Channel estimation and hybrid precoding in frequency selective mmWave channels

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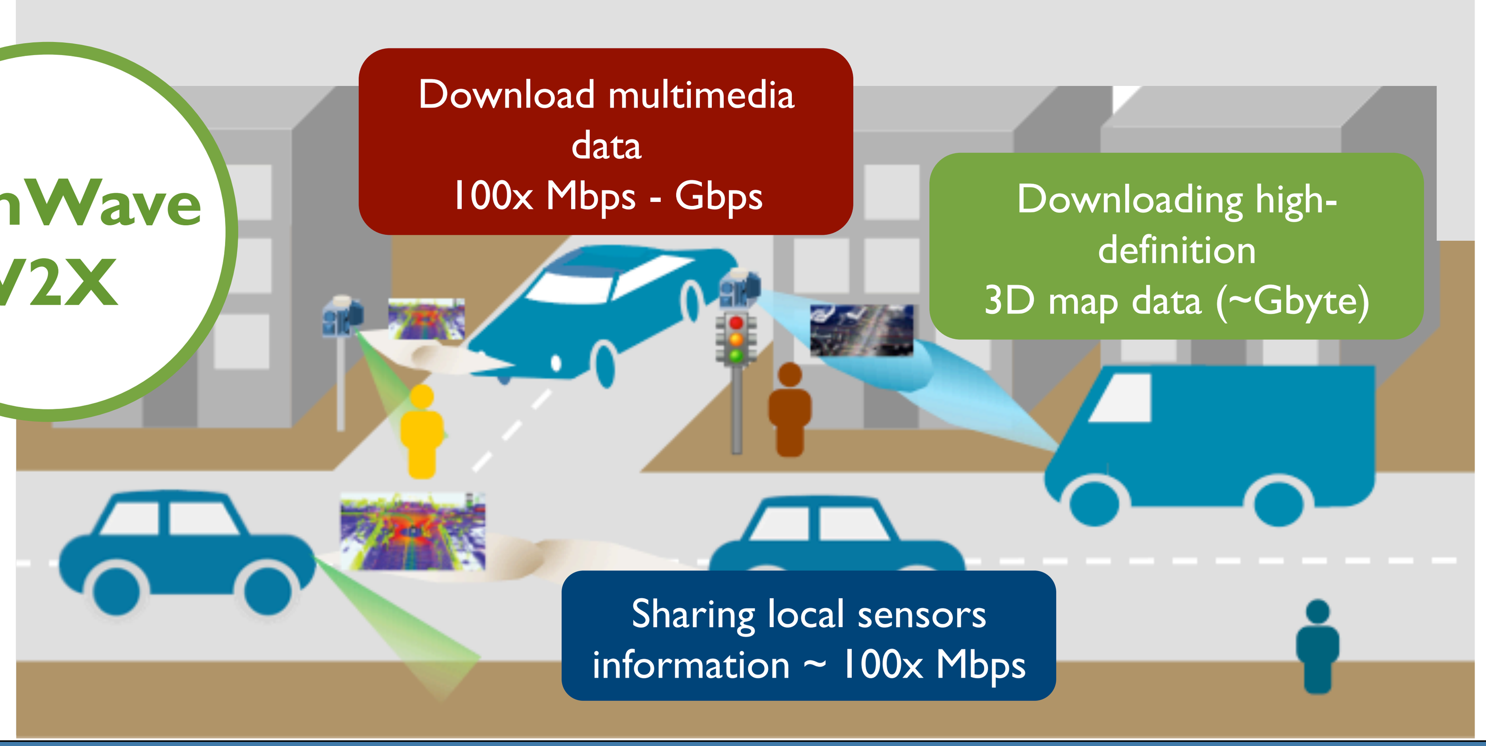
High data rate MmmWave applications

High bandwith mmWave channels are frequency selective

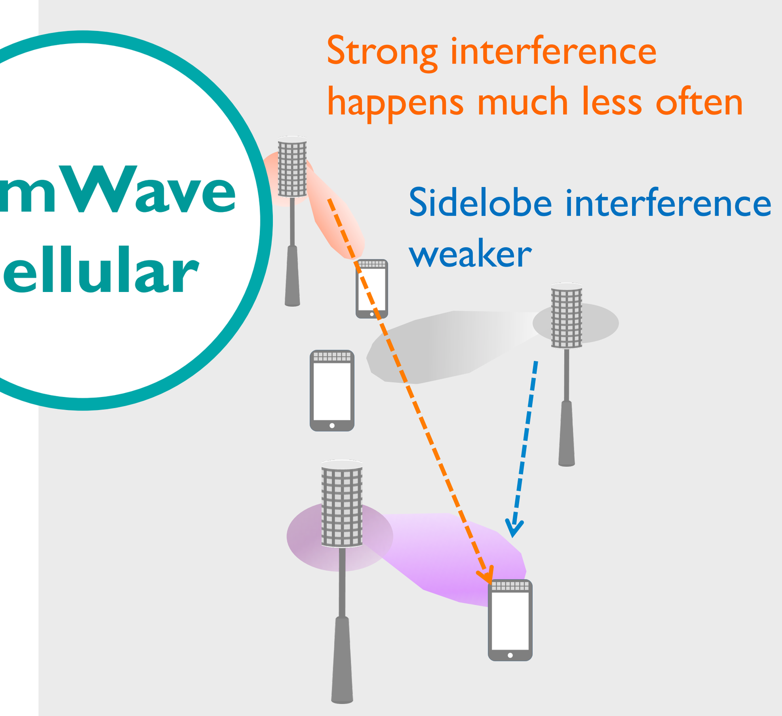
Most of prior work on SP for mmWave is narrowband

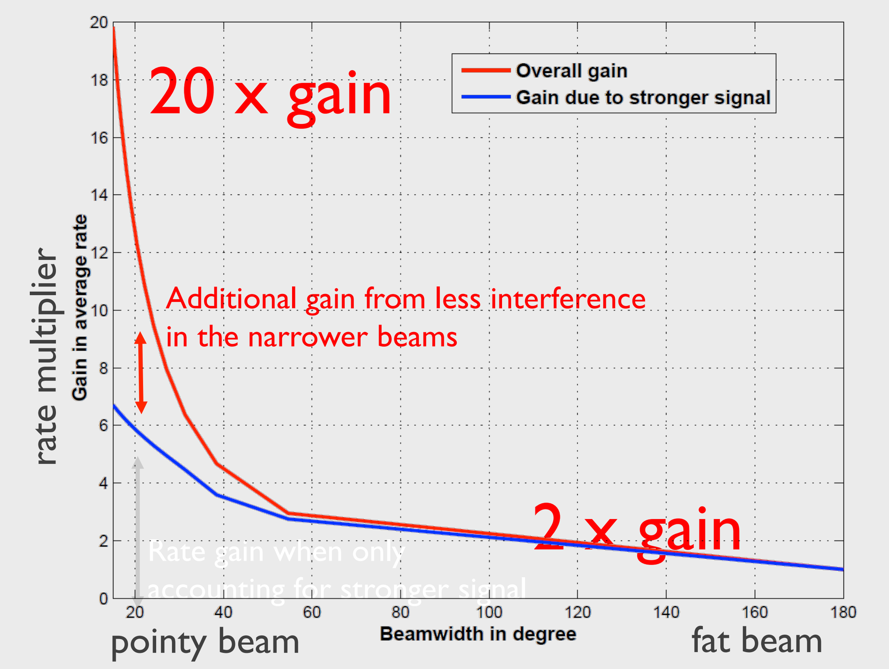
mmWave V2X



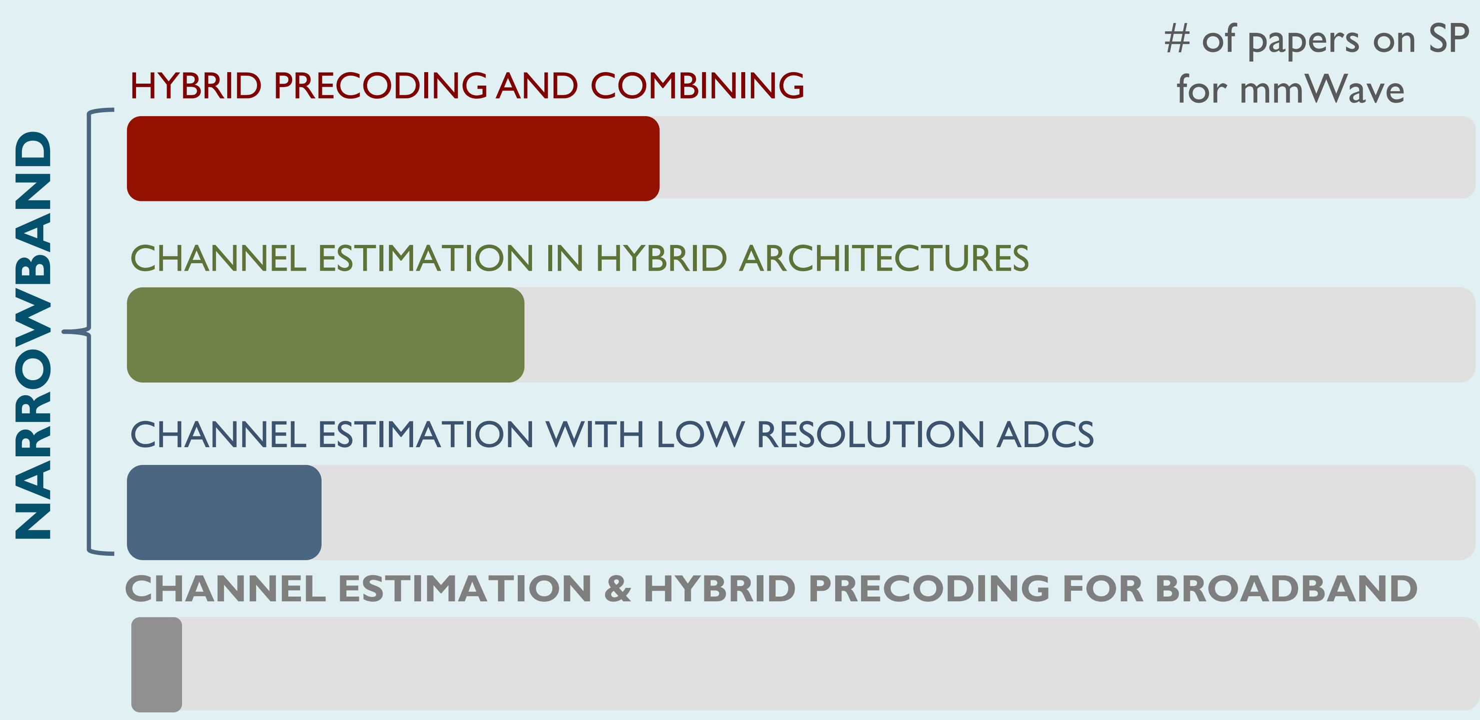
Virtual reality

mmWave cellular





Signal processing challenges @mmWave



Wideband channel model

Time domain

Pulse shaping filter evaluated at the delays of each cluster **USUALLY NEGLECTED**

sampled response for the dth delay tap

$$\mathbf{H}_d = \sqrt{\frac{N_r N_t}{L}} \sum_{\ell=1}^{L} \alpha_\ell p_{rc}(dT_s - \tau_\ell) \mathbf{a}_R(\phi_\ell)\mathbf{a}_T^*(\theta_\ell)$$

Complex gains for the L clusters

TX and RX array response vectors

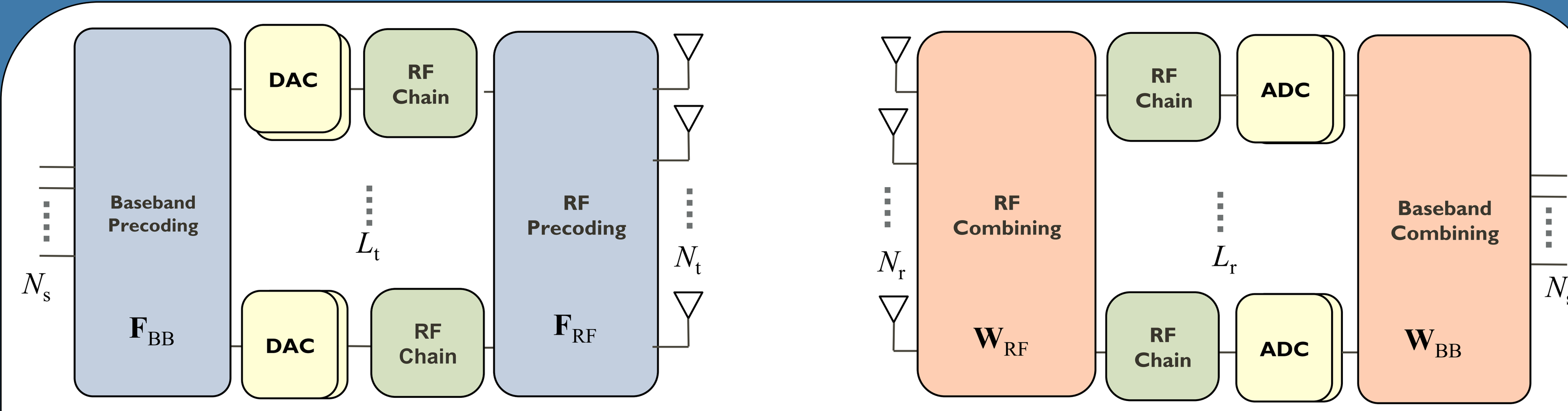
Frequency domain

N_c is the delay tap length

$$\beta_{k,\ell} = \sum_{d=0}^{N_c-1} p_{rc}(dT_s - \tau_\ell) e^{-j\frac{2\pi k d}{K}}$$

$$\boldsymbol{H}[k] = \sqrt{\frac{N_r N_t}{L}} \sum_{\ell=1}^{L} \alpha_\ell \beta_{k,\ell} \mathbf{a}_R(\phi_\ell)\mathbf{a}_T^*(\theta_\ell)$$

Freq. selective hybrid precoding



Received signal at subcarrier k → $\mathbf{y}[k] = \mathbf{H}[k]\mathbf{F}_{RF}\mathbf{F}[k]\mathbf{s}[k] + \mathbf{n}[k]$

RF precoding in the time domain – common for all subcarriers

Baseband precoding can be designed per subcarrier

Finding the precoders with perfect or imperfect CSI

Perfect CSI Design the hybrid precoders to maximize mutual information [1]

Formulation in the SU scenario

$$\left\{\mathbf{F}_{RF}^\star, \{\mathbf{F}^\star[k]\}_{k=1}^K\right\} = \arg\max_{\mathbf{F}_{RF}, \{\mathbf{F}[k]\}_{k=1}^K} \frac{1}{K}\sum_{k=1}^{K} \log_2 \left| \mathbf{I}_{N_{MS}} + \frac{\rho}{N_S} \mathbf{H}[k]\mathbf{F}_{RF}\mathbf{F}[k]\mathbf{F}[k]^*\mathbf{F}_{RF}^*\mathbf{H}[k]^* \right|$$

s.t. $[\mathbf{F}_{RF}]_{:,r} \in \mathcal{F}_{RF}, \quad r = 1, \ldots, N_{RF}$

$\mathbf{F}_{RF}\mathbf{F}[k] \in \mathcal{U}_{N_{BS}\times N_{RF}}, \quad k = 1, 2, \ldots, K.$

Assumes optimal combining at RX

RF precoders are taken from quantized codebooks (hardware constraints)

Unitary power constraint

Total power constraint also possible → $\sum_{k=1}^{K} \|\mathbf{F}_{RF}\mathbf{F}[k]\|_F^2 = K N_S$

Imperfect CSI Design the hybrid precoders from the covariance [2]

Formulation in a MU scenario

MIMO-FDM system

BB precoder for user i subband k

postcombining rx signal user for user j

$$\boldsymbol{y}_j[k] = \boldsymbol{H}_j[k] \sum_{i=1}^{U} \boldsymbol{P}_{RF}\boldsymbol{P}_{BB}^i[k]\boldsymbol{s}_i[k] + \boldsymbol{n}_j \qquad \hat{\boldsymbol{s}}_j[k] = \boldsymbol{W}_{BB}^{j,H}[k]\boldsymbol{W}_{RF}^{j,H}\boldsymbol{y}_j[k]$$

1. Design downlink hybrid combiners using covariance estimates and MSE
2. Use reciprocity to find the precoders during the uplink phase
3. Decompose the precoders combiners using an iterative method that alternates between RF and BB updates

Wideband channel estimation

Challenges

Find effective compressed estimation strategies with very low

Clear overhead comparison with beam training strategies

Compressive time domain solution [3]

$$\boldsymbol{\Gamma} = \begin{bmatrix} \mathbf{I}_{G_r G_t} \otimes \tilde{\mathbf{p}}_1^T \\ \mathbf{I}_{G_r G_t} \otimes \tilde{\mathbf{p}}_2^T \\ \vdots \\ \mathbf{I}_{G_r G_t} \otimes \tilde{\mathbf{p}}_{N_c}^T \end{bmatrix}$$

$\tilde{\mathbf{p}}_n$ has entries $\tilde{p}_n(k) \quad n = 1, 2, \cdots, N_c; \quad k = 1, 2, \cdots, G_c$

Sampled version

$p_n(\tau) = p_{rc}(n - \tau)$

Stack M measurements

Measurement 1 $\quad \mathbf{y}^{(1)} = \sqrt{\rho}\left(\mathbf{S}^{(1)} \otimes \mathbf{f}_1^T \otimes \mathbf{w}_1^*\right)\left(\mathbf{I}_{N_c} \otimes \bar{\mathbf{A}}_{tx} \otimes \mathbf{A}_{rx}\right)\boldsymbol{\Gamma}\mathbf{x} + \mathbf{e}^{(1)}$

$\vdots$

Measurement M $\quad \mathbf{y}^{(M)} = \sqrt{\rho}\left(\mathbf{S}^{(M)} \otimes \mathbf{f}_M^T \otimes \mathbf{w}_M^*\right)\left(\mathbf{I}_{N_c} \otimes \bar{\mathbf{A}}_{tx} \otimes \mathbf{A}_{rx}\right)\boldsymbol{\Gamma}\mathbf{x} + \mathbf{e}^{(M)}$

Sparse vector containing the channel coefficients

Quantized grid of AoA/AoD

Solve a sparse recovery problem

Random beamforming matrices

Dictionary with columns $\mathbf{a}_T^c(\tilde{\phi}_x) \otimes \mathbf{a}_R(\tilde{\theta}_y)$

Frequency domain solution [4]

measurements

$$\begin{bmatrix} \mathbf{r}^{(1)}[k] \\ \mathbf{r}^{(2)}[k] \\ \vdots \\ \mathbf{r}^{(M)}[k] \end{bmatrix} = \sqrt{\rho} \begin{bmatrix} \boldsymbol{\Phi}^{(1)} \\ \boldsymbol{\Phi}^{(2)} \\ \vdots \\ \boldsymbol{\Phi}^{(M)} \end{bmatrix} \boldsymbol{\Psi}\mathbf{h}_v[k] + \mathbf{n}[k]$$

$\boldsymbol{\Phi}^{(m)} = (\mathbf{f}_{tr}^{(m)})^T \otimes \mathbf{W}_{tr}^{(m)*} \in \mathbb{C}^{L_r \times N_t N_r}$

Sparse vector containing the channel coefficients

Exploit common support between subcarriers

$\boldsymbol{\Psi} = (\bar{\mathbf{A}}_T \otimes \mathbf{A}_R) \in \mathbb{C}^{N_t N_r \times G_r G_t}$

References to on going work

[1] A. Alkhateeb and R.W. Heath Jr., "Frequency selective hybrid precoding for limited feedback millimeter wave systems," IEEE Transactions on Communications, 2016

[2] José P. González-Coma, Nuria González-Prelcic, Luis Castedo and Robert W. Heath Jr., "Frequency selective multiuser hybrid precoding for mmWave systems with imperfect channel knowledge", Asilomar 2016

[3] K. Venugopal, A. Alkhateeb, N. González Prelcic, and R. W. Heath, Jr., "Channel Estimation for Hybrid Architecture Based Wideband Millimeter Wave Systems", submitted to IEEE JSAC, 2016

[4] J. Rodríguez-Fernández, K. Venugopal, N. González Prelcic, and R. W. Heath, Jr, "A Frequency-Domain Approach to Wideband Channel Estimation in Millimeter Wave Systems", submitted to ICC 2017.