Optimizing Resource Allocation in 60 GHz Wireless Access Networks

George Athanasiou
Research Scientist

Electrical Engineering School and Access Linnaeus Center,
KTH Royal Institute of Technology, Stockholm, Sweden
athanas@kth.se

BME 11.07.13
Group Activities

- **Research interests**
  - Wireless networking analysis and optimization with applications to 3/4/5G
  - Wireless sensor networks
  - Smart grids
  - Wireless industrial control

- **Research projects**
  - European Institute of Technology, Car2X Communications, 2013
  - European Institute of Technology, LTE in Smart Grids, 2013
  - Hycon2 EU project, Highly-complex and networked control systems, 2010-2014
  - Hydrobionets EU project, Autonomous control of large-scale water treatment plants based on self-organized wireless BI0MEM sensor and actuator networks, 2011-2014
  - Swedish Research Council, In-Network Optimization, 2012-2014

- **Educational activities**
  - Teaching at PhD, Master and Bachelor level
• Past, Present and Future in mobile communications

• 60 GHz millimeterWave wireless technology

• Optimizing resource allocation

• Distributed client association (DAA)

• Numerical analysis of DAA

• Conclusions and open research topics
Outline

• Past, Present and Future in mobile communications

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Growth of Mobile Traffic

Exabytes per Month

66% CAGR 2012-2017

Source: Cisco VNI Mobile Forecast, 2013
Growth of Mobile Traffic

2012: 70% mobile traffic growth compared to 2011
2012: 12 times the entire global internet traffic in 2000
Growth of Mobile Traffic

2017: 13 times higher compared to 2012
2012: 0.9% of mobile connections
End of 2013: # of mobile connected devices > earth population
2017: 4G will represent 10% of connections and 45% of mobile traffic
2017: 2,7 GB mobile traffic per smartphone per month
The amount of traffic offloaded from smartphones will be 46%, and the amount of traffic offloaded from tablets will be 71% in 2017 (Cisco, 2013)

90% of all cellular base stations will be small cells by 2016 (IEEE Spectrum Magazine, Informa Telecoms & Media, 2013)
Priorities

- High bandwidth
- High coverage
- Green
- Cheap
Evolution or Revolution?

- Infrastructure moves closer to the users

- Devices communicate directly (D2D)

- Base station is “dying”

- Heterogeneous networks converge
Mobile Data Offloading

Cost reduction

Capacity improvement

- $\$$
- $$$
- $$$$

Optimizing RA in 60 GHz WNs
Mobile Data Offloading

Cost reduction

Capacity improvement

Are there better solutions for mobile data offloading?
60 GHz to the Mobile

- 60 GHz small base stations (eg. on lamp posts)
- Downlink offload traffic in 60 GHz band with uplink LTE feedback
- 60 GHz radio on mobile device in receive-only mode
Outline

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- 60 GHz millimeterWave wireless technology
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60 GHz Wireless Access Networks

- Unlicensed short range transmissions in the 60 GHz millimeter wave (mmW) band
- Achieve Gbps communication
- Reduced interference
- Low-cost mmW transceivers
MillimeterWave Band

- History (J.C. Bose, 1897)
- High path loss
- High oxygen absorption
60 GHz Wireless Standards

- IEEE 802.11ad
- WiGig
- IEEE 802.15.3c
- WirelessHD
- ECMA-387
Applications

- Wireless Gigabit Ethernet
- Information Shower
- Wireless Pills
- File Transfer
- Wireless Video Cameras - Monitoring
- Aircraft Structure Monitoring
- In-Flight Entertainment
- Wireless Library
- In-Car Entertainment
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Optimizing Client Association in 60 GHz Wireless Access Networks
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Optimizing Client Association in 60 GHz Wireless Access Networks

• **Goal**: Minimize the maximum access point (AP) utilization in the network and ensure fair load distribution

• **Solution**: Distributed algorithm for client association based on Lagrangian duality theory and subgradient methods

• **Results**: Theoretical and numerical analysis

System Model

- \( \mathcal{N} = \{1, \ldots, N\} \) APs and \( \mathcal{M} = \{1, \ldots, M\} \) clients

- **Achievable rate** from AP \( i \) to client \( j \in \mathcal{M}_i \) is

\[
R_{ij} = W \log_2 \left( 1 + \frac{P_{ij}G_{ij}}{(N_0 + I_j)W} \right)
\]

- \( Q_j \) is the **demanded data rate** of client \( j \)
System Model

- **Channel utilization** between AP $i$ and client $j$ is

$$\beta_{ij} = \frac{Q_j}{R_{ij}}$$

- **Utilization** of AP $i$ is

$$\sum_{j \in M_i} \beta_{ij} x_{ij}$$

- $(x_{ij})_{j \in M_i}$ are binary decision variables, which indicate the client association

$$x_{ij} = \begin{cases} 
1 & \text{if client } j \text{ is associated to AP } i \\
0 & \text{otherwise}
\end{cases}$$
Client Association Problem Formulation

\[
\begin{align*}
\text{minimize} & \quad \max_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}_i} \beta_{ij} \ x_{ij} \\
\text{subject to} & \quad Q_j x_{ij} \leq R_{ij}, \quad i \in \mathcal{N}, \ j \in \mathcal{M}_i \\
& \quad \sum_{i \in \mathcal{N}_j} x_{ij} = 1, \quad j \in \mathcal{M} \\
& \quad x_{ij} \in \{0, 1\}, \quad j \in \mathcal{M}, \ i \in \mathcal{N}_j
\end{align*}
\]

- **Variable:** \((x_{ij})_{i \in \mathcal{N}, \ j \in \mathcal{M}_i}\)
- **Main problem parameters:** \((\beta_{ij})_{i \in \mathcal{N}, \ j \in \mathcal{M}_i}, (Q_j)_{j \in \mathcal{M}}, (R_{ij})_{i \in \mathcal{N}, \ j \in \mathcal{M}_i}\)
- **Constraints:** a) The demand of client \(j\) is less or equal to the achievable rate from AP \(i\) to client \(j\), b) Client \(j\) can only be assigned to one AP, c) The decision variables are binary
Equivalent Epigraph Form

minimize \ t
subject to \ \sum_{j \in M} \beta_{ij} \ x_{ij} \leq \ t, \ i \in N \\
\sum_{i \in N} \ x_{ij} = 1, \ j \in M \\
x_{ij} \in \{0, 1\}, \ j \in M, i \in N_j

- Variable: \ (x_{ij})_{i \in N, j \in M} \ and \ t

- Main problem parameters: \ (\beta_{ij})_{i \in N, j \in M_i}

- Mixed integer linear program (MILP)
Solution Method Challenges

- **Existing MILP solvers are centralized**

- Typically based on global branch and bound algorithms $\Rightarrow$ the **worst-case complexity grows exponentially** with the problem size

- **Even small** problems, with a few tens of variables, can take a **very long time**
Solution Method Challenges

- Existing MILP solvers are centralized

- Typically based on global branch and bound algorithms ⇒ the worst-case complexity grows exponentially with the problem size

- Even small problems, with a few tens of variables, can take a very long time

- Our approach: Lagrangian duality + Subgradient methods ⇒ decentralized
**Lagrangian Duality**

**Dual problem**

maximize \[ g(\lambda) = \sum_{j \in \mathcal{M}} g_j(\lambda) \]
subject to \[ \sum_{i \in \mathcal{N}} \lambda_i = 1 \]
\[ \lambda_i \geq 0, \ i \in \mathcal{N} \]

- **Variables:** \[ \lambda = (\lambda_i)_{i \in \mathcal{N}} \]
- \[ \mathcal{X}_j = \left\{ x_j = (x_{ij})_{i \in \mathcal{N}_j} \mid \sum_{i \in \mathcal{N}_j} x_{ij} = 1, \ x_{ij} \in \{0, 1\}, \ i \in \mathcal{N}_j \right\} \]
- \[ g_j(\lambda) \] is the optimal value of the **subproblem**

minimize \[ \sum_{i \in \mathcal{N}_j} \beta_{ij} \lambda_i x_{ij} \]
subject to \[ x_j \in \mathcal{X}_j \]

with the variable \( x_j \).
Lagrangian Duality

Dual problem

- maximize \( g(\lambda) = \sum_{j \in \mathcal{M}} g_j(\lambda) \)
- subject to \( \sum_{i \in \mathcal{N}} \lambda_i = 1 \)
- \( \lambda_i \geq 0, \ i \in \mathcal{N} \)

- Variables: \( \lambda = (\lambda_i)_{i \in \mathcal{N}} \)
- \( \mathcal{X}_j = \{ x_j = (x_{ij})_{i \in \mathcal{N}_j} \mid \sum_{i \in \mathcal{N}_j} x_{ij} = 1, \ x_{ij} \in \{0, 1\}, \ i \in \mathcal{N}_j \} \)
- \( g_j(\lambda) \) is the optimal value of the subproblem

\[
\begin{align*}
\text{minimize} & \quad \sum_{i \in \mathcal{N}_j} \beta_{ij} \lambda_i x_{ij} \\
\text{subject to} & \quad x_j \in \mathcal{X}_j,
\end{align*}
\]

solved \( @ \) client \( j \)

with the variable \( x_j \).
Subgradient Method

Subgradient method to solve dual problem

\[ \lambda^{(k+1)} = P(\lambda^{(k)} - \alpha_k u^{(k)}) \]

- \( P \): Euclidean projection onto the unit simplex \( \Pi = \{ \lambda \mid \sum_{i \in \mathcal{N}} \lambda_i = 1, \lambda_i \geq 0 \} \)

- \( \alpha_k > 0 \) is the \( k \)th step size

- \( u^{(k)} = \left( u_i^{(k)} \right)_{i \in \mathcal{N}} \): a subgradient of \(-g\) at \( \lambda^{(k)} \), where

\[ u_i^{(k)} = -\sum_{j \in \mathcal{M}_i} \beta_{ij} x_{ij}^* , \]

and \( (x_{ij}^*)_{j \in \mathcal{M}_i} \) is the solution of the \( i \)th subproblems with \( \lambda = \lambda^{(k)} \)
Subgradient Method

Subgradient method to solve dual problem

\[ \lambda^{(k+1)} = P(\lambda^{(k)} - \alpha_k u^{(k)}) \]

- \(P\): Euclidean projection onto the unit simplex \(\Pi = \{\lambda \mid \sum_{i \in N} \lambda_i = 1, \lambda_i \geq 0\}\)
- \(\alpha_k > 0\) is the \(k\)th step size
- \(u^{(k)} = (u_i^{(k)})_{i \in N}\): a subgradient of \(-g\) at \(\lambda^{(k)}\), where
  \[ u_i^{(k)} = -\sum_{j \in \mathcal{M}_i} \beta_{ij} x_{ij}^* , \]
  and \((x_{ij}^*)_{j \in \mathcal{M}_i}\) is the solution of the \(i\)th subproblems with \(\lambda = \lambda^{(k)}\)
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DAA Illustration

1. Price broadcast
2. Determine local association
3. Clients signals its best AP
4. AP \( i \) computes \( u_i \)
5. Construct \( u \) / compute prices

Stopping criterion?

YES

NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \( i \) computes \( u_i \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO

AP 1

AP 2

AP 3
DAA Illustration

- init
- price broadcast
- determine local association
- clients signals its best AP
- $\text{AP}_i$ computes $u_i$
- construct $u$ / compute prices
- stopping criterion?
  - YES
  - NO

- $\text{AP}_1$
- $\text{AP}_2$
- $\text{AP}_3$
DAA Illustration

- init
  - price broadcast
  - determine local association
  - clients signals its best AP
  - $AP_i$ computes $u_i$
  - construct $u$ / compute prices

stopping criterion? YES NO
DAA Illustration

**Algorithm Flowchart**

1. **Init**
2. Price broadcast
3. Determine local association
4. Clients signal its best AP
5. AP $i$ computes $u_i$
6. Construct $u$ / Compute prices
7. Stopping criterion?
   - **YES**
   - **NO**

**Diagram**

- **AP 1**, **AP 2**, **AP 3**
- Connections between APs and clients

**Notes**

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- Optimizing RA in 60 GHz WNs
- BME 11.07.13
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

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stopping criterion?

YES

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DAA Illustration

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AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

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price broadcast

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clients signals its best AP

AP \text{i} computes \( u_{\text{i}} \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO
DAA Illustration

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DAA Illustration

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price broadcast

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clients signals its best AP

AP \(i\) computes \(u_i\)

construct \(u\) / compute prices

stopping criterion?

YES

NO

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DAA Illustration

AP 1  AP 2  AP 3

init

price broadcast

determine local association

clients signals its best AP

AP \( i \) computes \( u_i \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \(i\) computes \(u_i\)

construct \(u\) / compute prices

stopping criterion ?

YES

NO

AP 1

AP 2

AP 3

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DAA Illustration

- AP 1
- AP 2
- AP 3

1. init
2. price broadcast
3. determine local association
4. clients signals its best AP
5. AP i computes $u_i$
6. construct $u$ / compute prices
7. stopping criterion?
   - YES
     - end
   - NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

AP 1 \to AP 2 \to AP 3

AP 1

Price broadcast

Determine local association

Clients signal its best AP

AP $i$ computes $u_i$

Construct $u$ / Compute prices

Stopping criterion?

\begin{align*}
\text{init} \\
\text{YES} & \quad \text{NO}
\end{align*}
DAA Illustration

- **init**
  - Price broadcast
  - Determine local association
  - Clients signals its best AP
  - AP $i$ computes $u_i$
  - Construct $u$ / Compute prices
  - Stopping criterion?
    - YES
    - NO
DAA Illustration

- init
- price broadcast
- determine local association
- clients signals its best AP
- AP \( i \) computes \( u_i \)
- construct \( u \) / compute prices
- stopping criterion?
- YES
- NO
DAA Illustration

- init
- price broadcast
- determine local association
- clients signals its best AP
- $AP_i$ computes $u_i$
- construct $\mathbf{u}$ / compute prices
- stopping criterion?
- YES
- NO
DAA Illustration

- init
- price broadcast
- determine local association
- clients signals its best AP
- AP $i$ computes $u_i$
- construct $u$ / compute prices
- stopping criterion ?
- YES
- NO
DAA Illustration

Initial price broadcast

Determine local association

Client signals its best AP

AP $i$ computes $u_i$

Construct $u_i$ / compute prices

Stopping criterion?

YES

NO
DAA Illustration

- **Init**
  - Price broadcast
  - Determine local association
  - Clients signals its best AP
  - $AP_i$ computes $u_i$
  - Construct $u$ / Compute prices
  - Stopping criterion?

- **AP 1**, **AP 2**, **AP 3**

---

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DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \( i \) computes \( u_i \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO

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DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion ?

YES

NO
DAA Illustration

- Init
- Price broadcast
- Determine local association
- Clients signal their best AP
- AP $i$ computes $u_i$
- Construct $u$ / Compute prices

Stopping criterion? YES/NO

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DAA Illustration

AP 1

AP 2

AP 3

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

init

- price broadcast
- determine local association
- clients signals its best AP
- AP $i$ computes $u_i$
- construct $u$ / compute prices
- stopping criterion?

AP 1
AP 2
AP 3
DAA Illustration

Determine local association

Clients signals its best AP

AP \( i \) computes \( u_i \)

Construct \( u \) / Compute prices

Stopping criterion?

Yes

No

Init

Price broadcast
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

- init
- price broadcast
- determine local association
- clients signals its best AP
- AP $i$ computes $u_i$
- construct $u / compute$ prices
- stopping criterion?
- YES
- NO

AP 1

AP 2

AP 3
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \(i\) computes \(u_i\)

construct \(u\) / compute prices

stopping criterion ?

YES

NO
DAA Illustration

AP 1  AP 2  AP 3

init

price broadcast

determine local association

clients signals its best AP

AP \( i \) computes \( u_i \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \( i \) computes \( u_i \)

construct \( u \) / compute prices

stopping criterion?

YES

NO
DAA Illustration

- **AP 1**, **AP 2**, and **AP 3** represent different access points in a network.
- **Clients** signal their best access point to determine local association.
- Access point **i** computes the utility $u_i$.
- Prices are constructed and computed.
- There is a stopping criterion check.
- If the stopping criterion is met, the process stops; otherwise, it continues with price broadcast.

Diagram details:
- **Init** node starts the process.
- **Price broadcast** node is followed by **determine local association**.
- Clients signal their best access point.
- Access point **i** computes utility $u_i$.
- Utilities are used to construct prices.
- There is a decision point for the **stopping criterion**.
- If the criterion is met, the process stops; otherwise, it goes back to price broadcast.
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO

init

AP 1

AP 2

AP 3

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Optimizing RA in 60 GHz WNs
init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \textit{i} computes \( u_i \)

construct \( u \) / compute prices

stopping criterion ?

YES

NO
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP $i$ computes $u_i$

construct $u$ / compute prices

stopping criterion?

YES

NO

init
DAA Illustration

init

price broadcast

determine local association

clients signals its best AP

AP \text{i} computes $u_i$

construct $\mathbf{u}$ / compute prices

stopping criterion ?

YES

NO

AP 1

AP 2

AP 3
DAA Illustration

init
price broadcast
determine local association
clients signals its best AP
AP $i$ computes $u_i$
construct $u$ / compute prices

stopping criterion?

YES

NO
DAA Illustration

1. init
2. price broadcast
3. determine local association
4. clients signals its best AP
5. $AP_i$ computes $u_i$
6. construct $u$ / compute prices
7. stopping criterion?
8. YES
9. NO
Proposition

Let $g_{\text{best}}^{(k)}$ denote the best dual objective value found after $k$ subgradient iterations, i.e., $g_{\text{best}}^{(k)} = \max\{g(\lambda^{(1)}), \ldots, g(\lambda^{(k)})\}$. Then, $\forall \epsilon > 0$ $\exists n \geq 1$ such that $\forall k \geq n \Rightarrow (d^* - g_{\text{best}}^{(k)}) < \epsilon$.

Theorem

The optimal duality gap of the mixed integer linear program is bounded as follows:

$$p^* - d^* \leq (N + 1)(\rho + \max_{j \in M} \rho_j),$$

where $\rho = \max_{i \in N, j \in M} \beta_{ij}$ and $\rho_j = \min_{i \in N, j} \beta_{ij}$. Moreover, the relative duality gap $(p^* - d^*)/p^*$ diminishes to 0 as $M \to \infty$. 
Implementation Over Existing Standards

- Initially the clients follow the RSSI-based association policy that IEEE 802.11ad and IEEE 802.15.3c define

- **DAA** is periodically executed to correct possible suboptimal client associations by reallocating the available resources
APs trigger the initialization of DAA by setting a special bit into the beacon frame.

Information exchange is performed through the control frames or piggy-backing the data frames.
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Numerical Analysis

- Consider a multi-user multi-cell environment

- Compare **DAA** to
  - Random association
  - RSSI-based association (IEEE 802.11)
  - Optimal association (IBM CPLEX)

- **Measure**
  - Convergence
  - Scalability
  - Time efficiency
  - Fairness
Topologies

- SNR operating point at a distance $d$ from any AP

$$\text{SNR}(d) = \begin{cases} 
\frac{P_0 \lambda^2}{(16\pi^2 N_0 W)} & d \leq d_0 \\
\frac{P_0 \lambda^2}{(16\pi^2 N_0 W)} \cdot (d/d_0)^{-\eta} & \text{otherwise}
\end{cases}$$

- Radius of each cell $r$ is chosen such that $\text{SNR}(r) = 10$ dB

- Clients are uniformly distributed at random, among the circular cells

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$</td>
<td>Far field reference distance</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Path loss exponent</td>
</tr>
</tbody>
</table>
Convergence of DAA

- Average primal objective value from DAA after $k$ subgradient iterations: $P^{(k)} = \left(1/\bar{T}\right) \sum_{T=1}^{\bar{T}} p_{\text{best}}^{(k)}(T)$

- Average dual optimal value by DAA: $D^* = \left(1/\bar{T}\right) \sum_{T=1}^{\bar{T}} d^*(T)$
Convergence of DAA

- Convergence time is affected by the number of APs and clients: The smaller the network, the faster DAA converges.
Scalability of DAA

- Performance improvement increases while the network becomes bigger and more loaded
- **DAA** performs close to optimal
Scalability of DAA

- Considering constant load, the average objective value decreases while the number of APs increases.

- **DAA** performs close to optimal.
Optimality of DAA

- Average relative duality gap:
  \[ \text{Ave-RDG} = \frac{1}{T} \sum_{T=1}^{T} \left( p^*(T) - d^*(T) \right) / p^*(T) \]

- Average relative duality gap taking into account the best primal feasible objective value from DAA after \( K \) iterations at time slot \( T \):
  \[ \text{Ave-RDG-best-achieved} = \frac{1}{T} \sum_{T=1}^{T} \left( p_{\text{best}}^{(K)}(T) - d^*(T) \right) / p_{\text{best}}^{(K)}(T) \]
Fairness Achieved by DAA

- Jain’s fairness index:

\[
J^{(k)}(T) = \left( \sum_{i \in \mathcal{N}} Y_i^{(k)}(T) \right)^2 / \left( N \sum_{i \in \mathcal{N}} Y_i^{(k)}(T)^2 \right),
\]

\[
Y_i^{(k)}(T) = \sum_{j \in \mathcal{M}_i} \beta_{ij} x_{ij}^{(k)}(T) \text{ and } x_{ij}^{(k)}(T) \text{ is the solution (best feasible) resulted from DAA at time slot } T \text{ after } k \text{ iterations}
\]
Speed and Resources Used by DAA

- Empirical CDF plots of the number of iterations for $M = 100, 200, 300$ clients, with $N = 10$ APs

- Trade-off between optimality and complexity
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Conclusions

- **60 GHz wireless technology**: characteristics, benefits, challenges, applications

- **Distributed association algorithm (DAA)** for optimizing resource allocation in 60 GHz wireless access networks

- Performance evaluation of **DAA**: Asymptotically optimal, convergence, time efficiency and fairness

- Integration of **DAA** into current standards
Open Research Topics

- 60 GHz channel modeling
- Medium Access Control (MAC)
- Connectivity maintenance, blockage and directivity
- Coexistence and cooperation with existing wireless technologies
- Multi-hop communications
- ...
Thank you

More information: http://www.ee.kth.se/~georgioa/
Optimizing Resource Allocation in 60 GHz Wireless Access Networks

George Athanasiou
Research Scientist

Electrical Engineering School and Access Linnaeus Center,
KTH Royal Institute of Technology, Stockholm, Sweden
athanas@kth.se

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