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THE ELISHA YEGAL BAR-NESS CENTER FOR WIRELESS COMMUNICATIONS AND SIGNAL PROCESSING RESEARCH

Cloud Processing for 5G Systems

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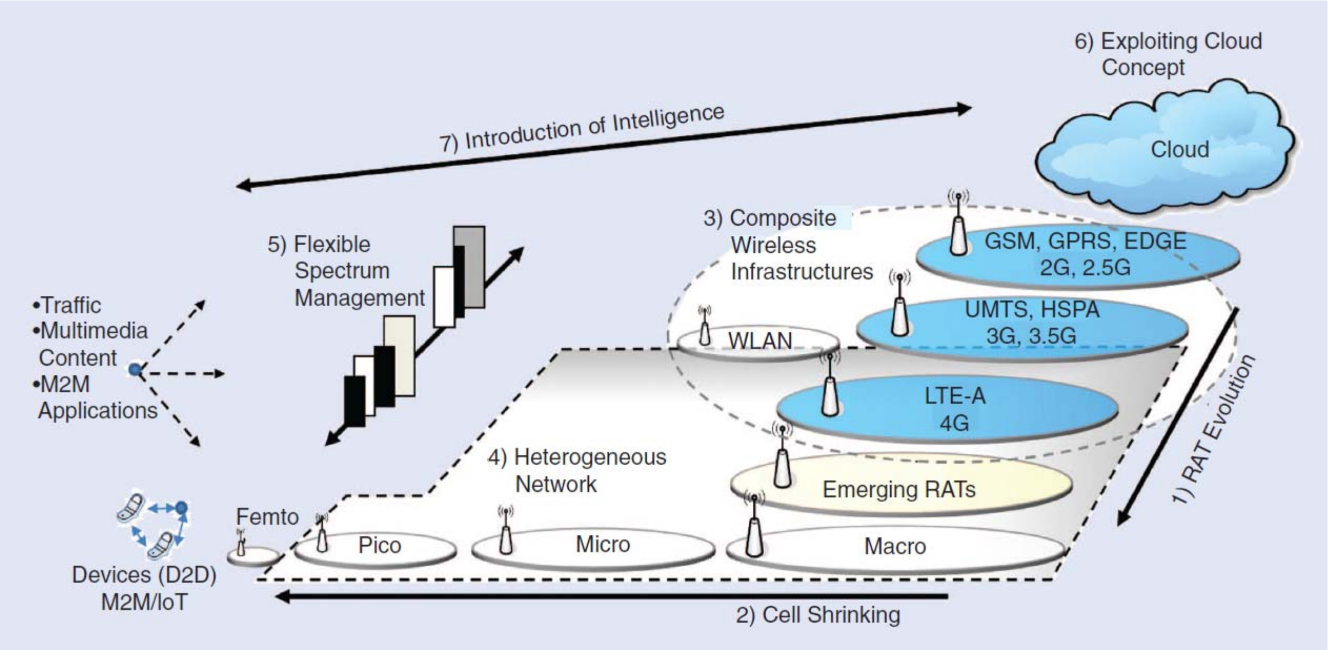
What Will 5G Be?

- Highly integrative system supporting a variety of applications
- Flexible and intelligent radio access network (RAN)
- Enabling technology: Cloud-RAN (C-RAN)



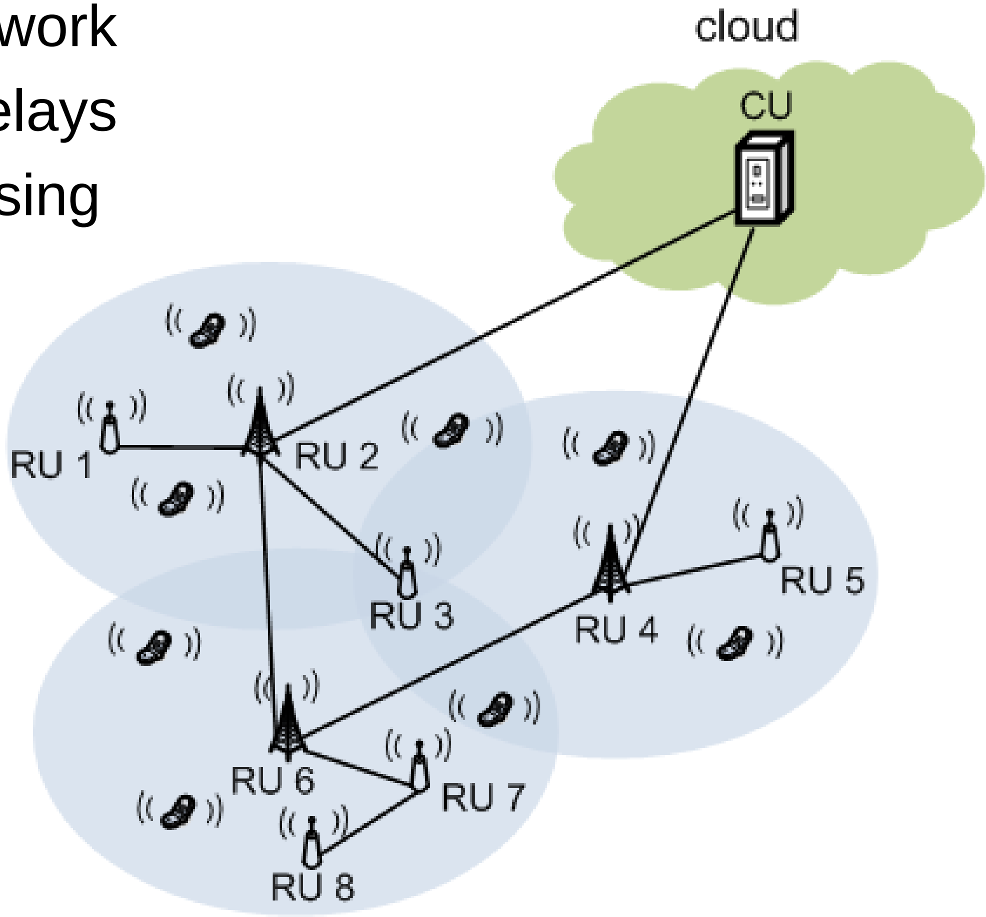
[Demestikas ’13]

Overview

- Introduction and Motivation
- System Model
- Point-to-Point Fronthaul Compression
- Multivariate Fronthaul Compression
- Numerical Results
- Conclusions

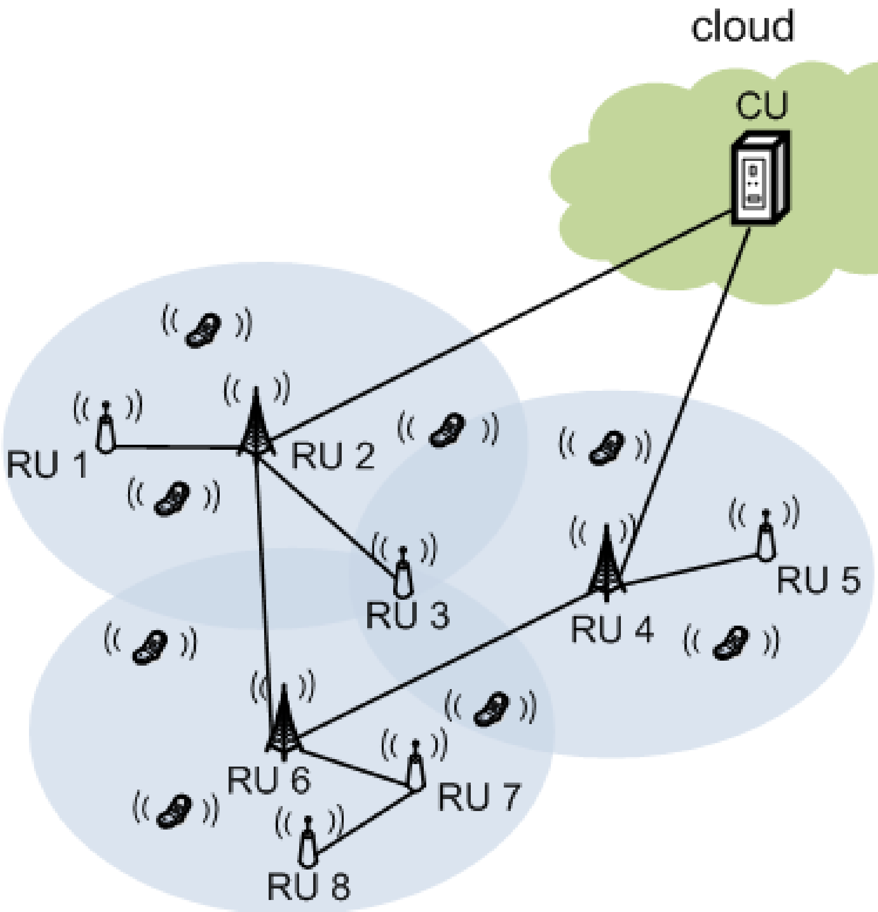
Cloud Radio Access Networks

- Heterogeneous dense network
- Macro, femto, pico-BSs, relays
- C-RAN: Baseband processing takes place in the “cloud” (virtualization)



Cloud Radio Access Networks

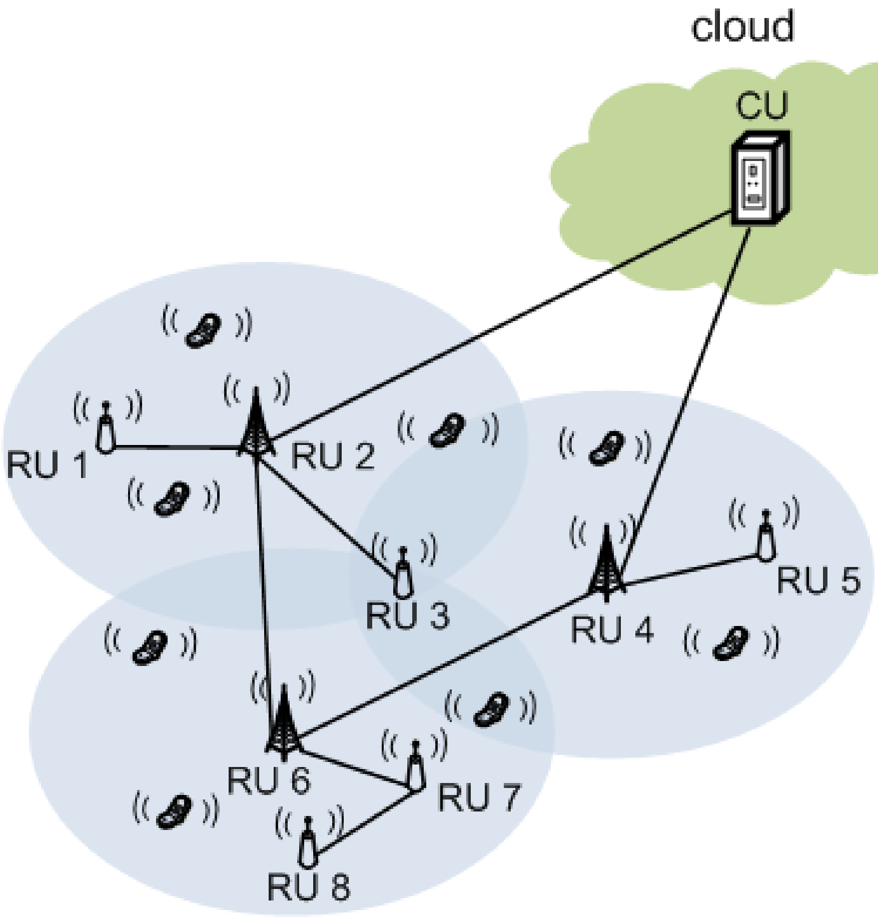
- Fronthaul links carry “radio” signals to/from control unit (CU)
- Base stations act as radio units (RUs) or remote radio heads (RRHs)



Cloud Radio Access Networks

- Analog (e.g., radio-over fiber) vs digital (e.g., CPRI) fronthaul transmission
- Digital transmission:

  digitized complex (IQ) baseband signals



Cloud Radio Access Networks

Advantages:

- Dense deployment with low-cost “green” BSs (RUs)
- Flexible radio and computing resource allocation (statistical multiplexing)
- Effective interference mitigation via joint baseband processing (e.g., eICIC and CoMP in LTE-A)
- Easier network upgrades and maintenance

Key challenge: Effective transfer of the IQ signals on the fronthaul links

Cloud Radio Access Networks

- CPRI standard based on ADC/DAC

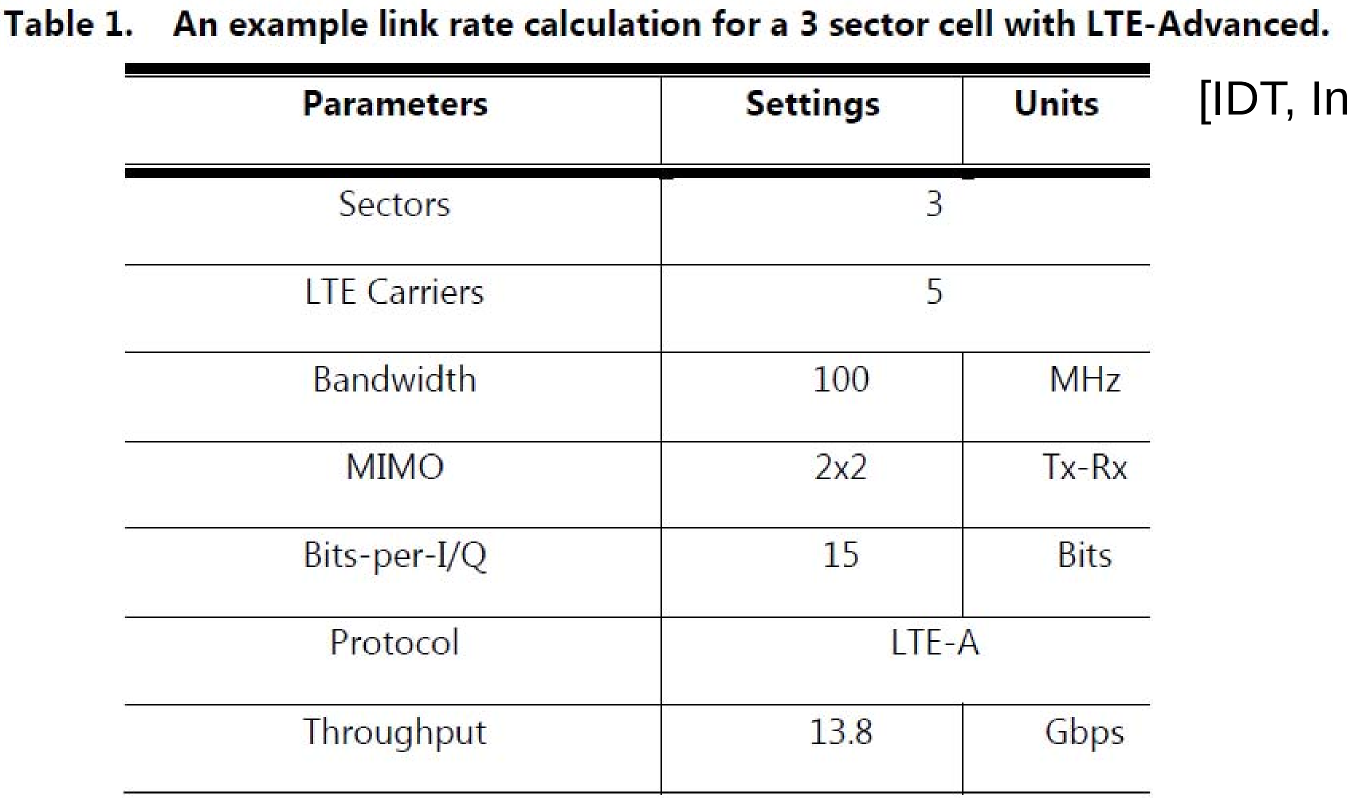


Table 1. An example link rate calculation for a 3 sector cell with LTE-Advanced.

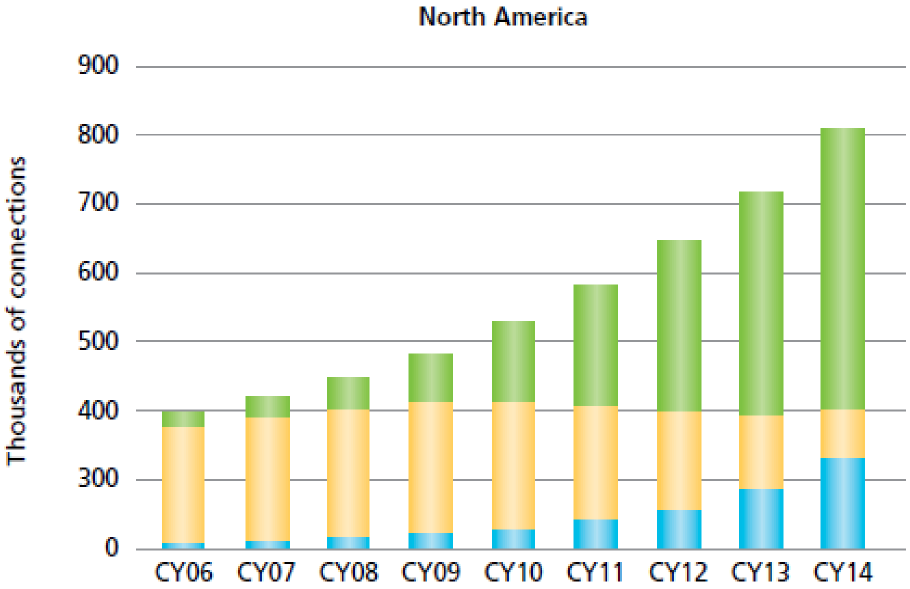
Parameters	Settings	Units
Sectors	3	
LTE Carriers	5	
Bandwidth	100	MHz
MIMO	2x2	Tx-Rx
Bits-per-I/Q	15	Bits
Protocol	LTE-A	
Throughput	13.8	Gbps

[IDT, Inc]

… Rate higher than supported by standard optical fiber channels (10GE)…

Cloud Radio Access Networks

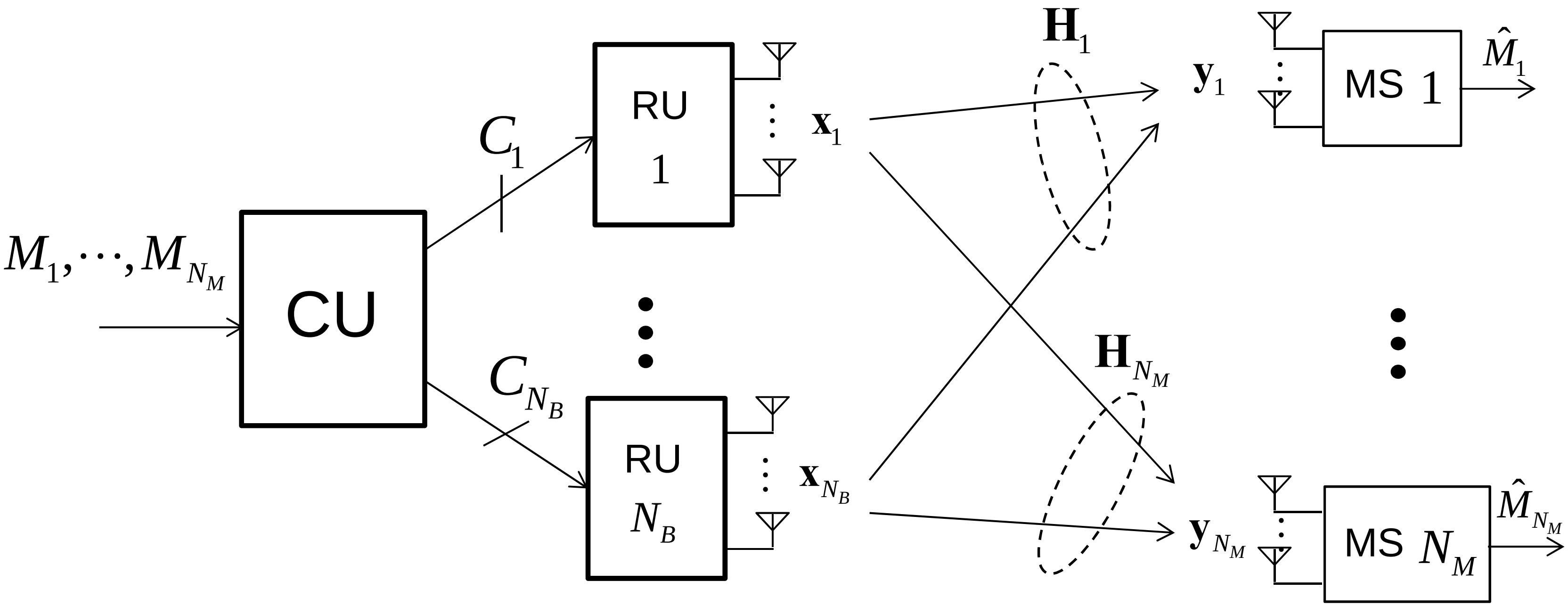
- Fronthaul links



The distribution of backhaul connections for macro BSs (green: fiber, orange: copper, blue: air) [Segel and Weldon].

- Mmwave front/backhauling for 5G systems [Ghosh '13] [Checko et al '15]
- Copper (LAN cable) for indoor coverage [Lu et al '14]

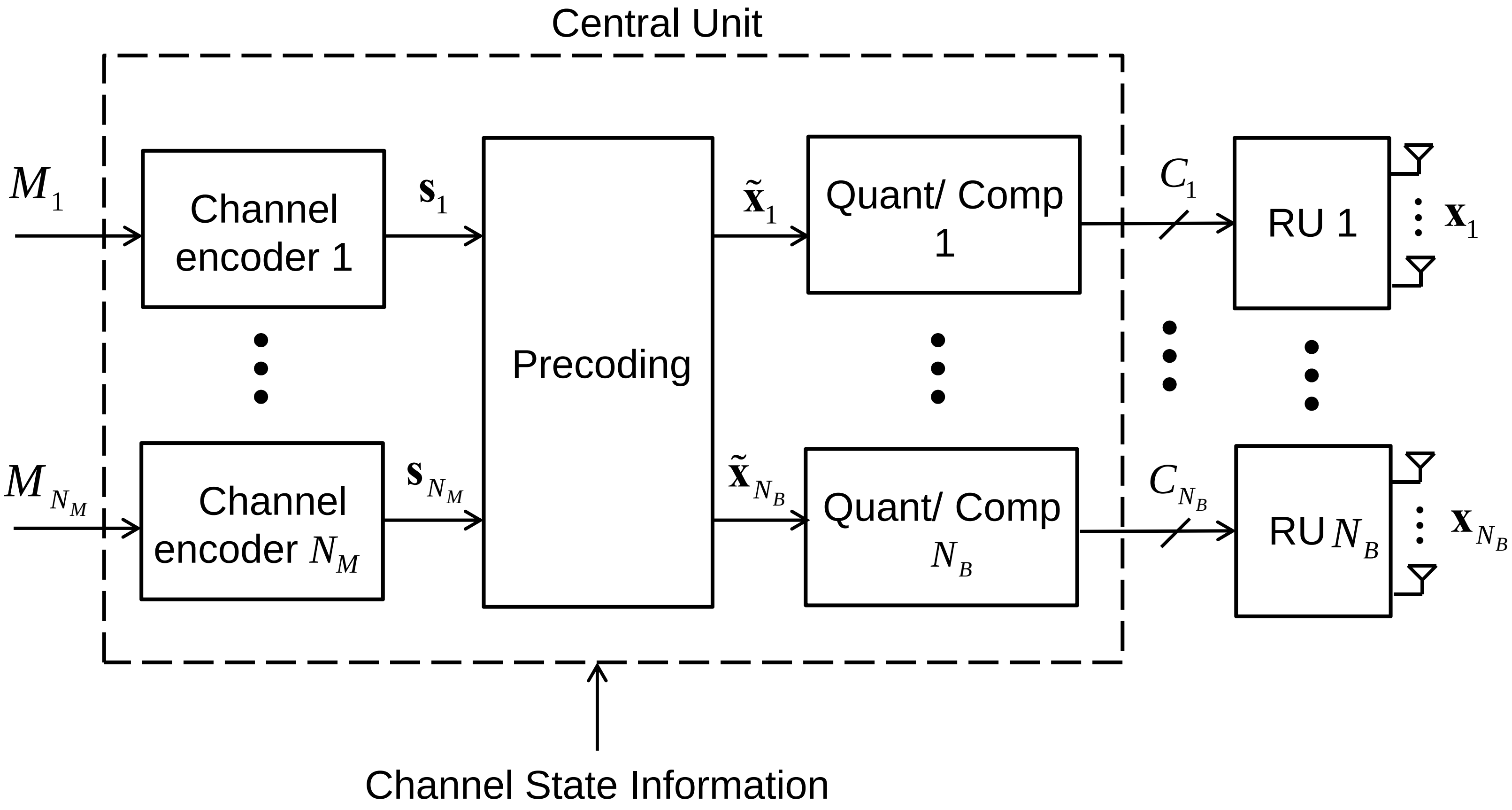
System Model



S.-H. Park. O. Simeone, O. Sahin and S. Shamai (Shitz), “Fronthaul compression for Cloud Radio Access Networks,” IEEE Signal Processing Magazine, vol. 31, no. 6, pp. 69-79, Nov. 2014.

Point-to-Point Fronthaul Quantization/ Compression

[Simeone et al ’09] [Patil and Yu ’14]



Central Unit

M_1

Channel encoder 1

$\mathbf{s}_1$

M_{N_M}

Channel encoder N_M

$\mathbf{s}_{N_M}$

Precoding

$\tilde{\mathbf{x}}_1$

Quant/ Comp 1

$\tilde{\mathbf{x}}_{N_B}$

Quant/ Comp N_B

C_1

C_{N_B}

RU 1

$\mathbf{x}_1$

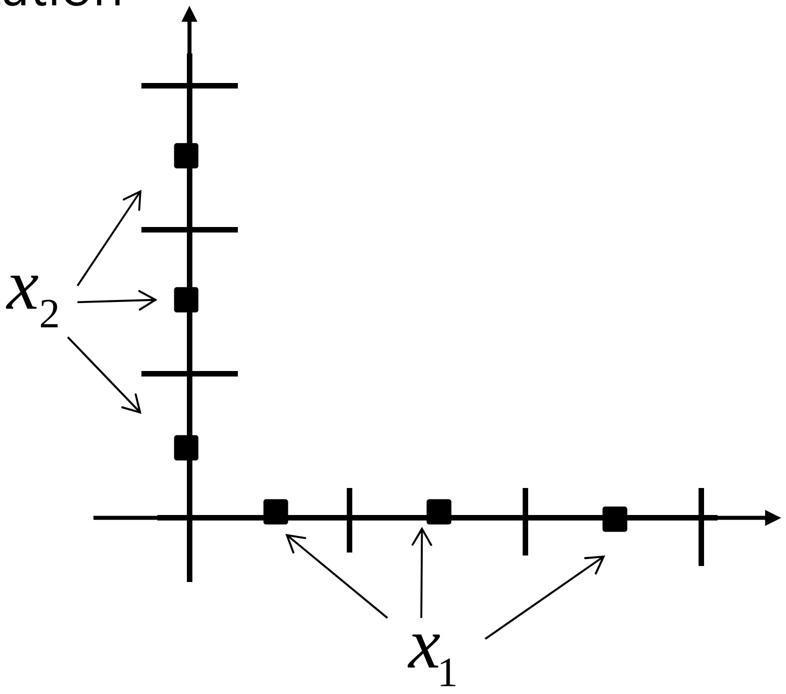
RU N_B

$\mathbf{x}_{N_B}$

Channel State Information

Point-to-Point Fronthaul Quantization/ Compression

Ex.: Scalar quantization



Point-to-Point Fronthaul Quantization/ Compression

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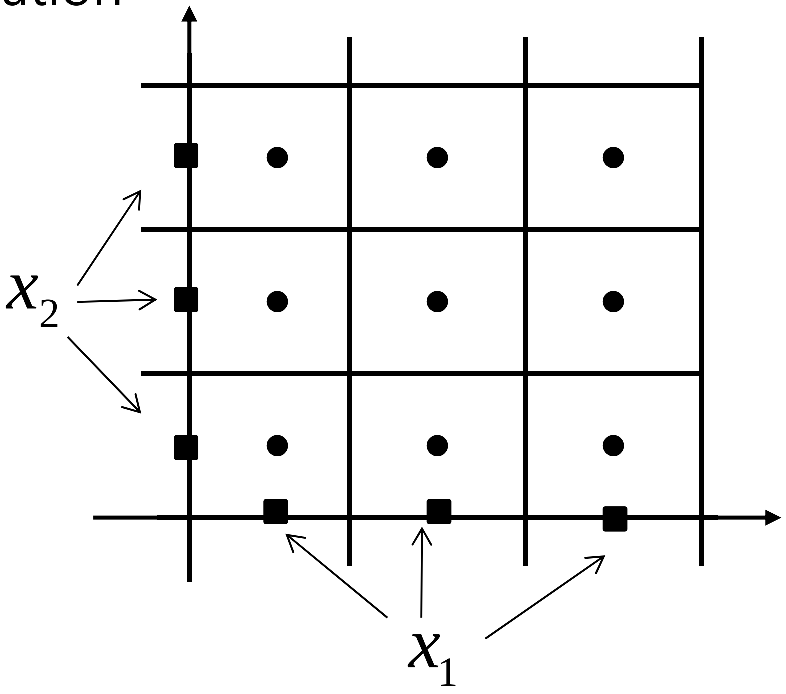

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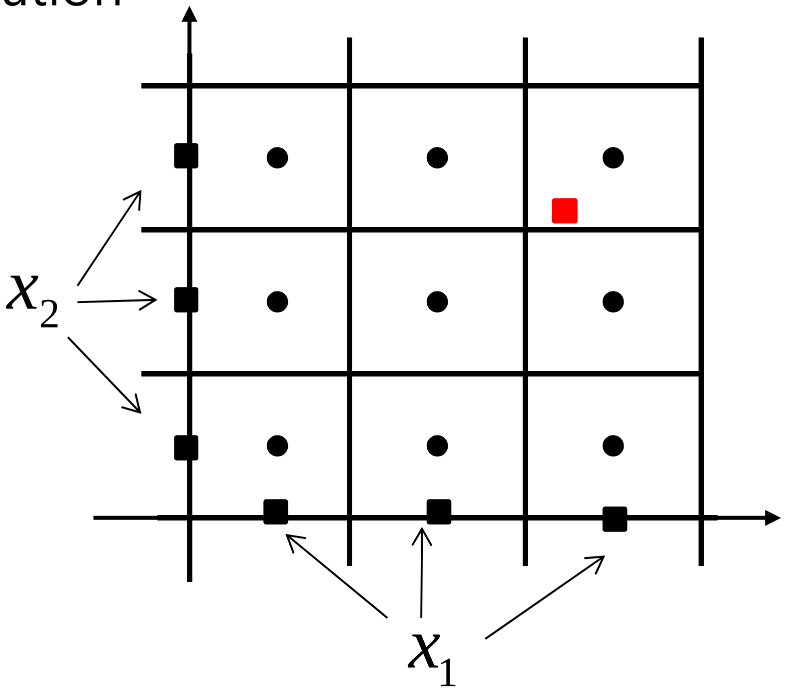

Point-to-Point Fronthaul Quantization/ Compression

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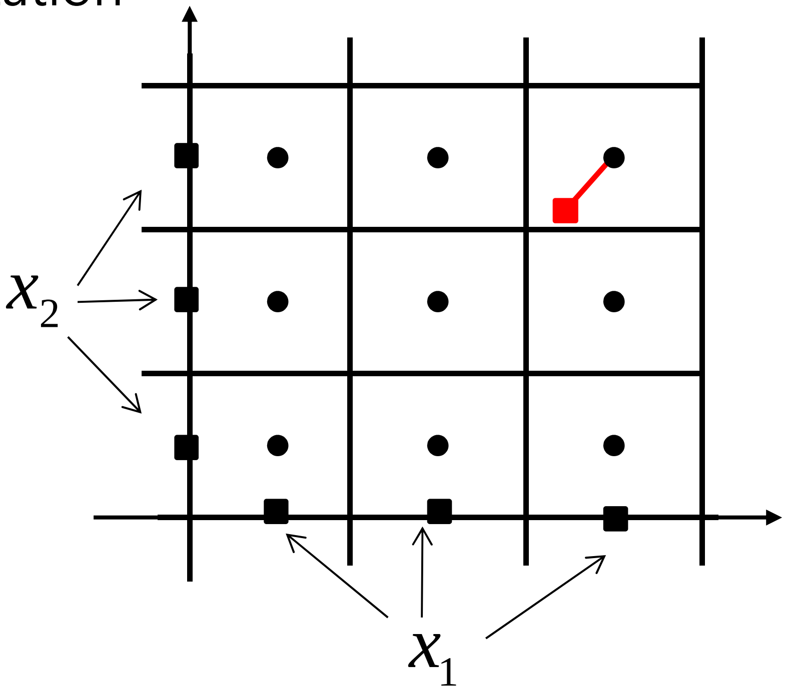


… uncorrelated quantization noise
… uniform “interference”

Multivariate Fronthaul Quantization/ Compression

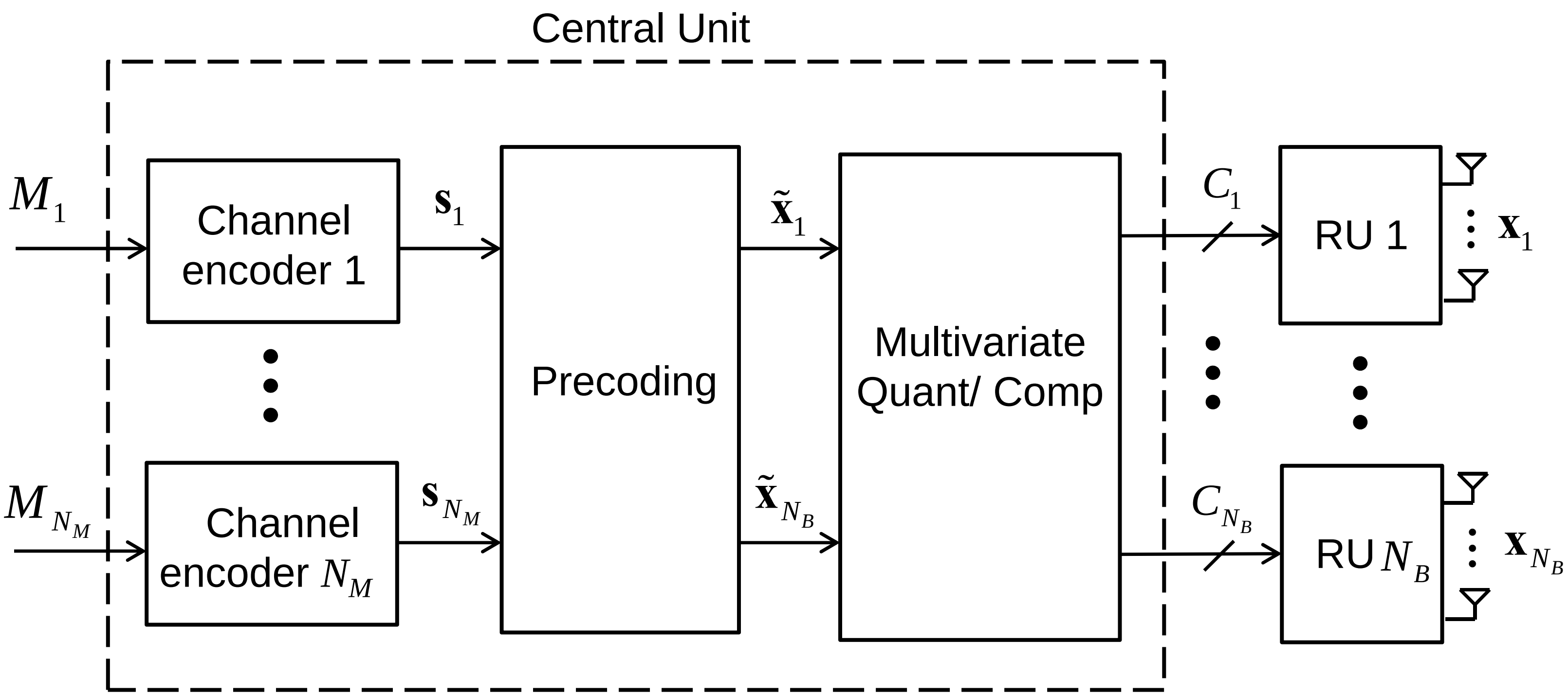
[Park et al ’14]

- Key idea: Controlling the impact of the interference on the signal space

- Akin to
  - quantization noise shaping techniques used in transform coding
  - interference control via linear precoding

Multivariate Fronthaul Quantization/ Compression

[Park et al ’14]



Multivariate Fronthaul Quantization/ Compression

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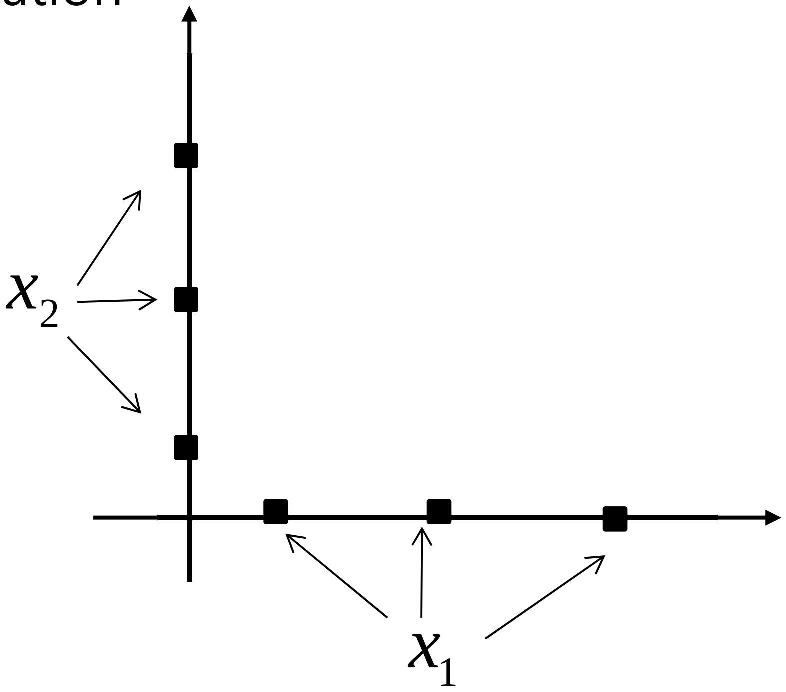
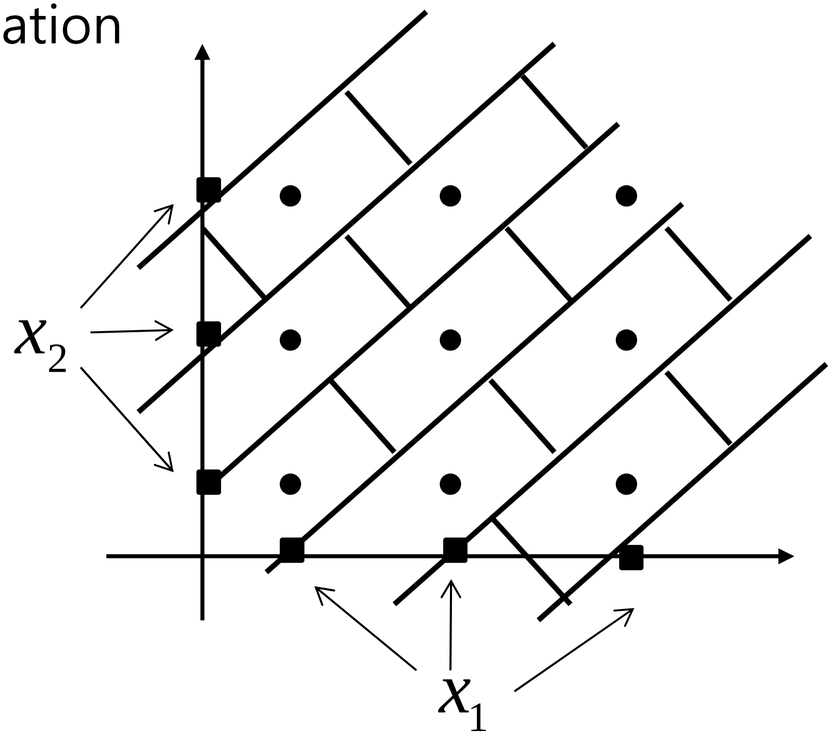


Multivariate Fronthaul Quantization/ Compression

Ex.: Scalar quantization



Multivariate Fronthaul Quantization/ Compression

- Joint optimization of precoding and compression:

$$\begin{aligned}
&\underset{\mathbf{A},\boldsymbol{\Omega}\geq 0}{\text{maximize}} && \sum_{k=1}^{N_M} w_k f_k\left(\mathbf{A},\boldsymbol{\Omega}\right) \\
&\text{s.t.} && g_{\mathcal{S}}\left(\mathbf{A},\boldsymbol{\Omega}\right) \leq \sum_{i\in\mathcal{S}} C_i, \text{ for all } \mathcal{S}\subseteq\mathcal{N}_B, \\
& && \operatorname{tr}\left(\mathbf{E}_i^H\mathbf{A}\mathbf{A}\mathbf{E}_i + \boldsymbol{\Omega}_{i,i}\right) \leq P_i, \text{ for all } i\in\mathcal{N}_B.
\end{aligned}$$

where $f_k\left(\mathbf{A},\boldsymbol{\Omega}\right) = I\left(\mathbf{s}_k;\mathbf{y}_k\right)$

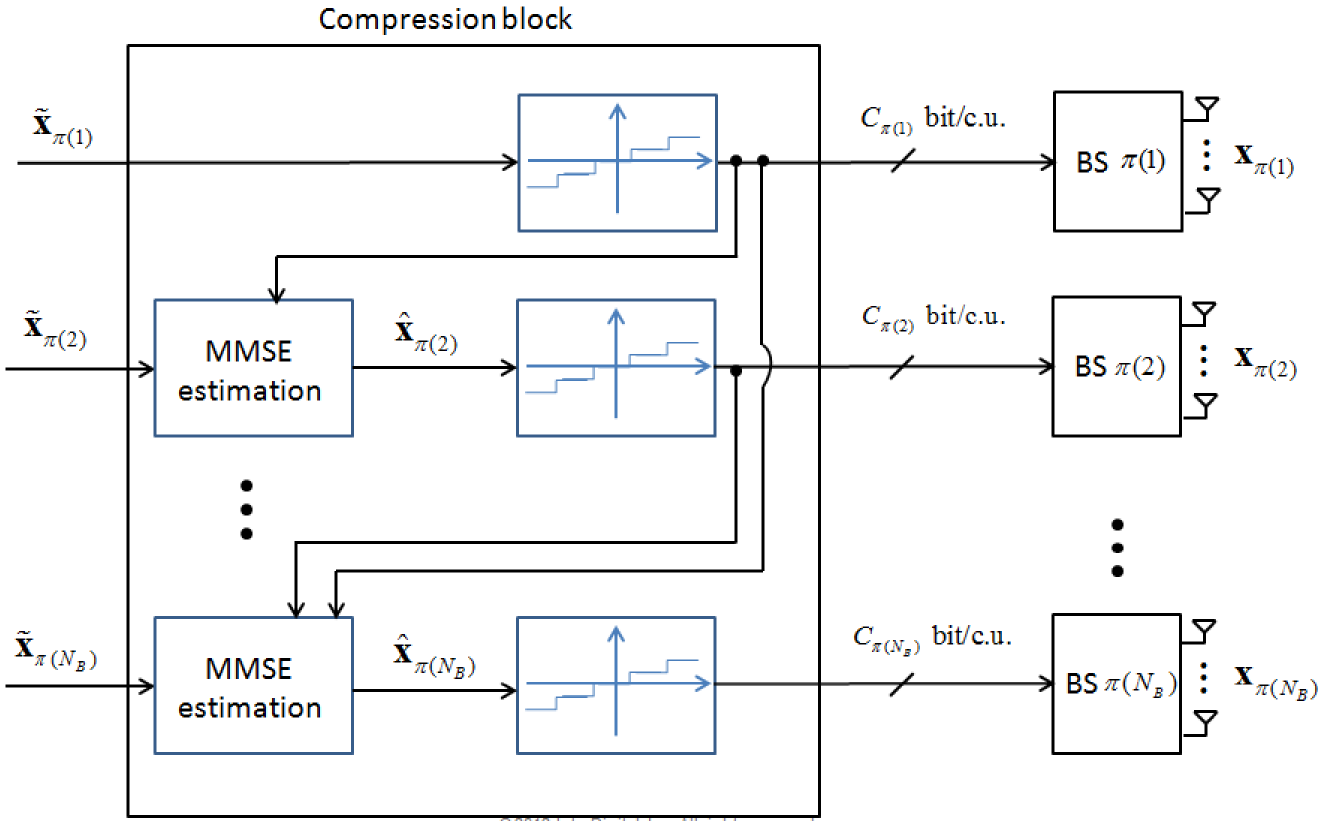
$$= \log\det\left(\mathbf{I}+\mathbf{H}_k(\mathbf{A}\mathbf{A}^H+\boldsymbol{\Omega})\mathbf{H}_k^H\right) - \log\det\left(\mathbf{I}+\mathbf{H}_k\left(\sum_{l\neq k}\mathbf{A}_l\mathbf{A}_l^H+\boldsymbol{\Omega}\right)\mathbf{H}_k^H\right),$$

$$g_{\mathcal{S}}\left(\mathbf{A},\boldsymbol{\Omega}\right) = \sum_{i\in\mathcal{S}} h\left(\mathbf{x}_i\right) - h\left(\mathbf{x}_{\mathcal{S}} \mid \tilde{\mathbf{x}}\right)$$

$$= \sum_{i\in\mathcal{S}} \log\det\left(\mathbf{E}_i^H\mathbf{A}\mathbf{A}^H\mathbf{E}_i + \boldsymbol{\Omega}_{i,i}\right) - \log\det\left(\mathbf{E}_{\mathcal{S}}^H\boldsymbol{\Omega}\mathbf{E}_{\mathcal{S}}\right) \leq \sum_{i\in\mathcal{S}} C_i.$$

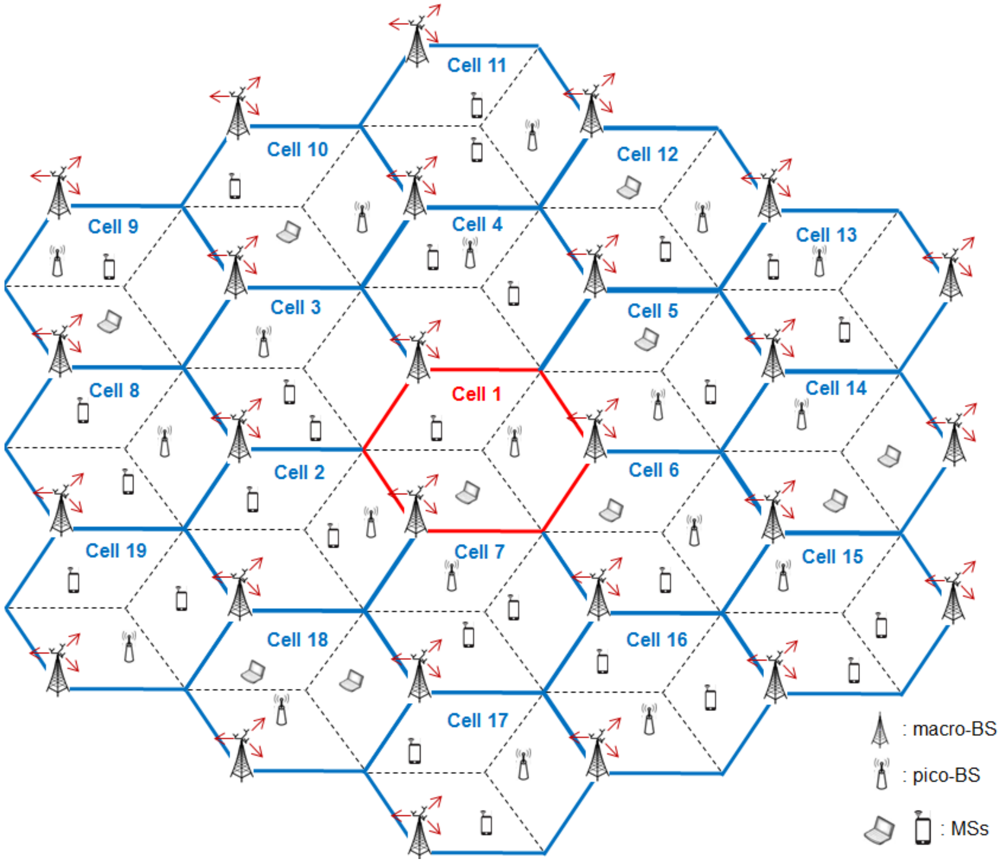
Multivariate Fronthaul Quantization/ Compression

- Successive estimation-compression architecture



Simulation Set-up

- In each macro-cell, N pico-BSs and K MSs are uniformly distributed



Simulation Set-up

- LTE rate model [3GPP-TR-136942]

$$\tilde{R}_k(\gamma_k) = \begin{cases} 0, & \text{if } \gamma_k \le \gamma_{\min} \\ \alpha_{\text{attenuate}} S(\gamma_k), & \text{if } \gamma_{\min} < \gamma_k \le \gamma_{\max} \\ R_{\max}, & \text{if } \gamma_k > \gamma_{\max} \end{cases}$$

where γ_k : SINR at MS k; $S(\gamma) = \log_2(1+\gamma)$; $\gamma_{\max} = S^{-1}(R_{\max} / \alpha_{\text{attenuate}})$;

$\alpha_{\text{attenuate}}$: attenuation factor representing implementation losses;

$R_{\max}$: Maximum and minimum throughput of the codeset, bps/Hz;

$\gamma_{\min}$: Minimum SINR of the codeset.

Parameter	UL	DL	Notes
$R_{\max}$	2.0	4.4	Based on 16-QAM 3/4 (UL) & 64-QAM 4/5 (DL)
$\gamma_{\min}$	-10 dB	-10 dB	Based on QPSK with 1/5 (UL) & 1/8 (DL)
$\alpha_{\text{attenuate}}$	0.4	0.6	Representing implementation losses

Simulation Set-up

- Proportional fairness metric

$$R_{\text{sum-PF}}(t) = \sum_{k=1}^{K} \frac{R_k(t)}{\bar{R}_k^{\alpha}} \qquad \cdots(\text{P1})$$

where α: fairness constant;

$R_k(t)$: instantaneous rate for MS k at time t;

$\bar{R}_k$: historical data rate for MS k until time $t-1$.

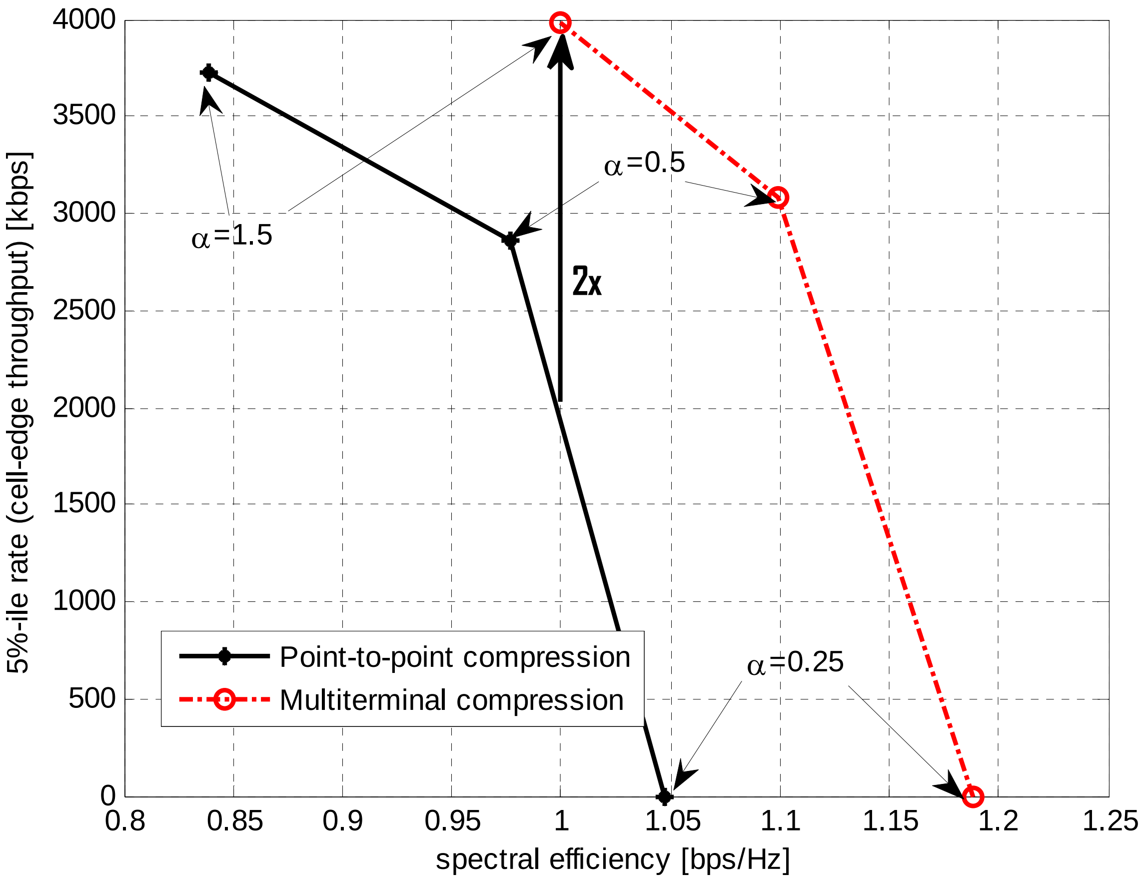
  - At each time t, the rate $\bar{R}_k$ is updated as

$$\bar{R}_k \leftarrow \beta \bar{R}_k + (1-\beta) R_k(t)$$

where $\beta \in [0,1]$: the forgetting factor.

Numerical Results

- Cell-edge throughput versus average spectral efficiency
  - Downlink, 1-cell cluster, $N=1$ pico-BS, $K=4$ MSs, $(C_{\text{macro}}, C_{\text{pico}})=(3,1)$ bps/Hz, $T_{\max}=5$, $\beta=0.5$, $F=1/3$



Conclusions and Outlook

- C-RAN design inspired by network information theory
- Other examples: distributed fronthaul compression, compute-and-forward, joint decompression and decoding, estimate-compress-forward, semi-coherent processing, in-network processing,…
- Implementation: linear codes, scalar quantization, successive estimation and compression,…
- Performance of conventional techniques can be drastically improved by strategies inspired by information theory

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