Inter-Cell Coordinated Napping (CoNap) for Energy Saving in Cellular Networks

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Power efficiency (PE) or energy efficiency (EE) has become one of the important metrics of cellular communication systems [1], [2].

Base station (BS) is a major power consumer in the wireless network, i.e., more than 50% of the whole network power is consumed at BSs.

Hence, the network power/energy consumption can be effectively reduced by reducing the power/energy consumption of the BS.
Introduction ~ Inter-Cell Interference ~

- Inter-cell interference (ICI) limits spectrum efficiency (SE) (Figure 1).
- Coordinated multi-point (CoMP) can eliminate the ICI by cooperatively processing users’ signals at multiple BSs [3], [4].
- For the improvement of PE/EE, ICI needs to be carefully dealt with. → CoMP is also effective to improve the PE/EE [5].

*Figure 1: Inter-cell interference (a) w/o CoMP (b) w/ CoMP.*
Introduction ~ Time-Varying Traffic Load ~

- The traffic load of cellular communication systems has dynamic nature in both time and space (location) as shown in Figure 2 [6].
  - *High traffic load condition*: almost all the resources are used to satisfy traffic demands.
    - No room for power/energy saving.
  - *Low traffic load condition*: a part of the resources is sufficient.
    - Room for power/energy saving.

![Traffic load graph](image)

**Figure 2**: Time varying traffic load.
Related Works ~ Cell Zooming [7] ~

- Deactivation of several BSs $\rightarrow$ Reduction of unnecessary power consumption during low traffic load conditions.
- By *adjusting/optimizing the parameters* (e.g., transmit power)
  - Coverage area expansion
  - Larger transmit power and/or more resources are necessary $\rightarrow$ large inter-cell interference.

**Figure 3:** BS deactivation with cell zooming.
Related Works \sim CoMP [8]\sim

- CoMP technologies, e.g., coordinated beamforming
  - Coverage area of deactivated BS can be covered.
  - Optimization of parameters and information exchange among cooperating (active) BSs are necessary \rightarrow Huge overhead & complex.

\textbf{Figure 4:} BS deactivation with CoMP.
Proposed Approach ~ Coordinated Napping ~

- In this paper, we propose “Coordinated Napping (CoNap)” → BSs intermittently transmit the signal in a coordinated manner.
- Each BS selects its mode from “transmit mode (TM)” and “nap mode (NM)” as if it is *flickering*.
  - **TM**: BS transmits the signal to its serving users.
  - **NM**: BS does not transmit signal.
- CoNap is realized by *a general binary flickering pattern matrix* and *a mapping matrix*.

![Figure 5: Flickering with TM and NM.](image-url)
CoNap ~ System Model ~

- Consider a downlink cellular system.
  
  $U$ : Number of users  
  $S$ : Number of time slots.  
  $M$ : Number of frequency domain resource blocks (RBs).  
  $t_{\text{frame}}$ : Length of one transmission period.  
  $t_{\text{ts}}$ : Length of one time slot, i.e., $(t_{\text{frame}}/S)$.

![Figure 6: Frame structure.](image-url)
CoNap ~ BS Clustering ~

- Each BS’s mode (TM or NM) is determined by the flickering pattern.
- The ICI cannot be reduced if each BS randomly selects the flickering pattern (Fig. 7 (a)).
  → BSs are divided into non-overlapping clusters with the size of $B$ (Fig. 7 (b)).

![Diagram](image)

**Figure 7:** ICI (a) w/o BS clustering (b) w/ BS clustering with $B = 3$. 
CoNap ~ General Binary Flickering Pattern Matrix ~

- A general binary flickering pattern matrix with $Q$-by-$S$:

$$F_G = \begin{pmatrix}
    f_1^T \\
    \vdots \\
    f_q^T \\
    \vdots \\
    f_Q^T \\
\end{pmatrix} = \begin{pmatrix}
    f_{1,1} & \cdots & f_{1,s} & \cdots & f_{1,S} \\
    \vdots & \ddots & \vdots & & \vdots \\
    f_{q,1} & \cdots & f_{q,s} & \cdots & f_{q,S} \\
    \vdots & & \ddots & & \vdots \\
    f_{Q,1} & \cdots & f_{Q,s} & \cdots & f_{Q,S} \\
\end{pmatrix}, \quad (1)$$

where

$$f_{q,s} = \begin{cases}
    1, & \text{BS is in a TM} \\
    0, & \text{BS is in a NM}
\end{cases} \quad (2)$$

$S$ : Flickering pattern cycle.
$Q$ : Number of patterns → whole pattern is covered by setting $Q = 2^S$.
$f_q$ : $S$-by-1 flickering pattern binary column vector.
CoNap \sim Mapping Matrix \sim

- A $B$-by-$Q$ binary mapping matrix $M_G$:

$$M_G \triangleq (e_{i_1} \cdots e_{i_b} \cdots e_{i_B})^T.$$  \hfill (3)

$$\begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ b-1 & B-b \end{pmatrix}$$

- A selected flickering pattern matrix is obtained as

$$N \triangleq (n_1 \cdots n_b \cdots n_B)^T.$$  \hfill (4)

$$\text{flickering pattern of BS } b$$

$$= (e_{i_1} \cdots e_{i_b} \cdots e_{i_B})^T (f_1 \cdots f_q \cdots f_Q)^T$$

$$= (f_{i_1} \cdots f_{i_b} \cdots f_{i_B})^T.$$
Orthogonal Pattern Assignment

- Each column of $N$ contains only one 1.
- No intra-cluster interference.
- The number of available time slots for each BS is reduced.

$$\mathbf{N}_{\text{orth}}^{(1)} = (e_5 \ e_3 \ e_2)^T \mathbf{F}_G = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix},$$

$$\mathbf{N}_{\text{orth}}^{(2)} = (e_3 \ e_2 \ e_7)^T \mathbf{F}_G = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}.$$  \hspace{1cm} (5)

\textbf{Figure 8}: Orthogonal pattern assignment with $S = B = 3$ (a) $\mathbf{N}_{\text{orth}}^{(1)}$ (b) $\mathbf{N}_{\text{orth}}^{(2)}$. 
Network Power Model ~ Traffic Load of BS ~

- The traffic load is calculated as

\[ \rho_{b,s} = \frac{1}{M} \sum_{u=1}^{U} w_{u,b,s}. \]  

  Number of allocated RBs to user \( u \).

- \( w_{u,b,s} \) is given so that the target rate is satisfied as

\[ R_{u}^{\text{tar}} \leq \sum_{b \in C} \sum_{s=1}^{S} w_{u,b,s} R_{u,b,s}. \]  

  Achievable rate of user \( u \).

- Since the total number of RBs is \( M \), some of users may not be allocated to sufficient number of RBs to satisfies (7).

- Those users are considered to be blocked.
Network Power Model \sim \text{Power Consumption of BS} \sim

- The power consumption of BS for traffic load $\rho_{b,s}$ is given as [9]

$$P_{tx}(\rho_{b,s}) = (P_{\text{fix}} + \rho_{b,s}P_{\text{dyn}} + P_{\text{PA}}(\rho_{b,s}))P_{\text{loss}}. \quad (8)$$

- $P_{\text{fix}}$: Power consumption at small-signal RF transceiver.
- $P_{\text{dyn}}$: Power consumption at base band interface.
- $P_{\text{PA}}(\rho_{b,s})$: Power consumption at power amplifier (PA) for given traffic load $\rho_{b,s}$.
- $P_{\text{loss}}$: Power loss due to AC-DC, DC-DC converters, and cooling equipment.

- The power consumption during NM is given as

$$P_{\text{nap}} = P_{tx}(0) = P_{\text{fix}}P_{\text{loss}}. \quad (9)$$

- Each value of the consumed power is given as $P_{\text{fix}} = 10.8$ Watt, $P_{\text{dyn}} = 14.8$ Watt, and $P_{\text{loss}} = 23.6\%$ [2].
Network Power Model ~ Energy Consumption of Cluster ~

- Total energy consumption of a cluster during one flickering pattern cycle:

\[
E_c(\{f_{i_b,s}, w_{u,b,s}\}) = t_{ts} \sum_{b \in C} \sum_{s \in \mathcal{S}_{tx,b}} P_{tx}(\rho_{b,s}) + t_{ts}P_{nap} \sum_{b \in C} (S - |\mathcal{S}_{tx,b}|),
\]

\[
\begin{align*}
\text{Energy consumption during TM} & \quad \text{Energy consumption during NM} \\
\end{align*}
\]

\(\mathcal{S}_{tx,b} : \text{Set of time slots with } f_{i_b,s} = 1, \text{ e.g., } \mathcal{S}_{tx,b} = \{b\} \text{ in Fig. 9.}
\]

Figure 9: Energy consumption of cluster.
Simulation Results ~ Simulation Environments ~

- Hexagonal cell layout is considered and cell radius is set to 290 (m).
- Path loss \((128.1 + 37.6 \log_{10} d \text{ with } d \text{ is the distance in km})\).
- Log-normally distributed shadowing loss with the standard deviation of 8 dB.
- For user scheduling, round robin (RR) is used.
- For CoNap, the following mapping matrix is used to generate orthogonal flickering pattern:
  \[ M_{\text{fix}} = (e_{i_1} \cdots e_{i_b} \cdots e_{i_B})^T, \]  \(11\)
  where \(i_b = 1 + 2^{S-b}\).
- For performance comparison, the following strategies are considered:
  - The conventional system with \(B = 1\), i.e., without flickering,
  - The case when flickering pattern is randomly chosen at each BS (pattern with all 0’s is omitted), i.e., without coordination, and flickering pattern cycle is set to \(S = B\).
Simulation Results \sim\ Average Energy Consumption \sim

- The total energy consumption per BS is shown as a function of the number of users per cell ($U/B$).
- The average energy consumption is significantly saved by flickering.
- From the figure, the additional energy saving can be obtained by CoNap.
- More that 50% energy saving can be achieved by CoNap.

**Figure 10:** Average energy consumption per BS (J).
Simulation Results ∼ Average Blocking Probability ∼

- As cluster size $B$ increases, the blocking probability becomes higher.
- For random flickering, the uncoordinated flickering pattern which introduce large interference. → the blocking probability is significantly higher than CoNap.

**Figure 11:** Average blocking probability.
Conclusion

- Coordinated napping (CoNap) is proposed in this paper.
- Intermittent transmission of multiple BSs within a cluster is performed in a coordinated manner.
- CoNap is realized by
  - A general binary flickering pattern matrix, which includes all the possible flickering patterns,
  - A mapping matrix, which maps flickering patterns to BSs.
- It was shown that the proposed CoNap can significantly reduce the network energy consumption, more than 50%, while satisfying the target rate requirement.
Reference


