Capacity and Scheduling in Small-Cell HetNets

Stephen Hanly

Macquarie University
North Ryde, NSW 2109

Joint Work with Sem Borst, Chunshan Liu and Phil Whiting

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1 Small Cells and Research Challenges
1. Small Cells and Research Challenges

2. Model
1. Small Cells and Research Challenges

2. Model

3. Main Stability Results
Talk Summary

1. Small Cells and Research Challenges
2. Model
3. Main Stability Results
4. Discrete Linear Program
1. Small Cells and Research Challenges
2. Model
3. Main Stability Results
4. Discrete Linear Program
5. Cell Association and Scheduling Algorithms
Small Cells and Research Challenges

Model

Main Stability Results

Discrete Linear Program

Cell Association and Scheduling Algorithms

Understanding the Converse
Small Cells and Data Offloading

- Re-use spectrum: make cells smaller
- Offload traffic from macro-cells onto pico and femto-cells
Small Cells: Theoretical Challenges

- What is the benefit? Base station densification gain?
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Characterizing capacity
Small Cells: Theoretical Challenges

- What is the benefit? Base station densification gain?
- Characterizing capacity
- Optimizing resource allocation and cell association
System Model

- One macro Base Station (BS)
- $L$ pico BSs
- All users in coverage of macro BS
- $C_{\ell}$ coverage area of pico BS $\ell$
- Power levels are fixed
- Macro BS uses higher power than pico BSs
Time Sharing and Cell Association

- Time Share Spectrum
  - Macro Cell versus Pico Cells
  - Almost Blanking SubFrames

Cell Range Expansion for Picos
- Expand pico-cells to cover more mobiles
- Contract pico-cells and send at higher rate
Time Sharing and Cell Association

- **Time Share Spectrum**
  - Macro Cell versus Pico Cells
  - Almost Blanking SubFrames

- **Cell Range Expansion for Picos**
  - Expand pico-cells to cover more mobiles
  - Contract pico-cells and send at Higher Rate
Research Problems

1. How to split the time between macro and picos?
2. How to decide the cell association?

For cell association, one way is via biasing: add a bias to the measured power level to encourage offloading. We will address both 1. and 2. in a joint approach. We will discover biasing based on rate ratios, not power levels.
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- We will address both 1. and 2. in a joint approach.
- We will discover biasing based on rate ratios, not power levels.
Files arrive at rate $\lambda_a$ files/slot (Poisson)

$\eta(\cdot)$ gives a probability measure on the macrocell area

Spatial arrival intensity is $\lambda(d\xi) = \lambda_a \eta(d\xi)$
Files arrive at rate $\lambda_a$ files/slot (Poisson)
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Spatial arrival intensity is $\lambda(d\xi) = \lambda_a \eta(d\xi)$

$n$th arrival has length $D_n$ bits; $\mathbb{E}[D_n] = D$

How large can $\lambda_a$ be?
Macro BS schedules files in macro-time.

All pico BSs can be scheduled simultaneously in pico-time.
Pico versus Macro time

- Macro BS schedules files in macro-time
- All pico BSs can be scheduled simultaneously in pico-time
- A pico BS schedules files in its coverage area
- Not all files need be scheduled

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A pico BS schedules files in its coverage area

Not all files need be scheduled

We will consider only clearing schedules

Clearing schedules include FCFS (one at a time) and PS (parallel processing)
Schedules determined via only the location $\xi$ and the size $F$ (bits) of the file.
Location based policies

- Schedules determined via only the location $\xi$ and the size $F$ (bits) of the file

- If $\pi$ is such a scheduler, $\xi \in C_\ell$, and $F$ is the file size then:
  - $x_\ell^\pi(\xi, F)$ bits are from pico BS $\ell$
  - $y_\ell^\pi(\xi, F)$ are from macro BS
Location based policies

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- If $\pi$ is such a scheduler, $\xi \in C_\ell$, and $F$ is the file size then:
  - $x_\ell^\pi(\xi, F)$ bits are from pico BS $\ell$.
  - $y_\ell^\pi(\xi, F)$ are from macro BS.

- If $n$th arrival is of size $D_n$ bits and located at $\xi_n$ then
  $$x_\ell^\pi(\xi_n, F_n) + y_\ell^\pi(\xi_n, F_n) = D_n$$
Assume no interference between picocells (will relax later)
So there is no interference in the system!
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So there is no interference in the system!

At any point \( \xi \) there is a macro-cell rate of \( S(\xi) \) bits/slot

At any point \( \xi \in C_\ell \) there is a pico-cell rate of \( R_\ell(\xi) \) bits/slot
Assume no interference between picocells (will relax later)

So there is no interference in the system!

At any point $\xi$ there is a macro-cell rate of $S(\xi)$ bits/slot

At any point $\xi \in C_\ell$ there is a pico-cell rate of $R_\ell(\xi)$ bits/slot

A file can be served by macro and pico BSs in the same slot
Fix a location-based policy $\pi$ and outcome $\omega \in \Omega$.

Let $V_T^{\pi}(\omega)$ be time needed to clear all files that arrive in $[0, T]$.
Buildup of work

Fix a location-based policy $\pi$ and outcome $\omega \in \Omega$.

Let $V^\pi_T(\omega)$ be time needed to clear all files that arrive in $[0, T]$.

Clearly $\pi$ is NOT stable if

$$\liminf_{T \uparrow \infty} \frac{V^\pi_T}{T} > 1$$

on an event of nonzero probability.
Talk Summary

1. Small Cells and Research Challenges
2. Model
3. Main Stability Results
4. Discrete Linear Program
5. Cell Association and Scheduling Algorithms
6. Understanding the Converse
Recall main parameters

\[ \lambda_a \eta (d \xi) = \lambda (d \xi), \eta (d \xi) \] spatial intensity of arrivals

\[ R_{\ell}(\xi), S_{\ell}(\xi) \] Rates for pico and macro at location \( \xi \)

\[ x_{\ell}(\xi), y_{\ell}(\xi) \] bit assignments at location \( \xi \)

\( D \) mean download file size
Consider the following continuous LP:

\[
\begin{align*}
\min \quad & \tau = f + \sum_{\ell=1}^{L} \int \frac{y_{\ell}(\xi)}{S_{\ell}(\xi)} \lambda (d\xi) \\
\text{subject to} \quad & \int \frac{x_{\ell}(\xi)}{R_{\ell}(\xi)} \lambda (d\xi) \leq f \quad \forall \ell \\
& x_{\ell}(\xi) + y_{\ell}(\xi) \geq D,
\end{align*}
\]

where \( f \) represents pico-time.

Let \( \tau^* \) be the optimal value of the program.
Theorem (Hanly, Whiting)

Let $\tau^*$ be optimal solution to the LP. If $\tau^* < 1$, $\exists$ a clearing schedule $\pi$ with ergodic properties.
Also define $S_n^\pi(\omega) :=$ sojourn time $n$th job, then $\pi$ satisfies,

$$E[S_n^\pi(\omega)] < \bar{S} < \infty$$  \hspace{1cm} (1)
Converse

Theorem (Hanly, Whiting)

Let $\tau^*$ be the solution to the continuous LP. Suppose that $\tau^* > 1$ then there is a fixed constant $\eta > 0$, such that for any clearing schedule $\pi$

$$\liminf_{T \uparrow \infty} \frac{V_{T}^{\pi}(\omega)}{T} = 1 + \eta \quad \text{almost surely.}$$
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Let instantaneous rate of $n$th user provided by pico BS be denoted by $R_n$

- Instantaneous rate of user provided by macro BS be denoted by $S_n$

\[
\rho_{3,n} = \frac{R_{3,n}}{S_{3,n}}
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Let instantaneous rate of $n$th user provided by pico BS be denoted by $R_n$.

Instantaneous rate of user provided by macro BS be denoted by $S_n$.

The rate ratio is defined by

$$\rho_{3,n} = \frac{R_{3,n}}{S_{3,n}}$$
Problem Formulation

Let $D_n$ denote the amount of bits of data required by a user. $D_n$ can be split into $x_n$ bits of data from pico BS and $y_n$ bits of data from the macro BS.
Let $D_n$ denote the amount of bits of data required by a user. $D_n$ can be split into $x_n$ bits of data from pico BS and $y_n$ bits of data from the macro BS. It therefore requires $\frac{x_n}{R_n}$ secs from pico BS and $\frac{y_n}{S_n}$ secs from macro BS. The problem is to minimize the total time to satisfy all the data demands in the network.
The problem to be solved is the following linear program:

\[
\begin{align*}
\text{min} & \quad f + \sum_{l=0}^{L} \sum_{n=1}^{N_l} \frac{y_{l,n}}{S_{l,n}} \\
\text{subject to} & \quad \sum_{n=1}^{N_l} \frac{x_{l,n}}{R_{l,n}} \leq f \quad \forall l \\
& \quad x_{l,n} + y_{l,n} \geq D_{l,n} \quad \forall l, \forall n = 1, 2, \ldots N_l \\
& \quad f \geq 0, x_{l,n} \geq 0, y_{l,n} \geq 0 \quad \forall l, \forall n = 1, 2, \ldots N_l
\end{align*}
\]

where \( f \) is the time allocated to the picocells.
A One Dimensional Formulation

Linear Programming theory tells us that the rate ratios $\rho := \frac{R}{S}$ are the key to the optimal cell association.

Order the users in pico cell in decreasing order of the rate ratio.

$m_j = 4$  \hspace{1cm} Pico cell $j$

$N_j = 6$

6 5 4 3 2 1
Linear Programming theory tells us that the rate ratios $\rho := \frac{R}{\delta}$ are the key to the optimal cell association.

Order the users in pico cell in decreasing order of the rate ratio.

Then there will be a user $m_j$ in pico cell $j$ such that:

- Users $1, 2, \ldots, m_j - 1$ will be 100% served by the pico cell BS ($y_{j,n} = 0$ for these users).
- Users $m_j + 1, 2, \ldots, N_j$ will be 100% served by the macro cell BS ($x_{j,n} = 0$ for these users).
- User $m_j$ may get its service from both base stations (pico and macro).
A One Dimensional Formulation

\[ \sum_n \frac{D_{j,n}}{R_{j,n}} \]

(time allocated to pico BSs)

served by macro

served by pico \( j \)

\[ \frac{D_{j,1}}{R_{j,1}} + \frac{D_{j,2}}{R_{j,2}} \]

\[ n_j (f) m_j (f) = 5 \]
The macro-cell time required to service users users near pico cell $j$ is

$$g_j(f) = p_j(f) \frac{D_{j,m_j(f)}}{S_{j,m_j(f)}} + \sum_{n=m_j(f)+1}^{N_j} \frac{D_{j,n}}{S_{j,n}}$$

The diagram illustrates the allocation of time to pico BSs versus users served by pico BSs and macro BSs.
The problem is therefore to minimize the following function of the scalar parameter $f$:

$$f + \sum_{l=1}^{L} g_l(f)$$
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The range for the optimization is $0 \leq f \leq \max_{l=1}^{L} \sum_{n=1}^{N_l} \frac{D_{l,n}}{S_{l,n}}$. 
A one dimensional formulation

\[ g_j(f) = \sum_{n=1}^{N_j} \frac{D_{j,n}}{S_{j,n}} \]

\[ \text{slope} = \frac{-R_{j,1}}{S_{j,1}} = -\rho_{j,1} \]

\[ \text{slope} = -\rho_{j,2} \]

\[ \text{slope} = -\rho_{j, N_j - 1} \]

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Recall that the problem is to minimize the function $f + \sum_{l=1}^{L} g_l(f)$.
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The derivative at any non-break-point $f$ is therefore $1 - \sum_{i=1}^{L} \rho_i(f)$.

But the optimum will occur at one of the break points, where the derivative changes.

The time allocation $f$ to pico-cells is optimal if and only if

$$\sum_{i=1}^{L} \rho_i(f),$$

We only need to check the $1 + \sum_{i=1}^{L} N_i$ break points, where the derivative changes, for the edge-rate condition.
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**edge rate condition:** The time allocation $f$ to pico-cells is optimal if and only if

$$\sum_{l=1}^{L} \rho_{l,f-} \geq 1 \geq \sum_{l=1}^{L} \rho_{l,f+}$$
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We only need to check the \( 1 + \sum_{l=1}^{L} N_l \) break points, where the derivative changes, for the edge-rate condition.
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6. Understanding the Converse
Recall theorem for existence of schedule

Theorem (Hanly, Whiting)

Let $\tau^*$ be optimal solution to the LP. If $\tau^* < 1$, there exists a clearing schedule $\pi$ with ergodic properties.
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Theorem (Hanly, Whiting)

Let $\tau^*$ be optimal solution to the LP. If $\tau^* < 1$, $\exists$ a clearing schedule $\pi$ with ergodic properties.

The optimal solution of the continuous LP is characterized by rate ratio thresholds $\rho^*_\ell$, $\ell = 1, 2, \ldots, L$:

$$x^*_\ell(\xi) = \begin{cases} D & \rho_\ell(\xi) > \rho^*_\ell \\ 0 & \text{o.w.} \end{cases}$$

(2)

We will now show that these thresholds can be used to construct an optimal schedule.
Construction of a stabilizing schedule

Suppose $\tau^* < 1$ and let $f^*$ be the optimal value of $f$ from continuous LP.

- Allocate $\frac{f^*}{\tau^*}$ of each slot to picos.
- Allocate $\frac{\tau^* - f^*}{\tau^*}$ of each slot to the macro.
- Assign each file to pico or macro based on rate-ratio threshold $\rho^\ell_\ell$. 
Construction of a stabilizing schedule

- All files that arrive during a slot are merged into one job
- Service time of each job can be computed (location-based policy)
- Each BS serves jobs in FCFS order
- D/G/1 queue at each base station.
The workload arriving at the macro BS queue can be shown to be $\tau^* - f^*$ slots/slot.

The service rate of the macro BS is $\frac{\tau^* - f^*}{\tau^*}$ slots/slot.

So the utilization of the macro BS is $\tau^*$.
The workload arriving at the macro BS queue can be shown to be \( \tau^* - f^* \) slots/slot.

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The workload arriving at a pico BS can be shown to be at most \( f^* \) slots/slot.

The service rate of each pico BS is \( \frac{f^*}{\tau^*} \) slots/slot.

So the utilization of each pico BS is at most \( \tau^* \).
Construction of a stabilizing schedule

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- The workload arriving at a pico BS can be shown to be at most \( f^* \) slots/slot.
- The service rate of each pico BS is \( \frac{f^*}{\tau^*} \) slots/slot.
- So the utilization of each pico BS is at most \( \tau^* \).

- If \( \tau^* < 1 \) then each D/G/1 queue is stable.
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2 Model

3 Main Stability Results

4 Discrete Linear Program

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6 Understanding the Converse
Suppose $\tau^* > 1$, and let $\pi$ be a clearing schedule.

Let $N_T$ be the number of arrivals during $[0, T]$.

Let $x_n$ be number of pico-cell bits for the $n$th arrival.

Let $y_n$ be number of macro-cell bits for the $n$th arrival.
Understanding the converse

Imagine all the $N_T$ arrivals being present at time zero

$$\rho_{3,n} = \frac{R_{3,n}}{S_{3,n}}$$
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Let $V_{LP}^T$ be the minimum time in the corresponding discrete LP.
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Let $V_{LP}^T$ be the minimum time in the corresponding discrete LP.

We can analyze this and show that $\liminf_{T \uparrow \infty} \frac{V_{LP}^T}{T} > 1 + \eta$. 

\[ \rho_{3,n} = \frac{R_{3,n}}{S_{3,n}} \]
Understanding the converse

\[ f_{20}^\pi(\omega) = \text{time when a pico is sending to at least one of } N_{20} \text{ arrivals} \]

Now consider the actual system under policy \( \pi \)

Let \( f_T^\pi \) be the total time in which at least one of the \( N_T \) files is getting pico-service

Discrete Linear Program

\[
\begin{align*}
\text{min} & \quad f + \sum_l \sum_n \frac{y_{l,n}}{S_{l,n}} \\
\text{sub.} & \quad \sum_n \frac{x_{l,n}}{R_{l,n}} \leq f \quad \forall l \\
& \quad x_{l,n} + y_{l,n} \geq D_{l,n} \quad \forall l, n
\end{align*}
\]
Now consider the actual system under policy $\pi$

Let $f^\pi_T$ be the total time in which at least one of the $N_T$ files is getting pico-service

Then

$$V^\pi_T = f^\pi_T + \sum_{n=1}^{N_T} \frac{y_n}{S_n},$$

$$\sum_{n \in C_\ell} \frac{x_n}{R_n} \leq f^\pi_T$$
Now consider the actual system under policy $\pi$

Let $f^\pi_T$ be the total time in which at least one of the $N_T$ files is getting pico-service

Then

$$V^\pi_T = f^\pi_T + \sum_{n=1}^{N_T} \frac{y_n}{S_n}$$

$$\sum_{n \in C_\ell} \frac{x_n}{R_n} \leq f^\pi_T$$

So $(f^\pi_T, x_n, y_n, \ldots)$ is feasible for the earlier discrete LP
Hence
\[
\liminf_{T \to \infty} \frac{V_T^\pi}{T} \geq \frac{V_T^{LP}}{T} > 1 + \eta
\]
which implies that \( \pi \) is unstable.
Extensions

- Given stabilizing schedule is NOT dynamic and can greatly be improved

- We can analyze Processor Sharing at each BS which gets much better delay performance

- Assumption that statistics are known can be relaxed

- The assumption that there is no pico-cell interference can be relaxed:
  - Assume fixed power levels when pico scheduled to be "on"
  - Many different modes: subsets of pico BSs that are simultaneously activated
  - The pico rates at a location are mode-dependent

- Problem remains a continuous LP, but with a huge number of variables

- Good but suboptimal schemes can be found focusing on the most important modes

- Extensions to multiple macro-cells
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Applications

- Theory can be used as a basis for the search for adaptive algorithms
- Can be used as a cell planning tool since capacity is a function of base station locations
Formulated a notion of capacity for a dynamic HetNet consisting of one macrocell, multiple picocells.
Concluding Remarks

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- Characterized capacity in terms of the solution of a deterministic, continuous Linear Program
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- Showed how ABS slot and cell association can be solved jointly

Questions?
Concluding Remarks

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- Characterized capacity in terms of the solution of a deterministic, continuous Linear Program
- Showed how ABS slot and cell association can be solved jointly
- Showed how rate ratio thresholds provide the right way to bias pico-cells
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- Questions?