D2D Resource Sharing and Beamforming

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Outline

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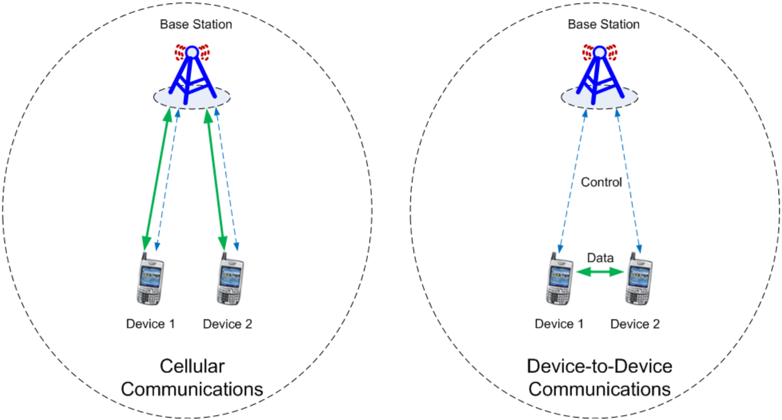
Project Outline

- This presentation discusses the **resource optimization problem** in a Device-to-Device communications network.
- The problem is examined under several different settings:
  - Single antenna, single carrier (Single-carrier SISO)
  - Single antenna, multiple carriers (Multi-carrier SISO)
  - Multiple antennas, single carrier (Single-carrier MIMO)
- Only brief summaries are presented for the SISO cases.
- The MIMO case is discussed in detail in three sub-topics:
  - Orthogonal Beamforming
  - Zero-forcing Beamforming
  - Tunable Beamforming

What is Device-to-Device (D2D) Communication?



- User Equipments (UE's) communicate directly with each other.
- D2D connections remain under the control of the base station.

D2D Link Budget I

- Assume 10 MHz bandwidth with the receiver operating at 290K.

a	Max. TX power (dBm)	24.0	
b	TX antenna gain (dBi)	0.0	
c	Body loss (dB)	0.0	
d	EIRP (dBm)	24.0	= a + b + c
e	RX UE noise figure (dB)	7.0	
f	Thermal noise (dBm)	-104.5	= k * T * B
g	Receiver noise floor (dBm)	-97.5	= e + f
h	SINR (dB)	-10.0	
i	Receiver sensitivity (dBm)	-107.5	= g + h
j	Interference margin (dB)	3.0	
k	Control channel overhead (dB)	1.0	
l	RX antenna gain (dBi)	0.0	
m	Body loss (dB)	0.0	
	Maximum path loss (dB)	127.5	= d - i - j - k + l - m

D2D Link Budget II

- Using simple a path loss model (Okumura-Hata model)

$$G_{avg} = C - 10\alpha \log_{10} r \tag{1}$$

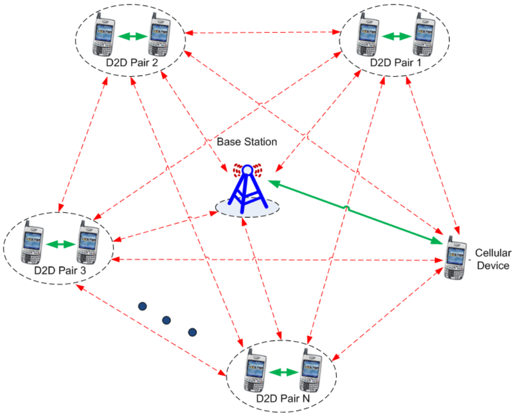
  Where C is a correction factor and $\alpha \approx 3 - 5$.

- Using $C = -15$ dB [1], corresponding to rural areas, and $\alpha = 5$ for lots of loss due to the fact both UE's are very close the the ground, the maximum range between devices can be computed to be

$$r = 10^{\frac{C - G_{avg}}{10\alpha}} = 10^{\frac{-15+127.5}{10\times 5}} = 10^{2.25} = 178m \tag{2}$$

- The D2D operating range is several hundred meters, depending on the environment and handset capabilities.

Multiple D2D Links

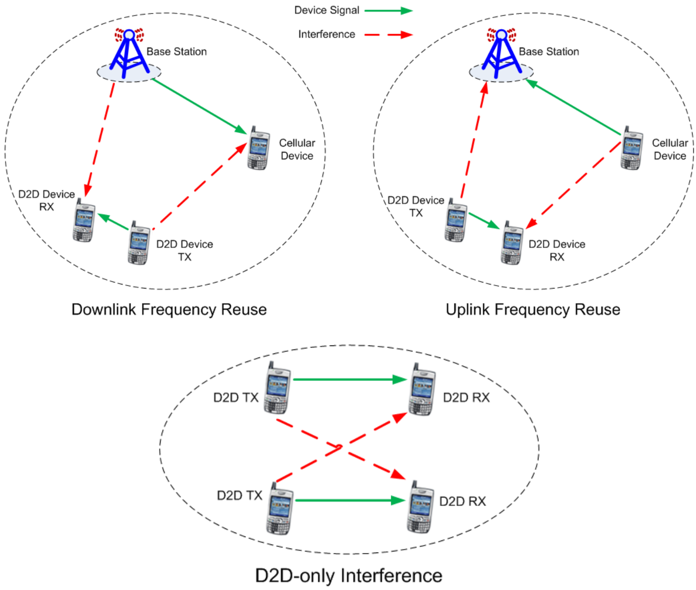


- Due to the short range of D2D communications, it is possible to have multiple D2D links sharing a common resource with little interference.

Benefits and Challenges of D2D Communications

- Benefits
  - For the UE's:
    - Better throughput
    - Lower power
    - Shorter delay
    - Transparent mode switching
  - For the system:
    - Less relay load for the base stations
    - Better channel resource reuse
  - For the service provider:
    - Easier to plan access, investment and interference coordination in a *licensed* band.
    - Resource can still be assigned to D2D in a dense network.
- Challenges
  - Peer Discovery
  - Mode Selection
  - Interference Management/Coordination

D2D Interference Scenarios



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Single-Antenna, Single-Carrier System

- The objective is to maximize the minimum SINR of the two links, Γ_c and Γ_d, subject to individual power constraints.

$$(P_c^*, P_d^*) = \arg\max_{P_c, P_d} \{\min\{\Gamma_c, \Gamma_d\}\} \text{ s.t. } 0 \leq P_c, P_d \leq P_{max} \quad \text{(P1)}$$

$$\text{Where } \Gamma_c = \frac{g_c P_c}{g_{dc} P_d + N_c}, \; \Gamma_d = \frac{g_d P_d}{g_{cd} P_c + N_d} \quad (3)$$

- The optimal solution must satisfy $P_d = P_{\max}$ or $P_c = P_{\max}$ [2].
- In either case, problem (P1) is a *quasi concave* problem in P_c or P_d.
- The solution can be obtained directly by setting $\Gamma_c = \Gamma_d$ and solving a simple quadratic equation for the power.

Single-Antenna, Multi-Carrier System

- We joint-optimize over the shared set of N sub-carriers.

$$\max_{\mathbf{x},\mathbf{y}} \min \{R_c, R_d\} \text{ s.t. } \mathbf{1}^T\mathbf{x} \le P_c^{tot},\ \mathbf{1}^T\mathbf{y} \le P_d^{tot} \qquad \text{(P2)}$$

$$R_{c,d} \triangleq \sum_{k=0}^{N-1} log_2(1 + \text{SINR}_{c,d}^{(k)}),\ x_k \triangleq P_c^{(k)},\ y_k \triangleq P_d^{(k)} \qquad (4)$$

- Rewriting problem (P2) using a *slack* variable s, we have

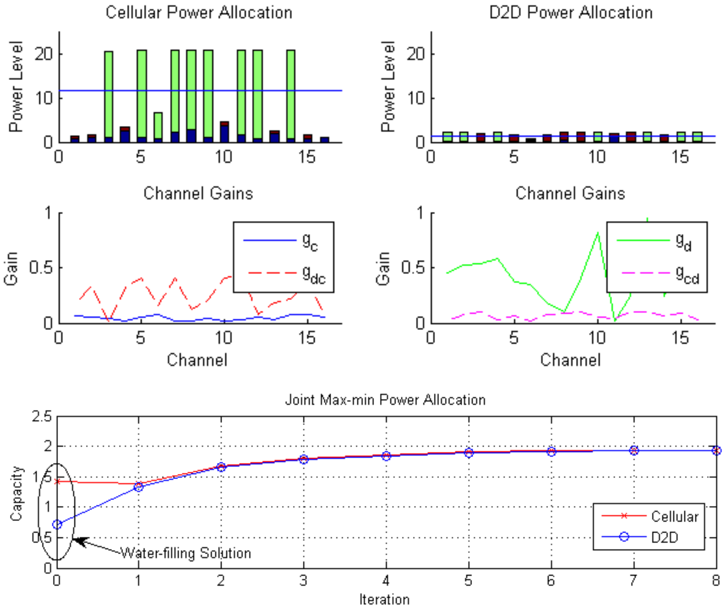
$$\max_{\mathbf{x},\mathbf{y},s} \{s\} \text{ s.t. } \mathbf{1}^T\mathbf{x} \le P_c^{tot},\ \mathbf{1}^T\mathbf{y} \le P_d^{tot} \qquad (5)$$

$$s \times \prod_{k=0}^{N-1} \frac{g_{dc}^{(k)} y_k + N_c^{(k)}}{g_{dc}^{(k)} y_k + N_c^{(k)} + g_c^{(k)} x_k} \le 1 \qquad (6)$$

$$s \times \prod_{k=0}^{N-1} \frac{g_{cd}^{(k)} x_k + N_d^{(k)}}{g_{cd}^{(k)} x_k + N_d^{(k)} + g_d^{(k)} y_k} \le 1 \qquad (7)$$

- This problem can be solved as a *geometric program* by using *monomial* approximation to the denominators of (6) and (7) [3].

Single-Antenna, Multi-Carrier System



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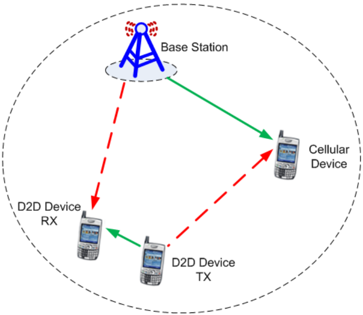
System Model I



Downlink Frequency Reuse

- We consider a downlink celular system [4] with D2D enabled under the following conditions:
  - The base station has N antennas.
  - The mobile devices have M antennas, where $M < N$.
  - Transmit and receive beamformers are used at all terminals.

System Model II

- The signals received at the D2D and cellular receivers are given by

$$y_d = \mathbf{u}_d^H \mathbf{H}_d \mathbf{v}_d \sqrt{P_d} x_d + \mathbf{u}_d^H \mathbf{H}_{cd} \mathbf{v}_c \sqrt{P_c} x_c + N_d \quad (8)$$

$$y_c = \mathbf{u}_c^H \mathbf{H}_c \mathbf{v}_c \sqrt{P_c} x_c + \mathbf{u}_c^H \mathbf{H}_{dc} \mathbf{v}_d \sqrt{P_d} x_d + N_c \quad (9)$$

  Where
  - x_c, x_d are scalar transmit signals for the cellular and D2D links
  - $\mathbf{v}_c, \mathbf{v}_d$ and $\mathbf{u}_c, \mathbf{u}_d$ are unit-norm transmit/receive beamformers
  - P_c, P_d are transmit powers
  - $\mathbf{H}_c, \mathbf{H}_d$ are MIMO channel matrices for the direct paths, $\mathbf{H}_{cd}, \mathbf{H}_{dc}$ are channel matrices for the interference paths
  - $N_c \sim \mathcal{N}(0, \sigma_c^2)$ and $N_d \sim \mathcal{N}(0, \sigma_d^2)$ are Gaussian noises.

Problem Formulation

- Consider the following joint optimization problem

$$\max_{\mathbf{u}_c,\mathbf{u}_d,\mathbf{v}_c,\mathbf{v}_d,P_c,P_d} \min\{\Gamma_c, \Gamma_d\} \tag{P3}$$

$$\text{s.t.: } 0 \le P_c \le P_c^{max},\ 0 \le P_d \le P_d^{max}$$

$$\|\mathbf{u}_c\| = 1, \|\mathbf{v}_c\| = 1, \|\mathbf{u}_d\| = 1, \|\mathbf{v}_d\| = 1$$

Where

$$\Gamma_c = \frac{|\mathbf{u}_c^H \mathbf{H}_c \mathbf{v}_c|^2 P_c}{|\mathbf{u}_c^H \mathbf{H}_{dc} \mathbf{v}_d|^2 P_d + \sigma_c^2} = \frac{\mathbf{u}_c^H (P_c \Phi_c) \mathbf{u}_c}{\mathbf{u}_c^H (P_d \Phi_{dc} + \sigma_c^2 \mathbf{I}) \mathbf{u}_c} \tag{10}$$

$$\Gamma_d = \frac{|\mathbf{u}_d^H \mathbf{H}_d \mathbf{v}_d|^2 P_d}{|\mathbf{u}_d^H \mathbf{H}_{cd} \mathbf{v}_c|^2 P_c + \sigma_d^2} = \frac{\mathbf{u}_d^H (P_d \Phi_d) \mathbf{u}_d}{\mathbf{u}_d^H (P_c \Phi_{cd} + \sigma_d^2 \mathbf{I}) \mathbf{u}_d} \tag{11}$$

$$\Phi_c = \mathbf{H}_c \mathbf{v}_c \mathbf{v}_c^H \mathbf{H}_c^H,\ \Phi_d = \mathbf{H}_d \mathbf{v}_d \mathbf{v}_d^H \mathbf{H}_d^H$$

$$\Phi_{dc} = \mathbf{H}_{dc} \mathbf{v}_d \mathbf{v}_d^H \mathbf{H}_{dc}^H,\ \Phi_{cd} = \mathbf{H}_{cd} \mathbf{v}_c \mathbf{v}_c^H \mathbf{H}_{cd}^H$$

- Problem (P3) is a *non convex* optimization problem.

D2D Optimization Procedure

- For the performance/complexity tradeoffs under D2D settings, we consider the following optimization procedure:
  1. The D2D link ignores the interference from the cellular link and optimizes its own SNR using *Maximal Ratio Transmission (MRT)* [5].

$$\gamma_d = \max_{\mathbf{u}_d, \mathbf{v}_d, P_d} \Gamma_d = \frac{|\mathbf{u}_d^H \mathbf{H}_d \mathbf{v}_d|^2 P_d}{\sigma_d^2} \text{ subject to: } 0 \leq P_d \leq P_d^{max} \quad (12)$$

  2. Given $\mathbf{v}_d$, and P_d, the base station solves for $\mathbf{u}_c, \mathbf{v}_c, P_c$ by minimizing the interference to the D2D link and maximizing the cellular link SINR Γ_c.

$$\min_{\mathbf{v}_c} \left(\mathbf{v}_c^H \mathbf{H}_{cd}^H \mathbf{u}_d\right) \left(\mathbf{u}_d^H \mathbf{H}_{cd} \mathbf{v}_c\right) \quad (13)$$

$$\text{subject to } \|\mathbf{v}_c\| = 1$$

- *Zero* interference can be achieved when
  - $\mathbf{v}_c \perp \left(\mathbf{H}_{cd}^H \mathbf{u}_d\right)$: Orthogonal beamforming.
  - $\mathbf{H}_{cd} \mathbf{v}_c = \mathbf{0}$: Zero-forcing beamforming.

Orthogonal Beamforming I

- In this case, $\mathbf{v}_c$ must lie in the *orthogonal complement* space of $\mathbf{H}_{cd}^H\mathbf{u}_d$, denoted as $\mathbf{W}^\perp$ with dimension $N-1$.
- Let $\mathcal{B} = \{\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_{N-1}\}$ be an ortho-normal basis of $\mathbf{W}^\perp$, then $\mathbf{v}_c$ must be a linear combination of $\mathcal{B}$.

$$\mathbf{v}_c = [\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_{N-1}]\mathbf{x} = \mathbf{K}\mathbf{x} \tag{14}$$

$$\Phi_c = \mathbf{H}_c\mathbf{v}_c\mathbf{v}_c^H\mathbf{H}_c^H = \mathbf{H}_c\mathbf{K}\mathbf{x}\mathbf{x}^H\mathbf{K}^H\mathbf{H}_c^H \tag{15}$$

Where $\mathbf{x} = [x_1, x_2, \ldots, x_{N-1}]^T$

- We want to maximize the SINR Γ_c for the cellular link:

$$\Gamma_c^{max} = \max_{\mathbf{x},\mathbf{u}_c} \Gamma_c = \max_{\mathbf{x}} \max_{\mathbf{u}_c} \frac{\mathbf{u}_c^H\left(\mathbf{H}_c\mathbf{K}\mathbf{x}\mathbf{x}^H\mathbf{K}^H\mathbf{H}_c^H\right)\mathbf{u}_c}{\mathbf{u}_c^H B\mathbf{u}_c} \tag{16}$$

s.t: $\mathbf{x}^H\mathbf{x} = 1$

Where $B = (P_d/P_c)\Phi_{dc} + (\sigma_c^2/P_c)\mathbf{I}$ and $\Phi_{dc} = \mathbf{H}_{dc}\mathbf{v}_d\mathbf{v}_d^H\mathbf{H}_{dc}^H$

Orthogonal Beamforming II

- Let $\mathbf{y} \triangleq B^{\frac{1}{2}}\mathbf{u}_c$, we have

$$\Gamma_c^{max} = \max_{\mathbf{x}} \max_{\mathbf{y}} \frac{\mathbf{y}^H \left(B^{-\frac{1}{2}}\right)^H \mathbf{H}_c\mathbf{K}\mathbf{x}\mathbf{x}^H\mathbf{K}^H\mathbf{H}_c^H B^{-\frac{1}{2}}\mathbf{y}}{\mathbf{y}^H\mathbf{y}} \quad (17)$$
$$\text{s.t: } \mathbf{x}^H\mathbf{x} = 1$$

- Without changing the problem, we can constrain $\|\mathbf{y}\| = 1$ and get

$$\Gamma_c^{max} = \max_{\mathbf{x}} \max_{\mathbf{y}} \mathbf{y}^H \left(B^{-\frac{1}{2}}\right)^H \mathbf{H}_c\mathbf{K}\mathbf{x}\mathbf{x}^H\mathbf{K}^H\mathbf{H}_c^H B^{-\frac{1}{2}}\mathbf{y} \quad (18)$$
$$\text{s.t: } \mathbf{x}^H\mathbf{x} = 1, \mathbf{y}^H\mathbf{y} = 1$$
$$\Leftrightarrow \Gamma_c^{max} = \max_{\mathbf{z}} \{\max_{\mathbf{y}} \mathbf{y}^H\mathbf{z}\mathbf{z}^H\mathbf{y}\} \quad (19)$$
$$\text{s.t: } \mathbf{x}^H\mathbf{x} = 1, \mathbf{y}^H\mathbf{y} = 1$$
$$\text{Where } \mathbf{z} \triangleq \left(B^{-\frac{1}{2}}\right)^H \mathbf{H}_c\mathbf{K}\mathbf{x}$$

Orthogonal Beamforming III

- The solution to the inner maximization of (19) is simply $\mathbf{y} = \frac{\mathbf{z}}{\|\mathbf{z}\|}$. Consequently, we have

$$\Gamma_c^{max} = \max_{\mathbf{z}} \frac{\mathbf{z}^H \mathbf{z} \mathbf{z}^H \mathbf{z}}{\mathbf{z}^H \mathbf{z}} = \max_{\mathbf{z}} \mathbf{z}^H \mathbf{z} = \max_{\mathbf{x}} \{\mathbf{x}^H \mathbf{A} \mathbf{x}\} \quad (20)$$

$$\text{s.t. } \mathbf{x}^H \mathbf{x} = 1$$

$$\text{Where } \mathbf{A} = \mathbf{K}^H \mathbf{H}_c^H B^{-1} \mathbf{H}_c \mathbf{K}$$

- Problem (20) can be recognized as finding the max eigen value $\lambda_{max}(\mathbf{A})$, which can be solved for $\mathbf{x}$. Once $\mathbf{x}$ is found, we can obtain $\mathbf{v}_c$ from (14) and then solve for $\mathbf{u}_c$ as follows:

$$\mathbf{u}_c = B^{-\frac{1}{2}} \mathbf{y} = B^{-\frac{1}{2}} \frac{\mathbf{z}}{\|\mathbf{z}\|} \quad (21)$$

$$\text{Where } \mathbf{z} = \left(B^{-\frac{1}{2}}\right)^H \mathbf{H}_c \mathbf{K} \mathbf{x} \quad (22)$$

Zero-forcing Beamforming I

- When $N > M$, it is possible to impose *zero-forcing* constraint on $\mathbf{v}_c$ in order to eliminate interference to the D2D link.
- For the cellular link, we maximize its SINR and get the following optimization problem:

$$\max_{\mathbf{v}_c,\mathbf{u}_c} \Gamma_c = \max_{\mathbf{v}_c} \max_{\mathbf{u}_c} \frac{\mathbf{u}_c^H \Phi_c \mathbf{u}_c}{\mathbf{u}_c^H B \mathbf{u}_c} \tag{23}$$

$$\text{subject to: } \mathbf{H}_{cd}\mathbf{v}_c = 0 \tag{24}$$

$$\|\mathbf{v}_c\| = 1 \tag{25}$$

- Constraint (24) means $\mathbf{v}_c$ lies in the null space of $\mathbf{H}_{cd}$. Let $\mathbf{H}_{cd} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H$ be the singular decomposition of $\mathbf{H}_{cd}$. A basis of the null space of $\mathbf{H}_{cd}$ is the last $(N - R)$ columns of $\mathbf{V}$, denoted as $\mathbf{v}_{R+1}, \mathbf{v}_{R+2}, \ldots, \mathbf{v}_N$, where R is the rank of $\mathbf{H}_{cd}$.

Zero-forcing Beamforming II

- As a result, $\mathbf{v}_c$ is a linear combination of this basis:

$$\mathbf{v}_c = [\mathbf{v}_{R+1}, \mathbf{v}_{R+2}, \ldots, \mathbf{v}_N]\mathbf{x} = \mathbf{K}'\mathbf{x} \quad (26)$$

$$\Phi_c = \mathbf{H}_c \mathbf{v}_c \mathbf{v}_c^H \mathbf{H}_c^H = \mathbf{H}_c \mathbf{K}' \mathbf{x}\mathbf{x}^H \mathbf{K}'^H \mathbf{H}_c^H \quad (27)$$

Where $\mathbf{x} = [x_1, x_2, \ldots, x_{N-R}]^T$

- Consequently, we have:

$$\max_{\mathbf{x}, \mathbf{u}_c} \frac{\mathbf{u}_c^H \left(\mathbf{H}_c \mathbf{K}' \mathbf{x}\mathbf{x}^H \mathbf{K}'^H \mathbf{H}_c^H \right) \mathbf{u}_c}{\mathbf{u}_c^H B \mathbf{u}_c} \quad (28)$$

subject to: $\|\mathbf{x}\| = 1$

- Problem (28) is identical to problem (16) in the *Orthogonal Beamforming* section with $\mathbf{K}'$ instead of $\mathbf{K}$.
- Hence, the solution $\mathbf{x}$ must be the max eigen vector corresponding to $\lambda_{max}(\mathbf{A}')$, where $\mathbf{A}' = \mathbf{K}'^H \mathbf{H}_c^H B^{-1} \mathbf{H}_c \mathbf{K}'$. The solutions for $\mathbf{u}_c$ and $\mathbf{v}_c$ can be obtained in the same way.

Tunable Beamforming I

- The zero-forcing solution can cause poor performance for the cellular link. Thus, it may be advantageous to add a *tunable* component outside of the null-space of $\mathbf{H}_{cd}$.

$$\mathbf{v}_c = [\mathbf{v}_R, \mathbf{v}_{R+1}, \mathbf{v}_{R+2}, \ldots, \mathbf{v}_N] \begin{bmatrix} t \\ \mathbf{x} \end{bmatrix} = \mathbf{K}''\mathbf{x}' \quad (29)$$

$$\Phi_c = \mathbf{H}_c \mathbf{v}_c \mathbf{v}_c^H \mathbf{H}_c^H = \mathbf{H}_c \mathbf{K}'' \mathbf{x}' \mathbf{x}'^H \mathbf{K}''^H \mathbf{H}_c^H \quad (30)$$

Where $\mathbf{v}_R$ corresponds to the smallest singular value of $\mathbf{H}_{cd}$, and $t \in [0, 1]$ is the *tuning* parameter.

- For a fixed t, we can solve for $\mathbf{x}$ and $\mathbf{u}_c$ by maximizing the SINR:

$$\Gamma_c^{max} = \max_{\mathbf{x}, \mathbf{u}_c} \Gamma_c = \max_{\mathbf{x}} \max_{\mathbf{u}_c} \frac{\mathbf{u}_c^H \left(\mathbf{H}_c \mathbf{K}'' \mathbf{x}' \mathbf{x}'^H \mathbf{K}''^H \mathbf{H}_c^H \right) \mathbf{u}_c}{\mathbf{u}_c^H B \mathbf{u}_c} \quad (31)$$

s.t: $\mathbf{x}'^H \mathbf{x}' = 1$

Tunable Beamforming II

- Following similar steps in the *Orthogonal Beamforming* section, we arrive at

$$\Gamma_c^{max} = \max_{\mathbf{x}} \{\mathbf{x}'^H \mathbf{A}'' \mathbf{x}'\} \tag{32}$$

$$\text{s.t. } \mathbf{x}'^H \mathbf{x}' = 1$$

$$\text{Where } \mathbf{A}'' = \mathbf{K}''^H \mathbf{H}_c^H B^{-1} \mathbf{H}_c \mathbf{K}'' \tag{33}$$

- Let $\mathbf{A}'' = \begin{bmatrix} a_{11} & \mathbf{q}^H \\ \mathbf{q} & \mathbf{Q} \end{bmatrix}$, we get

$$\Gamma_c^{max} = \max_{\mathbf{x}} \left\{\mathbf{x}^H \mathbf{Q} \mathbf{x} + (\mathbf{q}^H \mathbf{x} + \mathbf{x}^H \mathbf{q})t + a_{11} t^2\right\} \tag{P4}$$

$$\text{Subject to: } \mathbf{x}^H \mathbf{x} = (1 - t^2) \tag{34}$$

Tunable Beamforming III

- Problem (P4) can be solved using Lagrange method with the help of Wirtinger calculus. The solution is

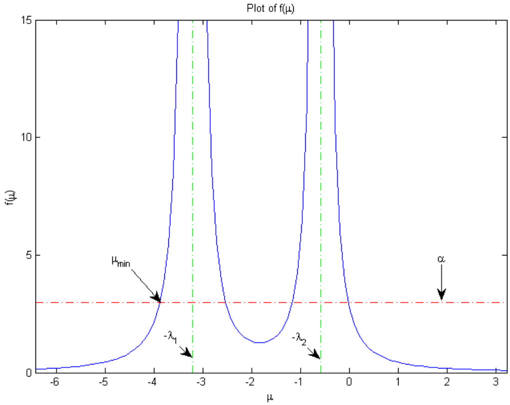
$$\mathbf{x} = -t(\mathbf{Q} + \mu\mathbf{I})^{-1}\mathbf{q} \tag{35}$$

- Here μ is the minimum real solution of the following equation

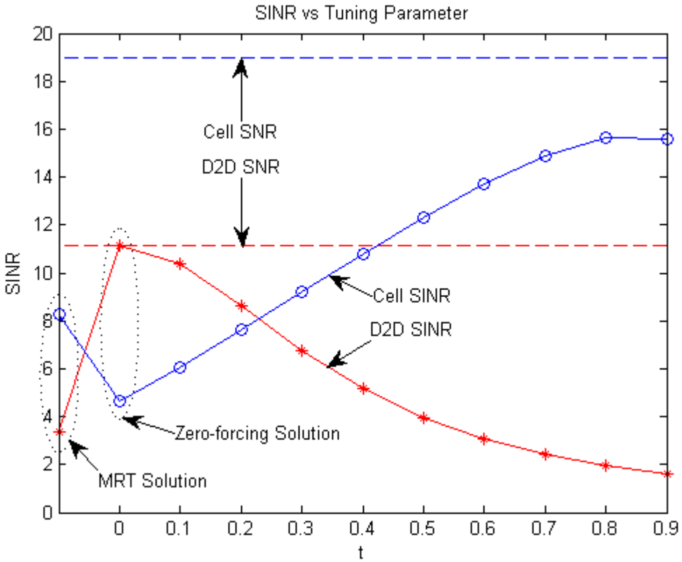
$$f(\mu) \triangleq \sum_{i=1}^{k} \frac{|p_i|^2}{(\lambda_i + \mu)^2} = \alpha \tag{36}$$

Where $\mathbf{Q} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H$ is an eigen-value decomposition of $\mathbf{Q}$, $\mathbf{\Lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \ldots, \lambda_k)$, $k = \mathrm{rank}(\mathbf{Q})$, $\alpha = \frac{1-t^2}{t^2}$, and $\mathbf{p} \triangleq \mathbf{U}^H\mathbf{q} = [p_1, p_2, \ldots, p_k]^T$.

Tunable Beamforming IV



Simulation Results



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