Ressource Allocation Schemes for D2D Communications

Mohamad Assaad
Laboratoire des Signaux et Systèmes (L2S), CentraleSupélec, Gif sur Yvette, France.

Indo-french Workshop on D2D Communications in 5G and IoT Networks - June 2016

Outline

Outline

General Introduction

- Future 5G networks must support the 1000-fold increase in traffic demand
- New physical layer techniques, e.g. Massive MIMO, Millimeter wave (mmWave)
- New network architecture
- Local caching of popular video traffic at devices and RAN edge
- Network topology
- Device-to-Device (D2D) communications

General Introduction

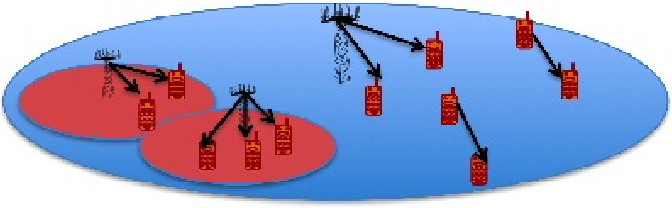


Figure: Wireless network

Resource Allocation in Wireless Networks

- Resource Allocation improves the network performance
- Resources: slots, channels, power, beamformers,...
- Hetnets architecture (small cells, macro cells, D2D)
- Existence/Non-existence of a central entity that can handle the allocation (e.g. D2D) and the amount of information exchange (signaling) between transmitters.
- Connectivity of the nodes (e.g. D2D communication).
- Services: voice, video streaming, interactive games, smart maps, ...
- Typical Utility functions: throughput, outage, packet error rate, transmit power,...
- Availability of the system state information (e.g. CSI).
- Low signaling overhead, low complexity solutions

Example of System Model

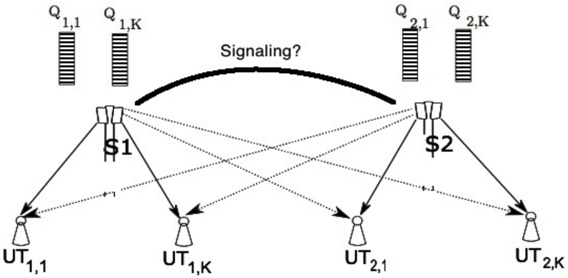


Figure: System Model

Existing Formulations of the Beamforming Allocation Problem

- Usually we define a continuous and nondecreasing function $f_{i,j}$ w.r.t. SINR (e.g. $Log(1+\Lambda_{i,j})$)
- The utility of the network is $g\left(f_{1,1},...,f_{i,j},...\right)$ where g is continuous and nondecreasing w.r.t to each $f_{i,j}$
- Two main issues: complexity and signaling overhead (centralized/decentralized)

$$\begin{aligned} \max_{\mathbf{w}_{i,j}\ \forall i,j} \quad & g\left(f_{1,1},...,f_{i,j},...\right) \\ s.t. \quad & h\left(\Lambda_{1,1},...,\Lambda_{i,j},...\right) \leq 0 \end{aligned} \tag{1}$$

Existing Formulations of the Beamforming Allocation Problem

- Examples:
  - Sum or weighted sum: $\sum_{i,j} f_{i,j}(\Lambda_{i,j})$
  - Proportional Fairness: $\sum_{i,j} log\left(f_{i,j}(\Lambda_{i,j})\right)$
  - MaxMin Fairness: $\max_{\mathbf{w}_{i,j}\ \forall i,j} \min_{i,j} f_{i,j}(\Lambda_{i,j})$
- Constraint $h\left(\Lambda_{1,1}, ..., \Lambda_{i,j}, ...\right) \leq 0$
  - $\Lambda_{i,j}^{\mathrm{DL}} \geq \gamma_{i,j} \qquad \forall i, j$: Not convex (but can be reformulated)
  - $\sum_j \mathbf{w}_{i,j}^H \mathbf{w}_{i,j} \leq P_{max}^i$: convex

Complexity of Optimization Problems

- Constraint $\Lambda_{i,j}^{\text{DL}} \geq \gamma_{i,j} \quad \forall i, j$; utility: $\sum_{i,j} \mathbf{w}_{i,j}^H \mathbf{w}_{i,j}$
- Constraint $\sum_j \mathbf{w}_{i,j}^H \mathbf{w}_{i,j} \leq P_{max}^i$; Other utility functions

Table: Complexity

Objective function	**MIMO**	**Single Antenna**
Weighted Sum	NP-hard	NP-hard
Proportional Fairness	NP-hard	Convex
MaxMin Fair	Quasi-Convex	Quasi-Convex
Harmonic Mean	NP-hard	Convex
Sum Power	Convex	Linear

Some references

- M. Bengtsson, B. Ottersten, "Optimal Downlink Beamforming Using Semidefinite Optimization," Proc. Allerton, 1999.
- A. Wiesel, Y. Eldar, and S. Shamai, "Linear precoding via conic optimization for fixed MIMO receivers," IEEE Trans. on Signal Processing, 2006.
- W. Yu and T. Lan, "Transmitter optimization for the multi-antenna downlink with per-antenna power constraints," IEEE Trans. on Signal Processing, 2007.
- E. Bjornson and E. Jorswieck, Optimal Resource Allocation in Coordinated Multi-Cell Systems, Foundations and Trends in Communications and Information Theory, 2013.
- Liu, Y.-F., Dai, Y.-H. and Luo, Z.-Q., "Coordinated Beamforming for MISO Interference Channel: Complexity Analysis and Efficient Algorithms," Accepted for publication in IEEE Transactions on Signal Processing, November 2010.
- Shi, Q.J., Razaviyayn, M., He, C. and Luo, Z.-Q., "An Iteratively Weighted MMSE Approach to Distributed Sum-Utility Maximization for a MIMO Interfering Broadcast Channel," IEEE Transactions on Signal Processing, 2011.
- N. Ul Hassan and M. Assaad, "Low Complexity Margin adaptive resource allocation in Downlink MIMO-OFDMA systems," IEEE Transactions on Wireless Communications, July 2009.
- etc...

Outline

Energy Efficient Beamforming Allocation [1]

- Hetnets architecture
- Delay tolerant traffic (flexibility to dynamically allocate resources over the fading channel states)
- Decentralized Solution (Lyapunov Optimization)
- Simple online solutions based only on the current knowledge of the system state
- Only local knowledge of CSI is required
- Does not require a-priori the knowledge of the statistics of the random processes in the system
- Joint design of feedback and beamforming

[1] S. Lakshminaryana, M. Assaad and M. Debbah, "Energy Efficient Cross Layer Design in MIMO Systems," in IEEE JSAC, Special issue on Hetnets, 33 (10), pp. 2087-2103, Oct. 2015.

Problem Formulation

- The transmission power by each transmitter $P_i[t] = \sum_{j=1}^{K} \mathbf{w}_{i,j}^H[t]\mathbf{w}_{i,j}[t],\ i = 1, \ldots, N.$
- The optimization problem is to minimize the time average power subject to time average QoS constraint

$$\min \quad \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E}\Big[\sum_{i=1}^{N} P_i[t]\Big] \tag{2}$$

$$s.t. \quad \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E}\left[\gamma_{i,j}[t]\right] \geq \lambda_{i,j}, \qquad \forall i, j \tag{3}$$

$$\sum_{j=1}^{K} \mathbf{w}_{i,j}^H[t]\mathbf{w}_{i,j}[t] \leq P_{\text{peak}} \qquad \forall i, t \tag{4}$$

where P_{peak} is the peak power

Static Problem

- Static Problem

$$\min \quad \sum_{i,j} \mathbf{w}_{i,j}^H \mathbf{w}_{i,j} \tag{5}$$

$$s.t. \quad \frac{|\mathbf{w}_{i,j}^H \mathbf{h}_{i,i,j}|^2}{\sum_{\substack{(n,k)\\ \neq (i,j)}} |\mathbf{w}_{n,k}^H \mathbf{h}_{n,i,j}|^2 + \sigma^2} \geq \gamma_{i,j}, \qquad \forall i,j \tag{6}$$

$$\tag{7}$$

where $\gamma_{i,j}$ is the instantaneous target SINR of $\mathrm{UT}_{i,j}$.

Lyapunov Optimization

- Suboptimal solution using Lyapunov optimization approach [2].
- Lyapunov vs. MDP base approach
- Nonconvex static problems but can be solved using SDP
- The complexity of our solution is at most $O(N * N_t^3)$. (usually $O(N + N_t^2)^{3.5}$ for SDP)
- Our solution is distributed (based on local CSI)
- The transmitters have to exchange the virtual queues (signaling overhead « CSIs)

Main Result

Optimality gap: $O(C_1/V)$*; Delay:* $O(V)$

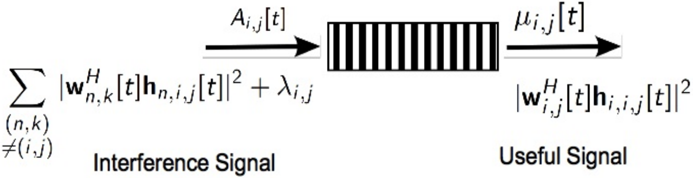
[2] M. Neely, Stochastic Network Optimization with Application to Communication and Queueing Systems. Morgan & Claypool, 2010.

Lyapunov Optimization - More details

- The QoS metric which we denote by $\gamma_{i,j}[t]$ is

$$\gamma_{i,j}[t] = |\mathbf{w}_{i,j}^H[t]\mathbf{h}_{i,i,j}[t]|^2 - \nu_{i,j} \sum_{\substack{(n,k)\\ \neq(i,j)}} |\mathbf{w}_{n,k}^H[t]\mathbf{h}_{n,i,j}[t]|^2 \quad (8)$$

- Virtual queue evolves as follows $Q_{i,j}[t+1] = \max\left(Q_{i,j}[t] - \mu_{i,j}[t], 0\right) + A_{i,j}[t]$ where $A_{i,j}[t] = \nu_{i,j} \sum_{\substack{(n,k)\\ \neq(i,j)}} |\mathbf{w}_{n,k}^H[t]\mathbf{h}_{n,i,j}[t]|^2 + \lambda_{i,j}$ and $\mu_{i,j}[t] = |\mathbf{w}_{i,j}^H[t]\mathbf{h}_{i,i,j}[t]|^2$



Queue Model

- Let $\mathbf{Q}(t)$ a discrete time queueing system with K queues.
- For each queue i, $a_i(t)$ and $r_i(t)$ denote the arrival and departure processes
- Arrivals occur at the end of slot t
- The $\mathbf{Q}(t)$ process evolves according to the following discrete time dynamic:

$$Q_i(t+1) = [Q_i(t) - r_i(t)]^+ + a_i(t) \tag{9}$$

- The time average expected arrival process satisfies
  - There exists $0 < \lambda_i < \infty$ such that

$$\lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\left(a_i(\tau)\right) = \lambda_i \tag{10}$$

  - There exists $0 < A_{max} < \infty$ such that $\forall\ t$

$$\mathbb{E}\{a_i^2(t)|\Omega[t]\} \leq A_{max} \tag{11}$$

  - $\Omega[t]$ represents all events (or the history) up to time t
- Similar assumptions for the departure process $r_i(t)$ ($r_i(t) \leq r_{max}$).

Queue Stability

Definition

A discrete time process $\mathbf{Q}(t)$ is rate stable if

$$\lim_{t\to\infty} \frac{1}{t}\mathbf{Q}(t) = 0 \qquad w.p.1$$

-

Definition

A discrete time process $\mathbf{Q}(t)$ is mean rate stable if

$$\lim_{t\to\infty} \frac{1}{t}\mathbb{E}\left[\mathbf{Q}(t)\right] = 0$$

-

Definition

A discrete time process $\mathbf{Q}(t)$ is strongly stable if

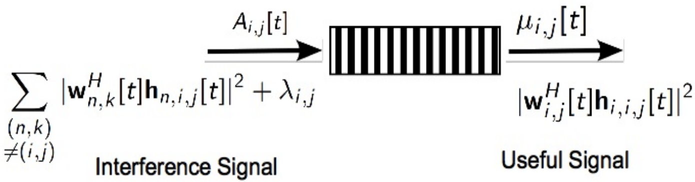
$$\lim_{t\to\infty} \sup \frac{1}{t}\sum_{\tau=1}^{t}\mathbb{E}\left[\mathbf{Q}(\tau)\right] < \infty$$

Lyapunov Optimization - More details

- The notion of strong stability of the virtual queue is given as $\sum_{i,j} \bar{Q}_{i,j}[t] < \infty$.
- Strong stability of the queues implies

$$\bar{A}_{i,j}[t] - \bar{\mu}_{i,j}[t]] \leq 0 \qquad \forall i,j. \tag{12}$$

- Virtual Queue stability implies that the time average constraint is satisfied
- Modified optimization problem - Minimize energy expenditure subject to virtual queue-stability



Lyapunov Optimization - More details

- $V(\mathbf{Q}[t]) = \frac{1}{2}\sum_{i,j}(Q_{i,j}[t])^2$. The Lyapunov function is a scalar measure of the aggregate queue-lengths in the system. We define the one-step conditional Lyapunov drift as

$$\Delta(\mathbf{Q}[t]) = \mathbb{E}\Big[V(\mathbf{Q}[t+1])) - V(\mathbf{Q}[t])|\mathbf{Q}[t]\Big] \tag{13}$$

- Lyapunov Optimization [Neely2006] - If there exist constants $B > 0, \epsilon > 0, V > 0$ such that for all timeslots t we have,
  $\Delta(\mathbf{Q}[t]) + V\mathbb{E}\Big[\sum_i P_i(t)|\mathbf{Q}[t]\Big] \leq B - \epsilon\sum_{i,j} Q_{i,j}(t) + VP_{inf}$
- Time average energy expenditure is bounded distance from P_{inf}
- Allows us to consider the result of queuing stability and performance optimization using a single drift analysis.

Lyapunov Optimization - Decentralized Solution

- Each BS must solve the optimization problem given by

$$\begin{aligned} \max_{\mathbf{w}} \quad & \sum_j \mathbf{w}_{i,j}^H \mathbf{A}_{i,j} \mathbf{w}_{i,j} \\ s.t. \quad & \sum_j \mathbf{w}_{i,j}^H \mathbf{w}_{i,j} \leq P_{\text{peak}}. \end{aligned} \tag{14}$$

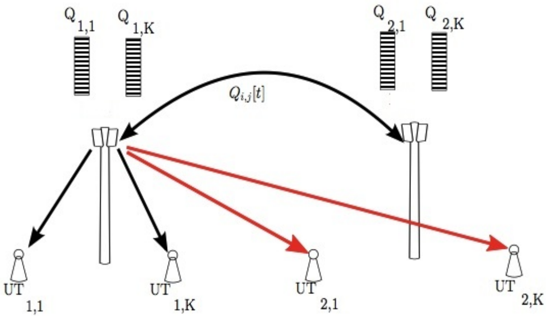
  where the matrix $\mathbf{A}_{i,j} = Q_{i,j}\mathbf{H}_{i,i,j} - \sum_{\substack{(n,k) \\ \neq (i,j)}} \nu_{n,k} Q_{n,k} \mathbf{H}_{i,n,k} - V\mathbf{I}$ and $\mathbf{H}_{i,n,k} = \mathbf{h}_{i,n,k}\mathbf{h}_{i,n,k}^H$.

- $$P_{i,j}^{\text{opt}} = \begin{cases} P_{\text{peak}} & \text{if } j = j^* \text{and } \lambda^{\max}(\mathbf{A}_{i,j^*}) > 0 \\ 0 & \text{else.} \end{cases} \tag{15}$$

  $j^* = \arg\max_j \lambda^{\max}(\mathbf{A}_{i,j})$.

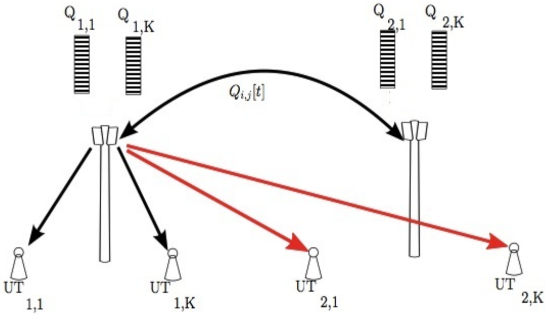
Lyapunov Optimization - Decentralized Solution

- The transmitters have to exchange the queue-length information
- No CSI exchange required



Lyapunov Optimization - Decentralized Solution

- The virtual queue is strongly stable and for any $V \geq 0$, the time average queue-length satisfies $\sum_{i,j} \bar{Q}_{i,j}^{\text{opt}}[t] \leq \frac{C_1 + VNKP_{\text{peak}}}{\epsilon}$ and the time average energy expenditure yields, $\sum_{i=1}^{N} \bar{P}_i^{\text{opt}}[t] \leq P_{\text{inf}} + \frac{C_1}{V}$.



Delayed Queues

- The transmitters exchange the queue-length information with a delay of $\tau < \infty$ time slots.
- Each transmitter i knows $Q_{i,j}[t]$ $\forall j$ and $Q_{n,k}[t-\tau]$, $\forall n \neq i, k$.

Main Result

Optimality gap: $O((C_1 + C_2)/V)$*; Delay:* $O(V)$

Lemma

There exists a $0 \leq C_2 < \infty$ *independent of the current queue-length* $Q_{i,j}[t]$, $\forall i, j$ *such that,*

$$\sum_{i,j} Tr(\mathbf{A}_{i,j}[t]\mathbf{W}^{opt}_{i,j}[t]) \leq \sum_{i,j} Tr(\mathbf{A}_{i,j}[t]\mathbf{W}^{del}_{i,j}[t]) + C_2 \; \forall t. \tag{16}$$

Numerical Result I

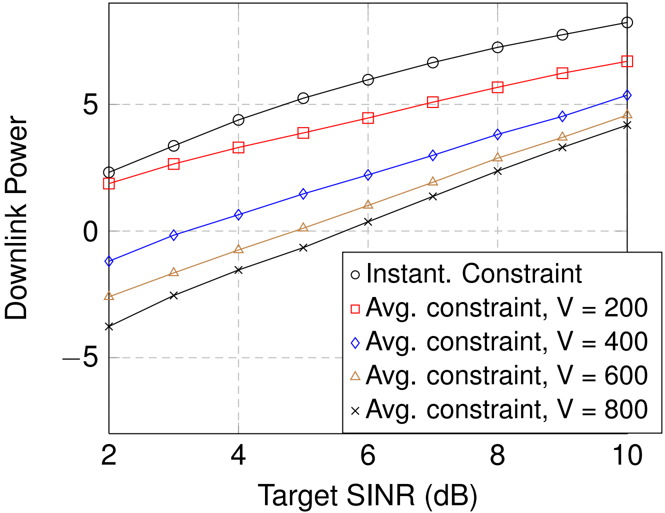


Figure: each transmitter is connected to two UTs, $N_t = 5$,

Numerical Results II

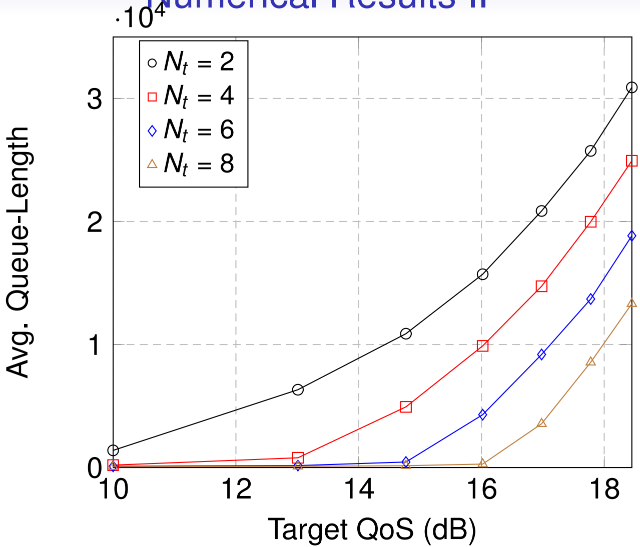


Figure: V = 100.

Numerical Results III

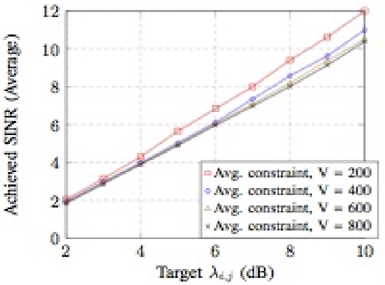


Figure: Achieved time average SINR Vs target QoS, each transmitter is connected to two UTs, N_t=5.

Lyapunov Optimization - Some References

- Junting Chen, Vincent K. N. Lau, "Large Deviation Delay Analysis of Queue-Aware Multi-User MIMO Systems With Two-Timescale Mobile-Driven Feedback," IEEE Transactions on Signal Processing 61(16): 4067-4076 (2013)
- M. Neely, Stochastic Network Optimization with Application to Communication and Queueing Systems. Morgan & Claypool, 2010.
- Ying Cui, Vincent K. N. Lau, Edmund M. Yeh, "Delay Optimal Buffered Decode-and-Forward for Two-Hop Networks With Random Link Connectivity," IEEE Transactions on Information Theory 61(1): 404-425 (2015)
- S. Lakshminaryana, M. Assaad and M. Debbah, "Energy Efficient Cross Layer Design in MIMO Multi-cell Systems," to appear in IEEE JSAC, 2015.
- S. Lakshminarayana, M. Assaad and M. Debbah, "Energy Efficient Design in MIMO Multi- cell Systems with Time Average QoS Constraints", in IEEE SPAWC, June 2013.
- H. Shirani-Mehr, G. Caire, and M. J. Neely, "MIMO Downlink Scheduling with Non-Perfect Channel State Knowledge," IEEE Transactions on Communications, July 2010.
- etc...

Queueing Stability in MIMO Systems

- A. Destounis, M. Assaad, M. Debbah and B. Sayadi, "Traffic-Aware Training and Scheduling in MISO Downlink Systems," IEEE Transactions on Information Theory, 61 (5), pp. 2574-2599, 2015.
- A. Destounis, M. Assaad, M. Debbah and B. Sayadi, "A Threshold-Based Approach for Joint Active User Selection and Feedback in MISO Downlink Systems," in proc. of IEEE ICC, London UK, June 2015.
- Kaibin Huang, Vincent K. N. Lau, "Stability and Delay of Zero-Forcing SDMA With Limited Feedback," IEEE Transactions on Information Theory, 2012.
- M. Deghel, M. Assaad, and M. Debbah, "Queueing Stability and CSI Probing in a Wireless Network with Interference Alignment in TDD Mode," in proc. of IEEE International Symposium on Information Theory (ISIT), HongKong, June 2015.
- Junting Chen, Vincent K. N. Lau, "Large Deviation Delay Analysis of Queue-Aware Multi-User MIMO Systems With Two-Timescale Mobile-Driven Feedback," IEEE Transactions on Signal Processing 61(16): 4067-4076 (2013)
- A. Destounis, M. Assaad, M. Debbah and B. Sayadi, "Traffic-Aware Training and Scheduling for the 2-user MISO Broadcast Channel," in IEEE ISIT, 2014.
- Ying Cui, Vincent K. N. Lau, Edmund M. Yeh, "Delay Optimal Buffered Decode-and-Forward for Two-Hop Networks With Random Link Connectivity," IEEE Transactions on Information Theory 61(1): 404-425 (2015)

Queueing Stability in MIMO Systems

- N. Pappas, M. Kountouris, A. Ephremides, A. Traganitis, "Relay-assisted Multiple Access with Full-duplex Multi-Packet Reception," IEEE Transactions on Wireless Communications, July 2015
- I. E. Telatar and R. G. Gallager, "Combining queueing theory with information theory for multiaccess," IEEE Journal on Sel. Areas in Communications, vol. 13, Aug. 1995.
- E. Yeh, Multiaccess and Fading in Communication Networks. Ph.D. Thesis, EECS, MIT, 2001.
- E. M. Yeh and A. S. Cohen, "Throughput and delay optimal resource allocation in multiaccess fading channels," in Proc. of IEEE Intl. Symposium on Information Theory, June/July 2003.
- etc...

End of the Talk

Thank you for listening!
Questions??