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Towards Energy Efficient Relay Placement and Load Balancing in Future Wireless Networks

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Abstract—This paper presents an energy efficient relay deployment algorithm which determines the optimal location and number of relays for Long Term Evolution (LTE)-Advanced heterogeneous networks. In this paper, we define an energy minimization problem for macro-relay heterogeneous networks using Mixed Integer Linear Programming (MILP). The proposed algorithm not only dynamically connects users to either relay or macro base station based upon transmission and circuit energy consumption but also allows macro base stations to switch into sleep mode. More specifically, we enable relay to relay communication which forms the basis for relays to act as donors for neighbouring relays instead of macro eNodeBs (eNB)s and relaxes traffic load of some eNBs in order to switch these eNBs into sleep mode. We carried out intensive performance evaluation of the proposed algorithm and our findings show that optimal relay deployment with relays acting as donors can significantly improve system energy efficiency.

Index Terms—LTE/LTE-Advanced, Energy Efficiency, Macro-relay, Heterogeneous Networks.

I. INTRODUCTION.

THE growing energy costs and ecological challenges in combating climate change have recently stimulated the curiosity of standardization bodies and researchers in an emerging research area termed energy efficient wireless networks [1], [2]. In this regard, several international research projects have recently started to address the energy efficiency in cellular systems namely “Energy Aware Radio and Network Technologies (EARTH)”, “Cognitive Radio and Cooperative strategies for Power saving in multi-standard wireless devices (C2POWER)” and “Towards Real Energy-efficient Network Design (TREND)” [3]-[5].

Energy efficiency in macro-relay network has received significant attention because relaying is a promising approach to improve capacity, and energy efficiency of wireless networks [6]-[8]. The energy consumption in macro-relay networks depends upon two aspects: (i) transmission energy; and (ii) circuit energy consumption. The circuit energy consumption of the macro base station and relay node should be considered jointly especially in low traffic load conditions in order to improve network wide energy efficiency.

In heterogeneous networks, energy minimization in macro-relay networks has been studied in [6] and [7]. The authors in [6] and [7] considered a macro-relay network in which not only the rate requirements of the users are guaranteed, but also the energy consumption of the wireless network

is minimized. More specifically, the authors formulated an integer optimization problem and proposed a dynamic macro-relay selection heuristic algorithm for energy minimization. However, each of the above contributions has some limitations. More specifically, the macro-relay network considered in [6] is restricted to only single cell and relay environments. Similarly, the authors in [7] considered a network scenario with M relays and one base station. However, the proposed solutions in [6] and [7] do not seem to be generalizable to standard Third Generation Partnership Project (3GPP) multi-cell environment. To the best of the authors’ knowledge, energy efficiency of a macro-relay network with relays acting as donors for neighbouring relays has never been proposed before in the literature.

In this paper, our high-level goal is to deploy the Relay nodes in such a way that minimizes the total energy consumption from Relays and eNodeBs (eNB)s. This is obtained in two ways: (i) by being able to turn off some of the eNBs; and (ii) by optimally deploying relay nodes. Note that optimally placing relay nodes should lead to shorter-range, and thus lower-power, transmissions, as well as enabling switching off some eNBs. Additional constraints include the need to guarantee a minimum throughput to users, and a maximum number of Relay Nodes (RNs) that can be deployed. For the present we focus on downlink traffic only. The rationale is that currently downlink traffic, i.e., content downloads, accounts for the majority of the traffic demand in cellular networks. We formulate the problem into a Mixed Integer Linear Programming (MILP) optimization problem. Then, we propose both exact and distributed solutions for energy minimization of macro-relay networks. Extensive performance evaluation results reveal that the proposed algorithm significantly reduces the energy consumption of the macro-relay network.

The rest of this paper is organized as follows. The system model is presented in Section 2. A unique algorithm for optimization of energy efficient relay placement and load balancing is proposed in Section 3. The performance evaluation curves for the proposed algorithm are presented in section 4. Finally, conclusion and future work is presented in section 5.

II. SYSTEM MODEL

In this paper, we consider a downlink macro-relay network consisting of macro eNBs, low power RNs and User Equipment (UE). An overview of multi-cell macro-relay network

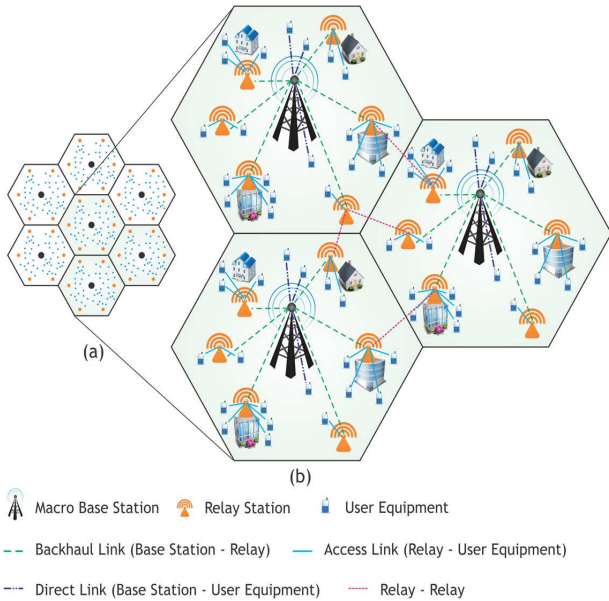


Figure 1. An illustration of a macro-relay network with relay to relay communication (a) An overview of a seven cell macro-relay network; (b) A detailed illustration of communication among different nodes in a macro-relay network.

is shown in Fig. 1 (a). The base stations, RNs and UEs are equipped with single antenna. In this paper, we consider in-band Type 1 LTE-Advanced RNs which utilize the same frequency resources for both backhaul (BS to relay) and access (relay to UE) links. Moreover, the backhaul and access links are time-division multiplexed in order to avoid interference between these links. The RNs must connect to a donor macro eNB either through a backhaul link or, in a multi-hop fashion, to another RN as shown in Fig. 1 (b). The users can connect to the network either through macro eNB directly or through RNs utilizing Decode and Forward (DF) technique as shown in Fig. 1 (b). The UEs are uniformly distributed in the macro-relay network under consideration. Moreover, the energy consumption of UEs can vary depending on the distance and path loss from macro eNBs or RNs. In this paper, we adopt a large-scale path loss propagation model which is endorsed by 3GPP [9]-[11].

A. Power model

The EARTH project [3] has provided a linear power model for different types of base stations which models the relation between base station power consumption P_{in} and Radio Frequency (RF) output power P_{out} . The EARTH project power model is represented below symbolically in equation (1) and equation (2).

$$P_{in} = P_0 + \nabla p \times P_{out}, \quad 0 < P_{out} \leq P_{max} \quad (1)$$

$$P_{in} = P_s, \quad P_{out} = 0 \quad (2)$$

where P_{max} represents the maximum RF output power at full load, P_0 is the minimum power consumption when the base

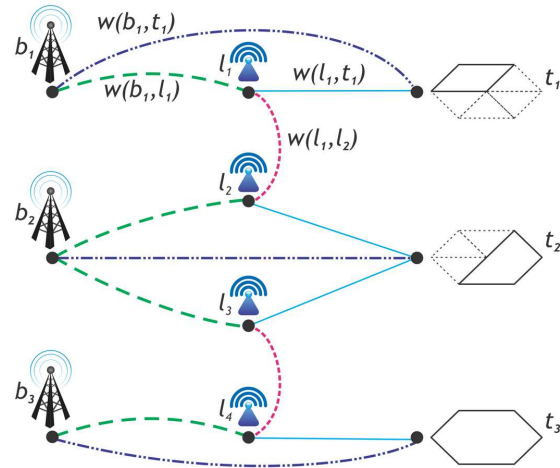


Figure 2. An illustration of a LTE-Advanced macro-relay network using graph colouring approach.

station is idling, P_s denotes the energy consumption when the base station is sleeping and ∇p denotes the power amplifier efficiency. The power consumption parameters for different types of base stations and relays, based on EARTH project state-of-the-art estimation, are presented in Table I and Table II respectively.

Table I. EARTH PARAMETERS FOR DIFFERENT BASE STATIONS

LTE BS Type	P_{max} [W]	P_0 [W]	∇p	P_s [W]
Macro	40	712	14.5	558
Micro	6.3	106	6.35	78
Pico	0.13	13.6	8.0	8.6
Femto	0.05	9.6	15	5.8

Table II. EARTH PARAMETERS FOR DIFFERENT RELAY STATIONS

LTE Relay Type	P_{max} [W]	P_0 [W]	∇p
Relay Urban 2014	1	19.91	5.6
Relay Rural 2014	5	28.5	5.6
Relay Advanced	5 or 1	13.91	20.4
Relay SOTA	5 or 1	84.13	6.35

III. OPTIMIZATION OF ENERGY EFFICIENT RELAY PLACEMENT & LOAD BALANCING

In this section, we present an analytical model for optimization of energy efficient relay placement and load balancing in macro-relay network using a graph colouring approach. Directly modeling the scenario in Fig. 1 is not particularly useful for our purpose. The main problem is represented by UEs because we do not, in general, know their position well enough to accurately forecast the quality of their links with Macro eNBs and potential RNs. Furthermore, positions, link qualities, and traffic demands significantly change over time, while our RN deployment will be much more static. Thus, we divide the network service area in a set τ of non-overlapping tiles. Tiles may have different sizes and shapes, and are in general no bigger than a cell as shown in Fig. 2.

For each tile t , we define τ_t as the amount of traffic (e.g., Mbits) requested by each user; we assume τ_t to be known. We also know the set B of eNBs, and the set L of candidate locations where RNs may be placed. The eNBs, relay candidate locations and tiles constitute the vertices of a graph, representing our network. The edges $E \subseteq (B \cup L) \times (L \cup \tau)$ of the graph represent the connectivity opportunities among the vertices. We assume that each macro base station provides single cell coverage. Therefore, we ignore redundant edges representing direct link connection opportunities in set E from each macro BS to its neighboring cells. Similarly, we ignore redundant edges representing backhaul link connection opportunities in set E from each macro BS to its neighboring cells.

For each edge $(e_1, e_2) \in E$, we know the weight $w(e_1, e_2)$, expressing how much data we can transfer from e_1 (corresponding to an eNB or a RN) to e_2 (corresponding to a RN or a tile). For each of the following pairs (candidate location, tile), (eNB, tile), (eNB, candidate location), (candidate location, candidate location) that are connected by an edge $(e_1, e_2) \in E$, we know the associated transmit power, $P(e_1, e_2)$. Furthermore, active eNBs and RNs consume an amount of power, respectively, $P_0(b)$ and $P_0(l)$, which depend on the transceiver electronics, cooling, etc., i.e., they are independent of the node traffic load. Finally, we have a maximum number R of RNs that can be deployed due to operators' budget constraint.

We formulate the energy efficient relay placement optimization algorithm as a MILP problem. First, we introduce a set of binary variables $y_l, y_b \in \{0, 1\}$, expressing, respectively, whether we place an RN in candidate location $l \in L$, and whether eNB $b \in B$ is on or not. Furthermore, we need to express how much traffic we transmit between UEs, RNs and eNBs. We do so through variables $x(e_1, e_2) \in R$. At last, we introduce a set of binary variables $z(b, l)$, each expressing whether $b \in B$ is a donor eNB for RN in location $l \in L$. To streamline the notation, we also indicate with $D_l \in B$ the donor eNB for RN in l .

Constraints. The first constraint we introduce concerns weights. For each pair of endpoints (UEs, RNs and eNBs) that can communicate, the amount x of transmitted data must not exceed the weight w of the edge:

$$x(e_1, e_2) \leq w(e_1, e_2). \quad (3)$$

Next, a flow conservation equation holds for RNs. These are purely relay nodes, so the amount of data entering and exiting each of them must be the same:

$$\sum_{e_1 \in B \cup L} x(e_1, l) = \sum_{e_2 \in L \cup \tau} x(l, e_2), \forall l \in L. \quad (4)$$

As far as the association between RNs and their donors (be them an eNB or another RN) is concerned, each active RN should be associated with exactly one donor only at the time:

$$\sum_{e \in B \cup L} z(e, l) = y_l, \forall l \in L. \quad (5)$$

Additionally, inactive eNBs and RNs cannot act as donor for any RN.

$$\sum_{e \in B \cup L} \sum_{l \in L} z(e, l) \leq \sum_{e \in B \cup L} y_e, \forall e \in B \cup L. \quad (6)$$

Clearly, no data flow can exit non-active candidate locations or eNBs, i.e., the ones with $y_l = 0$ or $y_b = 0$. We thus change the capacity constraint as follows:

$$x(e_1, e_2) \leq y_{e_1} \cdot w(e_1, e_2), \forall e_1 \in B \cup L. \quad (7)$$

When $y_{e_1} = 0$, i.e., the source endpoint (eNB or RN) is off, the right-hand side term is zero and no data can be transmitted. Similarly, we have to make sure that no data flow between eNBs and RNs that are not associated with each other, i.e., whose z -value is zero:

$$x(b, l) \leq z(b, l) \cdot w(b, l), \forall b \in B, l \in L. \quad (8)$$

Last, as mentioned earlier, at least τ_t traffic should be delivered to each tile t . This translates into the following constraint:

$$\sum_{b \in B} x(b, t) + \sum_{l \in L} x(l, t) \geq \tau_t. \quad (9)$$

Notice that in the above we do not have to insert y -variables, as they are enforced already in constraint.

It is worth mentioning here that in order to ensure the deployment of the maximum number of relays in all possible candidate relay locations we need to set the following constraint:

$$\sum_{l \in L} y_l \leq R, \forall l \in L. \quad (10)$$

Objective. Our objective is to minimize the total power consumed by the network. This includes:

- the fixed power P_0 for activated eNBs and RNs;
- the traffic-dependent power $P(e_1, e_2)$ for pairs of communicating endpoints.

In symbols, we have:

$$\min \sum_{b \in B} \left(y_b P_0(b) + \sum_{l \in L} P(b, l) x(b, l) + \sum_{t \in \tau} P(b, t) x(b, t) \right) + \sum_{l \in L} \left(y_l P_0(l) + \sum_{t \in \tau} P(l, t) x(l, t) \right). \quad (11)$$

Objective (11) is linear, and so are all our constraints. Our problem is a fairly MILP problem, where the complexity issue is represented by the binary variables y .

A. Optimization Problem Complexity and Solution

The energy efficient optimal relay deployment MILP problem in (11) can be solved optimally using the state-of-the-art IBM CPLEX Mixed Integer Optimizer. However, the large instances of the above problem can prove challenging to be solved optimally. More specifically, it is obvious from the objective function and constraints in equation (3)-(10) that the total number of terms inside constraints can rise significantly with the increase in the number of nodes such as macro base stations, candidate relay locations and users. The rationale behind it is that the number of connection opportunities among different nodes increase with the addition of more nodes. Therefore, the complexity of CPLEX Mixed Integer Optimizer optimal solution increases dramatically as we move from smaller clusters of hexagonal cells to larger clusters. This

Table III. PERFORMANCE EVALUATION PARAMETERS

Parameter	Value
System Parameters	
Carrier Frequency	2 GHz
Bandwidth	20 MHz
Thermal Noise PSD	-174 dbm/Hz
eNB Parameters	
Transmit Power	43 dbm
Antenna Configuration	Tx-1, Rx-1
Relay Parameters	
Transmit Power	30 dbm
Antenna Configuration	Tx-1, Rx-1
UE Parameters	
Transmit Power	23 dbm
Antenna Configuration	Tx-1, Rx-1
User Distribution	Uniform + Hotspot
Channel Models	
Distance & Path Loss	R[km] & PL [dB]
Direct Link (Macro-UE)	
$PL_{LOS}(R)=103.4+24.2\log_{10}(R)$ $PL_{NLOS}(R)=131.1+42.8\log_{10}(R)$ $P(LOS)=\min(0.018/R,1)*(1-\exp(-R/0.063))+\exp(-R/0.063)$	
Access Link (Relay-UE)	
$PL_{LOS}(R)=103.8+20.9\log_{10}(R)$ $PL_{NLOS}(R)=145.4+37.5\log_{10}(R)$ $P(LOS)=0.5-\min(0.5,5\exp(-0.156/R))+\min(0.5,5\exp(-R/0.03))$	
Backhaul Link (Donor eNB-Relay & Relay-Relay)	
$PL_{LOS}(R)=100.7+23.5\log_{10}(R)$ $PL_{NLOS}(R)=125.2+36.3\log_{10}(R)-b$	
$P(LOS)=1-(1-\min(0.018/R,1)*(1-\exp(-R/0.072))+\exp(-R/0.072))^c$ $b=5$ and $c=3$.	
Deployment Scenario	
3GPP Case 1 Urban scenario	ISD=500 m

complexity issue forms the basis to investigate for improved solution strategies. In this regard, one practical and effective approach is to apply a distributed solution technique in which we can make repetition of smaller cells clusters in order to formulate a larger cluster. These smaller cells clusters can firstly be solved efficiently in a distributed manner and then we can merge all the distributed solutions in order to obtain the whole network wide solution. As a result, we can achieve sub-optimal energy efficient optimal relay deployment solution with much lower complexity as compared to optimal CPLEX solution. However, this improvement in computational complexity comes at the cost of performance gap between optimal CPLEX solution and sub-optimal distributed solution.

IV. PERFORMANCE EVALUATION

In this section, we present performance evaluation of our proposed energy efficient optimal relay deployment algorithm. We have presented parameter values for macro-relay network performance evaluation in Table III. The first scenario which we considered for performance evaluation consists of 7 cells macro-relay network with uniformly distributed users as shown in Fig. 3. A graph of number of macro base stations in operation versus total offered traffic load in seven cells is shown in Fig. 4. It is evident from Fig. 4 that most of the macro base stations are operating in sleep mode at lower total offered traffic load while these macro base stations switch into active mode as the total offered traffic load increases in seven cells. A comparison of power consumption versus total offered traffic load in seven cells is shown in Fig. 5. The bar labelled “optimal” in Fig. 5 represents the scenario where we take into

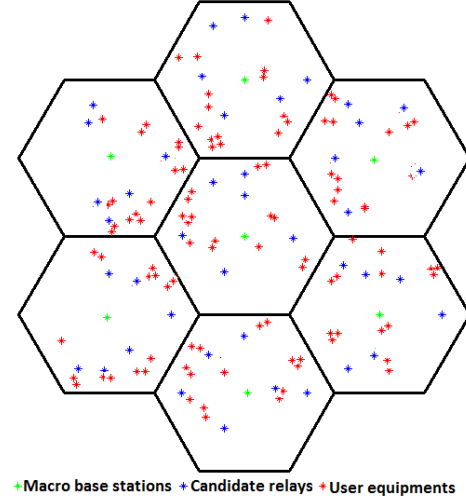


Figure 3. An illustration of a 7 cell LTE-Advanced macro-relay network with uniformly distributed users.

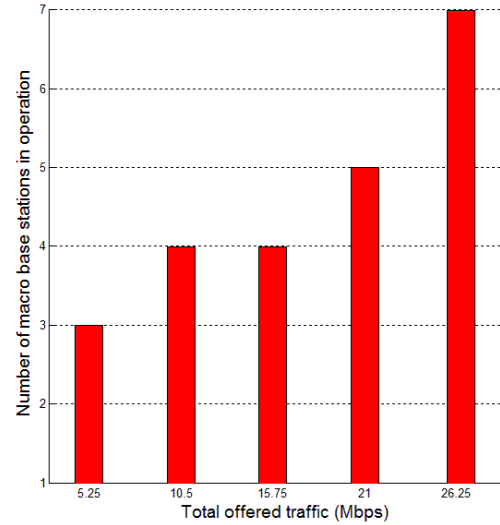


Figure 4. A graph of active macro base stations versus offered traffic load for a seven cell LTE-Advanced macro-relay network.

account transmission and circuit energy of both macro base stations in active mode along with deployed relays which are obtained by solving the problem using CPLEX. Similarly, the bar labelled “macro relay network without sleep mode” in Fig. 6 represents the scenario where we consider transmission and circuit energy of all macro base stations in the network along with deployed relays. Finally, the curve “no relays” in Fig. 5 represents the scenario where we only deploy macro base stations and no relays. A graph of Energy Consumption Index (ECI) or (Power/Data rate) versus total offered traffic load in seven cells is shown in Fig. 6. It must be mentioned here that both power consumption and ECI of optimal solution is significantly lower than both “no relays” and “macro relay network without sleep mode”. The rationale behind this fact is that some of the macro base stations are operating in sleep mode for the optimal scenario. More specifically, the proposed multi-hop relay to relay communication allows some of the

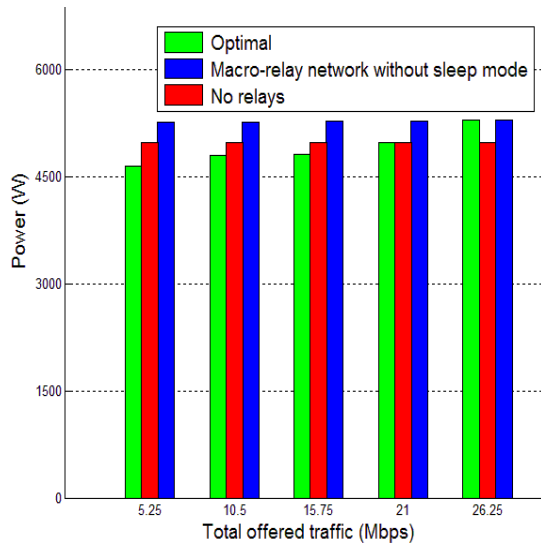


Figure 5. A comparison of power consumption for a 7 cell LTE-Advanced macro-relay network.

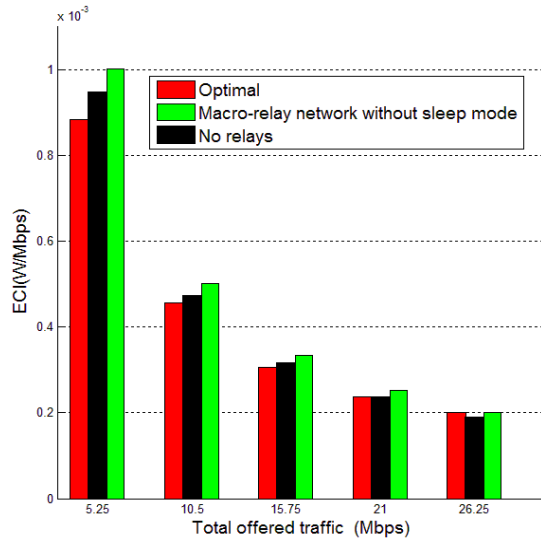


Figure 6. A graph of energy consumption index for a seven cell LTE-Advanced macro-relay network.

relays to act as donors for neighboring cell relays and put some of the macro base stations in sleep mode. As a result, the macro-relay network consumes less circuit energy as compared to the macro network without relays. It is evident from Fig. 5 that power consumption of the optimal solution is 6.8% lower than the no relays case at offered traffic load of 5.25 Mbits/s in Fig. 5. It must be mentioned here that power consumption of optimal solution can further improve dramatically with the advancement in sleep mode power consumption (P_s) of macro base stations. A distribution of deployed relay positions in seven cells obtained from CPLEX optimal solution is shown in Fig. 7.

In the second scenario, we have utilized optimal MILP CPLEX solution for a 19 cell macro-relay network as a benchmark in order to determine the optimality gap with distributed solution complement. The 19 cells distributed sce-

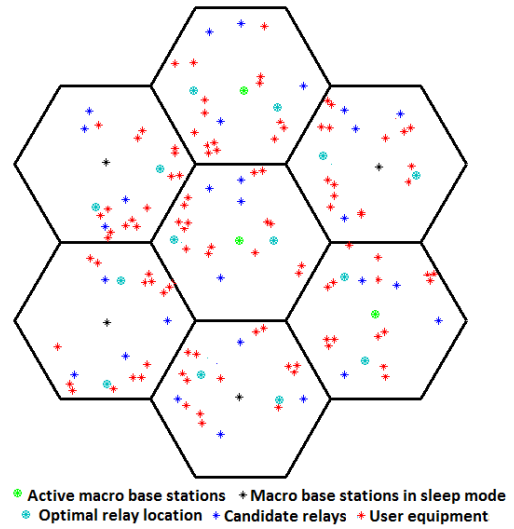


Figure 7. An illustration of optimal relays deployment locations and active macro base stations positions.

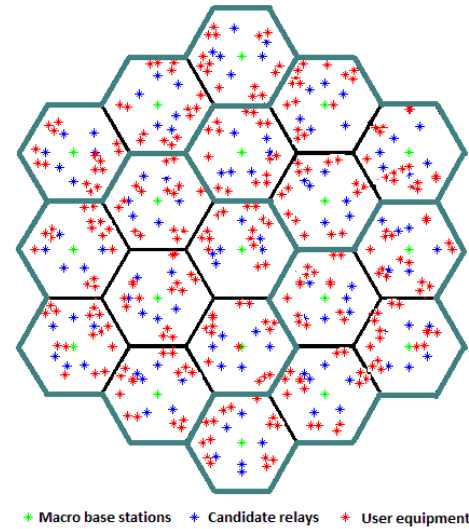


Figure 8. An illustration of a 19 cell LTE-Advanced macro-relay network with distributed clusters.

nario is shown in Fig. 8. A graph of number of macro base stations in operation versus total offered traffic load for 19 cells is shown in Fig. 9. It is evident from Fig. 9 that more macro base stations are in sleep mode for the optimal CPLEX solution as compared to the sub-optimal distributed solution. A comparison of power consumption versus total offered traffic load in 19 cells is shown in Fig. 10. The maximum optimality gap between optimal and sub-optimal solutions is 3.5% at the offered traffic load of 42.75 Mbps. A graph of Energy Consumption Index versus total offered traffic load in a 19 cell macro-relay network for both optimal CPLEX and sub-optimal distributed solution is shown in Fig. 11. It must be mentioned here that both the power consumption and energy consumption index of the sub-optimal distributed solution is very close to the optimal MILP CPLEX solution. The rationale behind this fact is explained with the help of Fig. 9. It is evident from Fig. 9 that the number of macro base stations in sleep mode for the

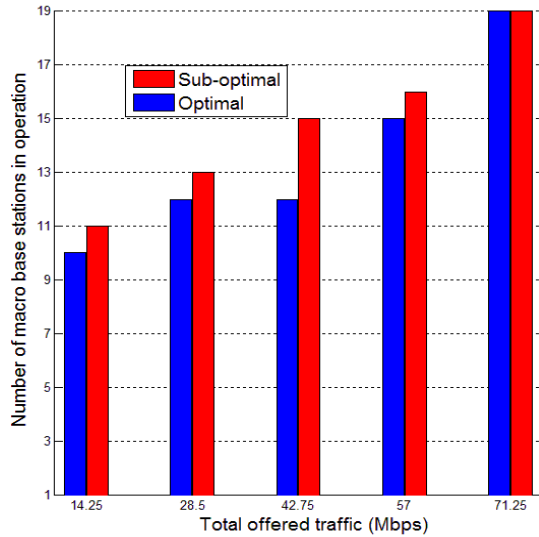


Figure 9. A graph of active macro base stations versus offered traffic load for a 19 cell LTE-advanced macro-relay network.

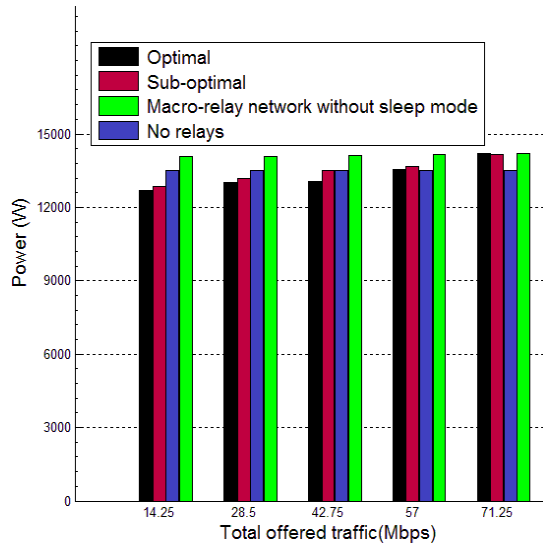


Figure 10. A comparison of power consumption for a 19 cell LTE-Advanced macro-relay network.

sub-optimal distributed solution is slightly lesser or equal to the number of macro base stations in operation for the optimal MILP CPLEX solution.

V. CONCLUSION & FUTURE WORK

In this paper, we present an efficient energy minimization algorithm for LTE-Advanced macro-relay networks which not only determines the optimal location and number of relays to be deployed in the network but also enables macro base stations to switch into sleep mode at low traffic load. We have presented both optimal CPLEX and sub-optimal distributed solutions for energy efficient optimal relay deployment problem. We have shown that optimal CPLEX and sub-optimal distributed solutions are in close agreement with each other. It is worth mentioning here that our unique approach of relay to relay communication forms the basis for relays to act as

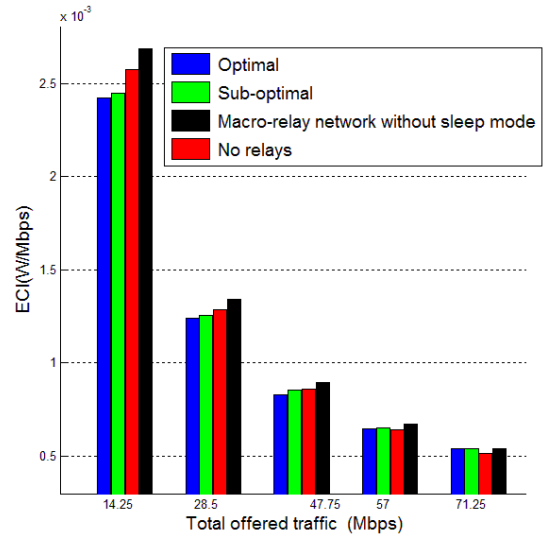


Figure 11. A graph of energy consumption index for a 19 cell LTE-Advanced macro-relay network.

donors for neighbouring relays instead of macro eNBs and enables macro base stations to switch these eNBs into sleep mode at low traffic. As a result, our proposed energy efficient optimal relay deployment algorithm can reduce at most 6.8% overall network energy consumption.

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