Call Completion Probability in Heterogeneous Networks with Energy Harvesting Base Stations

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Outline

- **Motivation and Research Challenge**
- **System Model**
  - Network Model
  - BS Energy and Operational Model
- **Call Completion Performance Analysis**
- **Results and Discussions**
- **Conclusions**

Motivation

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- **Why self-powered (i.e., renewable energy powered) BSs are attractive?**
  - Base stations (BSs) account for more than **50%** of the energy consumption in wireless cellular networks[1].

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  - Regulatory pressure for greener techniques in developing countries and lack of dependable electrical grid in developing countries is driving the push towards self-powered BSs.

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Literature Survey

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- **Research on self-powered BSs:**
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  - Modelling of the uncertainty in the **availability of BSs** in a K-tier HetNet[2].

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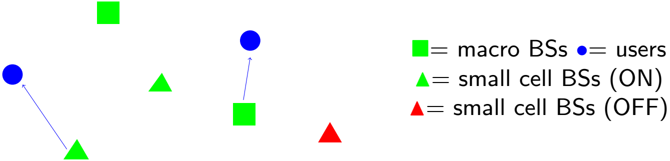

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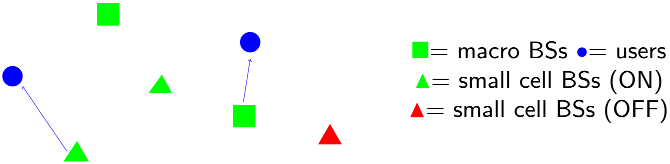

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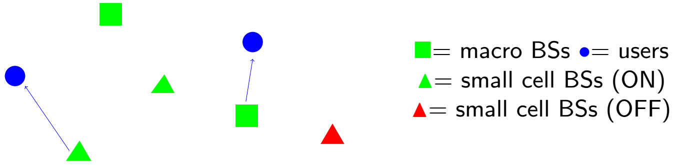
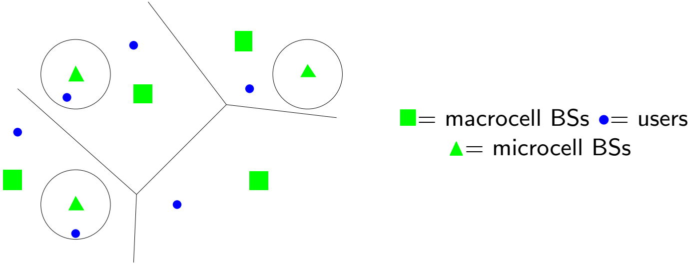


- **How does hand-off impact the call performance from a users point of view?**

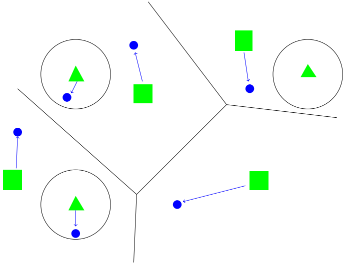
Network Model

- $K = 2$-tier HetNet downlink (tier 1=macrocells and tier 2=microcells);
- Location of macro BSs, micro BSs and users are modelled by an independent **Poisson Point Process (PPP)** with constant densities λ_1, λ_2 and λ_u, respectively;



Network Model (contd.)

- BSs in each tier are allocated the same constant transmit power P_1 and P_2, respectively;
- **Channel model**: path loss plus Rayleigh fading channel model;
- **Cell association policy**: each user is associated with the BS in the k-tier that provides the highest long term received power.



■= macrocell BSs •= users
▲= microcell BSs

BS Energy Harvesting Model

- Each BS has its own energy harvesting module and an **energy storage device of finite capacity** N_k.

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- Each BS has its own energy harvesting module and an **energy storage device of finite capacity** N_k.

- The **energy arrival process** at each tier BS is modelled as a Poisson process with mean energy harvesting rate μ_k[3].

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BS Energy Utilization Model

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- Energy utilisation is composed of two parts[4]:
  - **static energy utilization** related to energy utilization without any traffic load S_k;
  - **dynamic energy utilization** related to the traffic load (i.e., the number of users served by a BS) v_k;

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- BS energy utilization rate at kth tier BS

$$\gamma_k = S_k + v_k = S_k + D_k \overline{A_k} \lambda_u, \tag{1}$$

where D_k is the dynamic energy utilization rate per user, $\overline{A_k}$ is the kth tier BS's average service area and λ_u is the user density.

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BS Operational Model

- Each BS transmits to its users in each resource block over a short time scale, while each BS harvests energy over a long time scale;
- The BS energy state, J_k, can be modelled as a **continuous-time Markov chain**, with birth rate μ_k (i.e., mean energy harvesting rate) and death rate v_k (i.e., mean dynamic energy utilization rate);
- Two operational modes for each BS: ON and OFF

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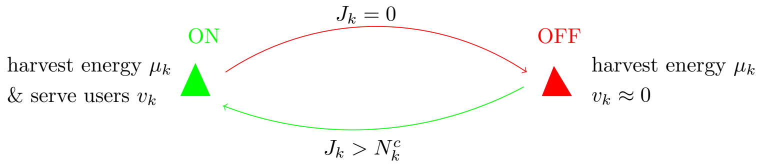

where N_k^c **($< N_k$) is the minimum energy level at which BS switches back ON**.

BS Availability Analysis

- **Lemma 1**: The mean time a kth tier BS spends in the ON state is given by the solution of the following equation

$$\mathbb{E}[J_k^{ON}] = \frac{\left(\frac{\mu_k}{v_k}\right)^{N_k} - \left(\frac{\mu_k}{v_k}\right)^{N_k - N_k^c + S_k \mathbb{E}[J_k^{ON}]}}{(v_k - \mu_k)^2 \mu_k^{-1}} - \frac{N_k^c - S_k \mathbb{E}[J_k^{ON}]}{\mu_k - v_k}, \quad (2)$$

where μ_k is the mean energy harvesting rate, v_k is the mean dynamic energy utilization rate, N_k is the battery capacity, N_k^c is the minimum energy level at which BS switches back ON and S_k is the static energy utilization rate.

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- **Lemma 2**: The mean time a kth tier BS spends in the OFF state is

$$\mathbb{E}[J_k^{OFF}] = \frac{N_k^c}{\mu_k}. \qquad (3)$$

Call Completion Probability

- For a traditional cellular network, corresponding to $K = 1$-tier, the call completion probability is the probability that[5]:
  - a call is **successfully connected** to the network in an arbitrary cell,
  - it experiences successful **handoffs**,
  - it survives bank-link periods, i.e., no **link breakage**,
  - it ends at an arbitrary cell when it is **terminated by the user**.

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- The call holding time T_c is a random variable. The cell-dwell time T_i is defined as the time duration that a user resides in the i the cell (independent and identically distributed T);

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Call Completion Performance Analysis

For a traditional cellular network, corresponding to $K = 1$-tier, the call completion probability can be expressed as[6]

$$\mathcal{P}^{\mathrm{c}} = (1-\rho_0)\mathbb{P}\left(T_{\mathrm{c}} < \left(R + \sum_{i=2}^{N} T_i\right), T_{\mathrm{c}} < \sum_{i=1}^{M} V_i\right) \qquad (4)$$

where ρ_0: the probability that a new call is blocked;
T_{c}: the call holding time of a user;
N: the index of the last cell where the user ends the call;
T_i: the ith cell dwell time (independent and identically distributed T);
R: the residual life of the call in the first cell;
V_i: the ith good link period;
M: the index of the last good link where the user ends the call.

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Call Completion Performance Analysis (contd.)

$$\mathcal{P}^{\mathrm{c}} = (1-\rho_0)\mathcal{M}_{T_{\mathrm{c}}}(-(a+b)), \quad (5)$$
$$a = \frac{\rho_f}{\rho_f \mathbb{E}[R] + (1-\rho_f)\mathbb{E}[T]},$$
$$b = \frac{\rho_{\mathrm{link}}}{\mathbb{E}[V]},$$

where
$\mathcal{M}_{T_{\mathrm{c}}}(\cdot)$: MGF of the random variable T_c;
ρ_f: the probability of handoff failure;
ρ_{link}: the probability of a link breakage;
$\mathbb{E}[R]$: the mean residual life of the call in the first cell which depends on the distribution of T;
$\mathbb{E}[V]$: the expected time of a good link period;
$\mathbb{E}[T]$: the mean cell dwell time.

Call Completion Performance Analysis

Assumptions:

- User mobility does not trigger a hand-off and only BSs turning ON and OFF causes the hand-off;
- Inside the two-tier HetNet, **cross tier hand-offs** can occur. The mean cell dwell time $\mathbb{E}[T]$ in term a is

$$\mathbb{E}[T] = \mathcal{P}_1^{\mathrm{s}}\mathbb{E}[J_1^{ON}] + \mathcal{P}_2^{\mathrm{s}}\mathbb{E}[J_2^{ON}].$$

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- In general, $\mathbb{E}[R] = \mathbb{E}[T^2]/2\mathbb{E}[T]$. The distribution of T is hard to derive in this case. However, from its definition, since R is bounded as $0 \leq R < T$, $\mathbb{E}[R]$ is bounded by 0 and $\mathbb{E}[T]$;

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- Assume an **exponential distribution for the call holding time T_c**, which is a commonly used model in the literature;
- Assume that a **call** initiated by the user is **never blocked by the network**, i.e., $\rho_0 = 0$.

Call Completion Performance Analysis

- **Lemma 3:** For a $K = 2$-tier HetNet with energy harvesting BSs, assuming the call initiated by the user is never blocked by the network, the call holding time follows an exponential distribution and hand-off is only caused by BSs turning ON and OFF, the overall call completion probability is bounded by

$$\frac{1}{M_{T_{\mathrm{c}}}(a_1 + b) + 1} \leq \mathcal{P}^{\mathrm{c}} \leq \frac{1}{M_{T_{\mathrm{c}}}(a_2 + b) + 1}, \qquad (6)$$

where $M_{T_{\mathrm{c}}}$ is the average call holding time, $a_1 = \frac{\rho_f}{(1-\rho_f)\left(\mathcal{P}_1^{\mathrm{s}}\mathbb{E}[J_1^{ON}]+\mathcal{P}_2^{\mathrm{s}}\mathbb{E}[J_2^{ON}]\right)}$, $a_2 = \frac{\rho_f}{\mathcal{P}_1^{\mathrm{s}}\mathbb{E}[J_1^{ON}]+\mathcal{P}_2^{\mathrm{s}}\mathbb{E}[J_2^{ON}]}$, $b = \frac{\rho_{\mathrm{link}}}{\mathbb{E}[V]}$, $\mathbb{E}[J_k^{ON}]$ is the mean kth tier BS ON time and $\mathcal{P}_k^{\mathrm{s}}$ is the kth tier association probability.

Call Completion Performance Analysis

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- The **average service area** of a kth tier BS is

$$\overline{A_k} = \frac{P_k^{\frac{2}{\alpha}}}{\sum_{j=1}^{2} \lambda_j \mathcal{P}_j^{\mathrm{a}} P_j^{\frac{2}{\alpha}}}. \tag{7}$$

where the **availability** of kth tier BS is

$$\mathcal{P}_k^{\mathrm{a}} = \frac{\mathbb{E}[J_k^{ON}]}{\mathbb{E}[J_k^{ON}] + \mathbb{E}[J_k^{OFF}]}, \tag{8}$$

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where $\mathbb{E}[J_k^{ON}]$ and $\mathbb{E}[J_k^{OFF}]$ represent the mean kth tier BS ON and OFF times and $\mathbb{E}[\cdot]$ denotes expectation.

- The probability that a typical user is **associated** with the kth tier BS is

$$\mathcal{P}_k^{\mathrm{s}} = \lambda_k \mathcal{P}_k^{\mathrm{a}} \overline{A_k}. \tag{9}$$

Results and Discussions

The overall energy utilization of a macro BS only varies about 3% for a 3G BS and 2% for a 2G BS over a period of several days, while its traffic load varies from no load to peak load[7]. Thus, we ignore the dynamic energy utilization of a macro BS and set $D_1 = 0$. we then have

$$\gamma_1 = S_1,$$
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For the macro BS, the expected ON time can be solved as

$$\mathbb{E}[J_1^{ON}] = \frac{N_1^{\mathrm{c}}}{S_1 - \mu_1}, \tag{10}$$

and the macro BS availability is

$$\mathcal{P}_1^{\mathrm{a}} = \frac{\mu_1}{S_1}. \tag{11}$$

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System Parameters

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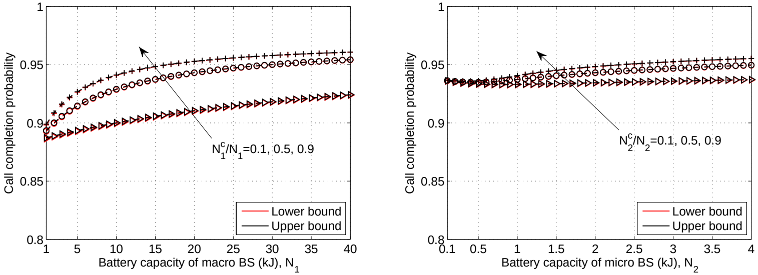
Parameters	Notation	Value
Path loss exponent	α	4
Ratio of transmit power	P_1/P_2	10
Macro BS density (per km^2)	λ_1	1.4
Micro BS density (per km^2)	λ_2	3.7
User density (per km^2)	λ_u	18
Static energy utilization rate of micro BSs (kJ/s)	S_2	0.025
Dynamic energy utilization rate of micro BSs (kJ/s)	D_2	0.007
Static energy utilization rate of macro BSs (kJ/s)	S_1	1.43
Dynamic energy utilization rate of macro BSs (kJ/s)	D_1	0
Average call duration (s)	M_c	180
Handoff failure probability	ρ_f	0.01
Link breakage probability	ρ_link	0.01
Expected good link period (s)	$\mathbb{E}[V]$	60
Energy harvest rate of macro BSs (kJ/s)	μ_1	1.3
Energy harvest rate of micro BSs (kJ/s)	μ_2	0.2
Battery capacity of macro BSs (kJ)	N_1	20
Battery capacity of micro BSs (kJ)	N_2	2
Ratio of switching state and battery capacity	N_k^c/N_k	0.5

Results and Discussions

Effect of Battery Capacity

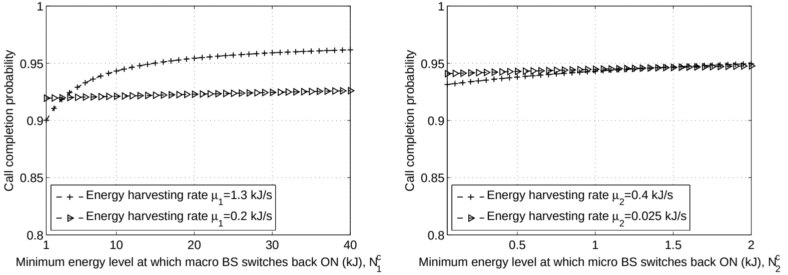


(a) Effect of battery capacity for macro BSs. (b) Effect of battery capacity for micro BSs.

Fig.1 Call completion probability versus the battery capacity for macro BS and micro BS, respectively, with different ratio of the minimum energy level at which BS switches back ON and battery capacity (i.e., $N_k^c/N_k = 0.1, 0.5, 0.9$) for $k = 1, 2$.

Results and Discussions

- **Effect of the Minimum Energy Level at which BS switches back ON**



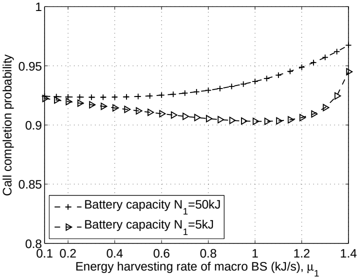
(a) Effect of the minimum energy level at which macro BS switches back ON.

(b) Effect of the minimum energy level at which micro BS switches back ON.

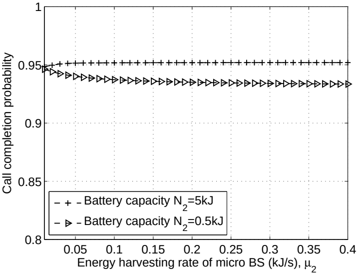
Fig.2 Call completion probability versus the minimum energy level at which BS switches back ON, for macro BS and micro BS respectively, with different energy harvesting rate.

Results and Discussions

- **Effect of the Minimum Energy Level at which BS switches back ON**



(a) Effect of energy harvesting rate for macro BSs.



(b) Effect of energy harvesting rate for micro BSs.

Fig.3 Call completion probability versus the energy harvesting rate for macro BS and micro BS, respectively, with different battery capacity.

Conclusions

- We derived tight upper and lower bounds on the call completion probability of a two-tier heterogeneous network with energy harvesting BSs, using a realistic BS energy consumption model, where the hand-off of a call is governed by BSs switching the ON and OFF;
- We examined the impact of the system parameters (i.e., battery capacity, the minimum energy level at which BS switches back ON and energy harvesting rate) on the call completion probability.
- Results showed that the macro BS energy harvesting parameters have the dominant impact on the call completion probability.

Thank you for your attention!