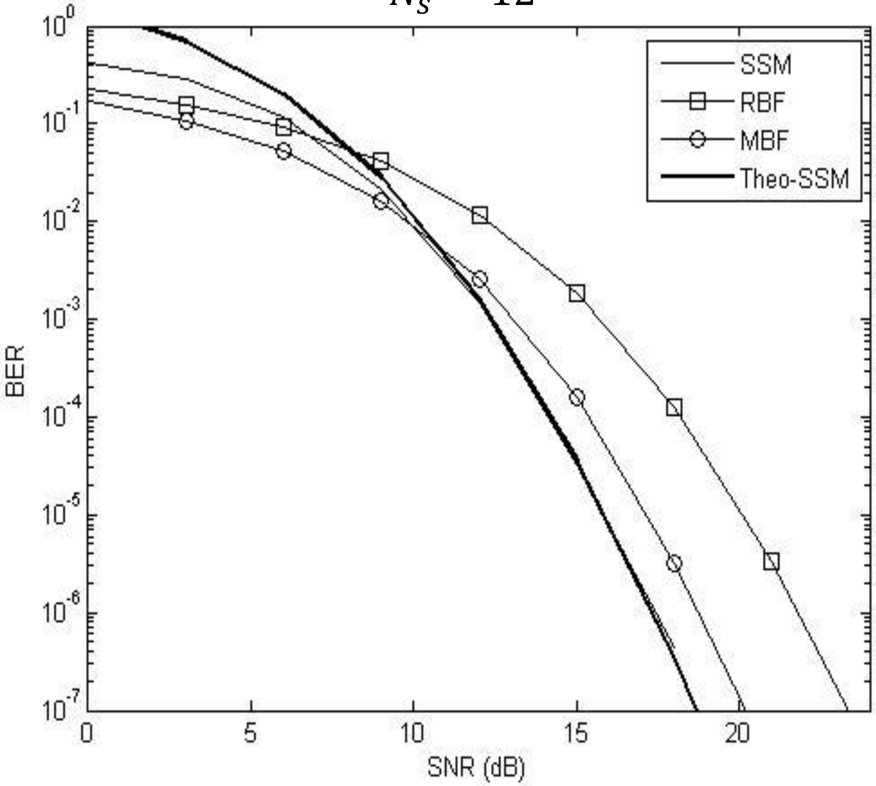






Simulation results: Spectral efficiency: 4-bits/Hz

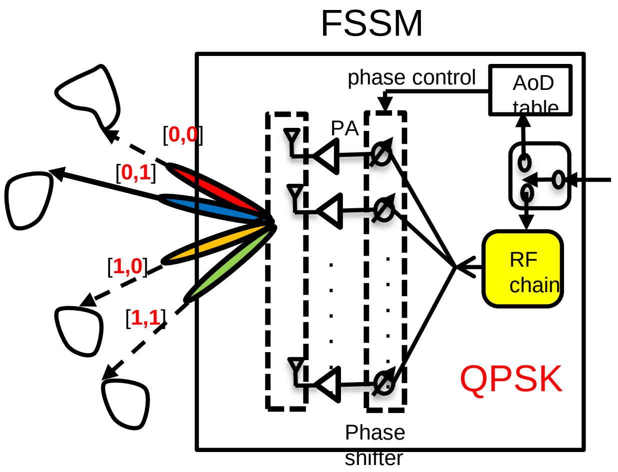

$N_s = 6$

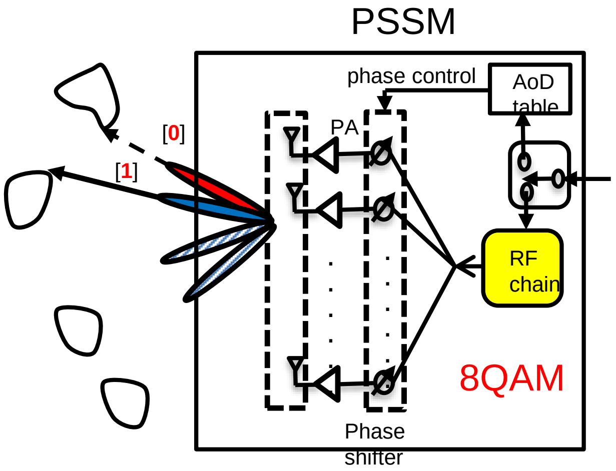

$N_s = 12$

- 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

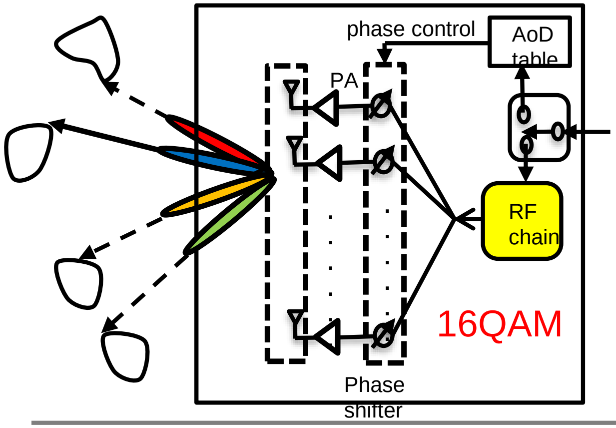




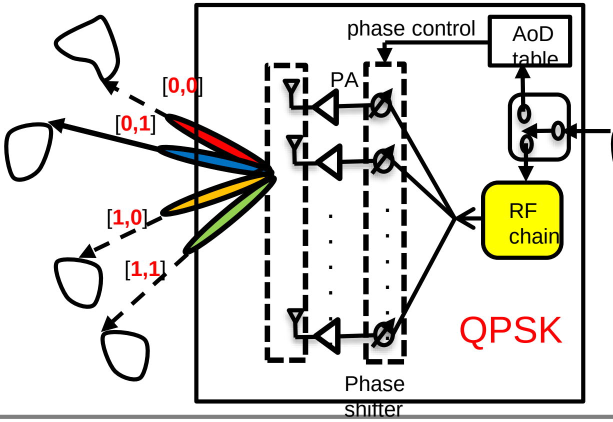
Simulation setup

- 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 :
  - $N_{T_s} = 4$, with gains $\beta_l \sim \mathcal{CN}(0, \gamma_l), \gamma_l = 10^{-0.1 z_l}, z_l \sim N(0, \epsilon^2), \forall l$: lognormal distribution with a variance ϵ
- Receiver:
  - Maximum likelihood detector

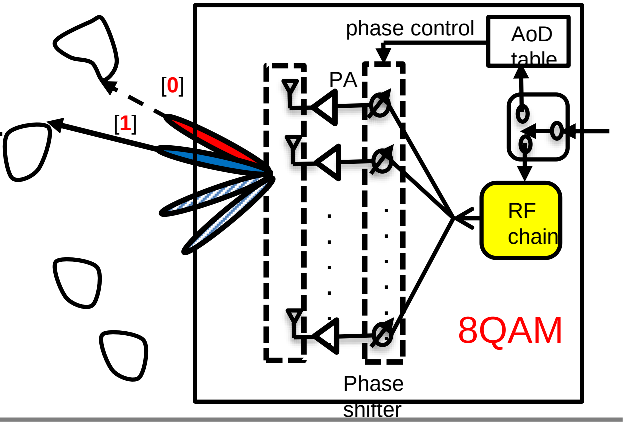
MBF



FSSM

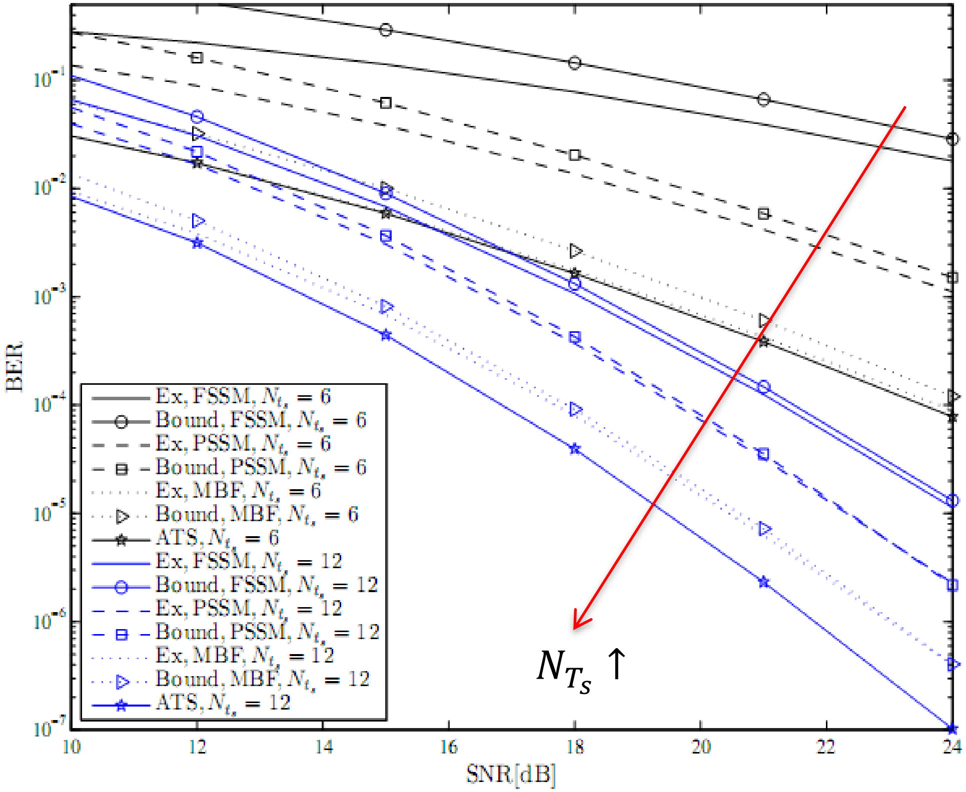


PSSM



Simulation results: adaptive SSM

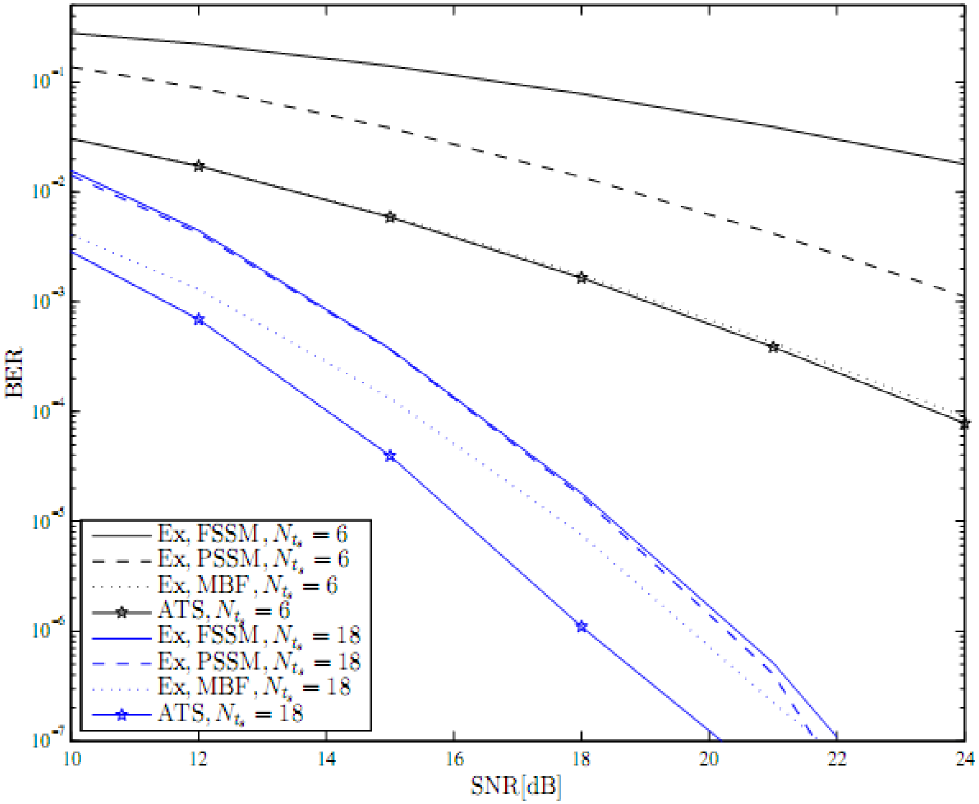
$\epsilon^2 = 1, N_{T_s} = 6/12$



- Analytical bounds and simulation results match well as the SNR increases
- MBF achieves better average BER performance comparing to FSSM and PSSM
- As N_{T_s} 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.

$\epsilon^2 = 1, N_{T_s} = 18$

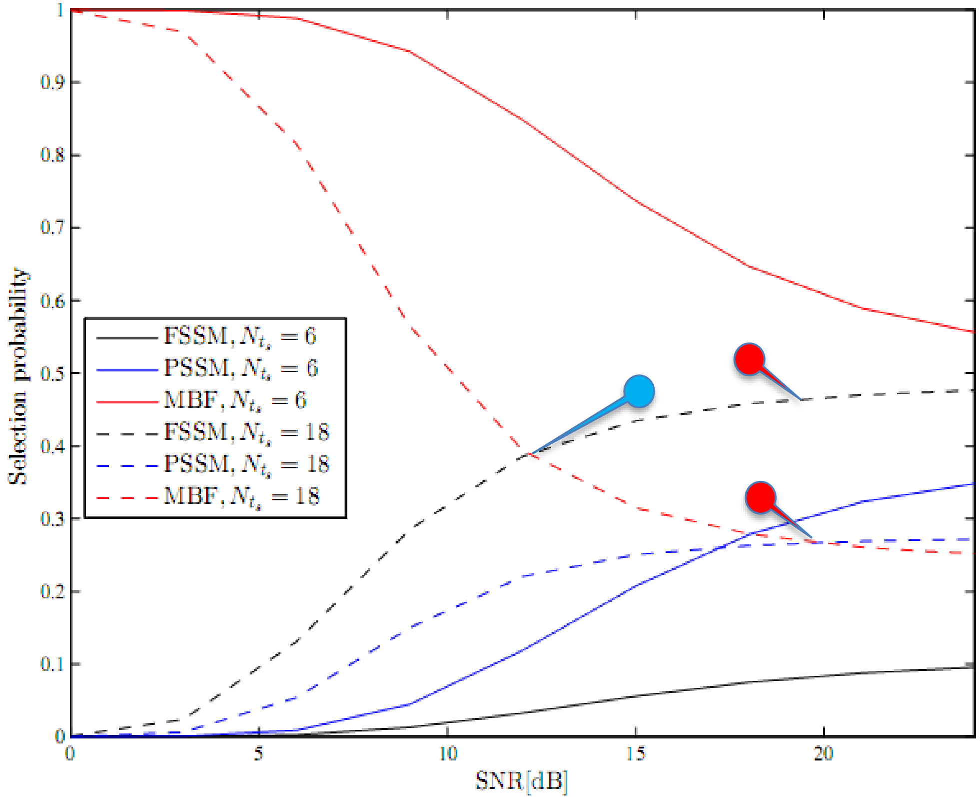


- Shows the impact of a large number of total scattering clusters N_{T_s} on the BER
- Existence of a larger number of total scattering clusters is more beneficial to SSM (for both FSSM and PSSM)
- Adaptive SSM achieves the best BER performance in all the SNR range.
- N_{T_s}= 18 provides adaptive SSM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

Simulation results: adaptive SSM: cont.

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

Selection probability of each scheme



- When $N_{T_s} = 18,$ 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 $N_{T_s} = 6,$ 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_{T_s}

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