An Efficient Method for Minimizing Energy Consumption of User Equipment in Storage-Embedded Heterogeneous Networks

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An Efficient Method for Minimizing Energy Consumption of User Equipment in Storage-Embedded Heterogeneous Networks

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Abstract—Recently, the issue of energy consumption of the user equipment (UEs) in the heterogeneous networks has rapidly become a focused research area of the entire telecommunications community. This issue is evidently critical because the energy consumption of the UEs can severely degrade their already limited battery capacity. In this article, we consider a heterogeneous network environment comprising base stations (each of which is also referred to as an “Evolved Node B” or eNB) with embedded storage that can serve as an effective cache-based traffic offloading technology in scenarios where many UEs simultaneously want to access popular contents of sports matches, live music events, and so forth. If many UEs are, however, connected to few of the eNBs, they suffer from degraded throughput and increased transmission time. Their longer transmission time eventually leads to the increased energy consumption of the UEs. To deal with this challenge, we propose an algorithm to reassign the UEs to the eNBs to minimize the total energy consumption of the UEs with the constraint that their throughput is guaranteed. The effectiveness of our proposed algorithm is evaluated through computer-based simulations.

Index Terms—Storage-embedded heterogeneous network, energy consumption, user equipment (UE).

I. INTRODUCTION

Deployment of various base-stations, each of which is also referred to as an “Evolved Node B” (eNB), is seen as a cost-effective way for increasing the system capacity while offering connectivity to the mobile users. These new types of deployments are commonly called heterogeneous networks, which are currently gaining significant research attention from both academia and telecommunications industry [1]. Fig. 1 depicts the architecture of a typical heterogeneous network, which involves a mix of radio technologies and cell types operating together in a seamless fashion. The heterogeneous network cells depicted in the figure comprise (in descending order of hierarchy) a macro cell, several micro cells, many pico cells, and numerous femto cells. The macro base station (i.e., the macro eNB) can cover a large area and many users, and acts as the backbone in the considered heterogeneous network. Additionally, there are several micro eNBs in the heterogeneous network that are exploited for covering indoor and outdoor crowded areas. The pico eNBs take over the connection when moving into indoor places (e.g., buildings, enterprises, stations) where macro/micro eNBs cannot provide coverage. Furthermore, the indoor femto eNBs are typically WiFi radio networks deployed in the small cells (i.e., various levels and rooms of a building). The mobile operators can exploit such a heterogeneous network for offloading data at these various eNBs in order to reduce traffic traversing the mobile core networks [2]. This can also be useful from the users (referred to as the user equipment or UEs) point of view since the UEs can reduce the round-trip-time (i.e., transmission time with the eNBs) to achieve improved user experience. For effective offloading of popular multimedia contents, in this article, we consider a heterogeneous network environment comprising eNBs with embedded storage that can serve as an effective cache-based traffic offloading technology. This can be applicable to scenarios where many UEs simultaneously want to access popular contents of sports matches, live music events, and so forth. However, in the considered heterogeneous network, the energy consumption of the UEs can be a critical issue [3], [4] because this severely degrades their already constrained battery capacity. Particularly, if many UEs are, however, connected to few of the eNBs, they suffer from degraded throughput and increased transmission time. Their longer transmission time eventually leads to the increased energy consumption of the UEs. To deal with this challenge, we propose an algorithm to reassign the UEs to the eNBs to minimize the total energy consumption of the UEs with the constraint that their throughput is guaranteed.

The remainder of the article is organized as follows. Section II surveys relevant research works. Section III describes the formulation of our considered problem. Section IV presents our proposed solution for minimizing the energy consumption of the UEs while guaranteeing their throughput. The performance of our proposal is evaluated in Section V. Finally, the article is concluded in Section VI.

II. RELEVANT RESEARCH WORKS

In this section, we provide a brief survey of the relevant research works from two aspects. First, we delineate the research works on base stations with embedded storage. Then, we describe several recent works on improving energy consumption in heterogeneous networks.

A. Researches on Base Stations with Embedded Storage

Recently, the embedded storage in the eNBs has become a widely adopted technology whereby the eNBs are attached with extra storage (e.g., Universal Serial Bus (USB) flash drive and Secure Digital (SD) card) in order to easily share the large amount of data such as pictures and videos in home networks [5]. In academia, researchers aimed to realize an efficient communication by using the access points with
embedded storage technology [6]. Furthermore, the research work conducted in [7] by Zhang et al. proposed a cache system for content distribution in vehicular networks. The cache system is exploited to buffer the transmission data from the server to the vehicles. Additionally, in the research conducted by Dandapat et al. in [8], a method for video streaming through optimal placement of the storage-equipped access points was designed. It was shown to be able to transmit data in an effective fashion.

On the other hand, several researchers expected the base stations with embedded storage to function quite similar to a “proxy server” in order to allow the mobile users to perform energy-efficient transmissions. In the work in [9], Koutsogiannis et al. demonstrated that the storage equipped base stations can provide the proxy function for the mobile users, and thereby reduce the latency for their considered wireless network. On the other hand, in their research in [10], Hoque et al. proposed a proxy-based traffic shaping by taking into account the current amount of traffic. In that method, the proxy server (i.e., the base station with embedded storage) stores the received data from the client (i.e., the UE) so that the client can enjoy a shorter transmission time. Also, according to the method, the server forwards the data according to the current traffic situation. In [11], Ding et al. proposed that the clients can enter the sleep state when the base station with storage performs end-to-end communication with the server.

The NerveNet, a research project carried out by the National Institute of Information and Communications Technology (NICT) [12], is a prominent example of the implementation of the access points with storage toward the energy consumption minimization of the clients. The NerveNet is constructed from several access points comprising on-memory databases. The NerveNet provides services such as sharing and exchanges of sensor information and regional information in order to solve social problems in a number of regions in Japan, and to improve the life standard of the residents of those regions.

It is worth noting that even though researchers used eNBs with embedded storage in the afore-mentioned research works [5]–[12], the issue of energy consumption in those works was not particularly considered. In the remainder of the section, we provide the leading works of recent time in improving energy consumption in heterogeneous networks.

B. Researches on Improving Energy Consumption in Heterogeneous Networks

Frenger et al. discussed a technique based on Discontinuous Transmission (DTX) on the base station side for significantly reducing the energy consumption in mobile networks. By adopting cell DTX (i.e., by applying DTX on the downlink), they demonstrated that it is possible to achieve substantial energy reductions in an Long Term Evolution (LTE) network. They found the cell DTX to be particularly effective when the traffic load is low. However, their work did not consider the energy consumption problem from the UEs’ view point.

In a recent research project called the Energy Aware Radio and network technology (EARTH), combined effort from academia and industry was dedicated to address energy consumption in mobile systems [14]. As a part of the Seventh Framework Programme (FP7) of the European Community, the project was conducted by fifteen partners including network operators and providers, component manufacturers, universities, and research institutes. Along with its main focus on energy efficiency in the eNBs, the EARTH project also addressed wider network and system aspects of the Third Generation Partnership Project (3GPP) mobile broadband technologies such as the LTE. However, the issue of
energy consumption of the UEs was not taken into account in
the research works carried out in the afore-mentioned project.

On the other hand, from the UEs’ view point, Deng et al.
identified the 3G/LTE energy consumption to be a significant
challenge in their work conducted in [15]. According to their
work, there are several types of energy mitigation strategies in
existing literature that include inactivity timer reconfiguration,
tail cutting, traffic batching, WiFi power-saving algorithms,
power-saving for processors, and resource usage profiling.
The work suggested that the 3G/LTE wireless interface is a
principal contributor to battery drain on mobile devices (i.e.,
UEs). Much energy of the UEs is consumed by unnecessarily
keeping a UE’s radio in its “active” mode even in case of no
traffic. As a solution, Deng et al. proposed a traffic patterns
learning method for predicting when a burst of traffic would
commence or end, and accordingly changed the radio’s state
from active to idle, or vice versa.

III. PROBLEM FORMULATION

With the traditionally available battery technology, a UE
is unable to communicate for a long period without charging
its battery. For example, the battery capacity of the “Nexus
One” is 1200mAh. On the other hand, its energy consump-
tion in case of using the Global System for Mobile (GSM)
communications module is 700mW, and its average energy
consumption during a phone call reaches 1054mW. Thus, if the
Nexus One communicates always with the GSM technology,
its battery may deplete within just five hours. Transferring
multimedia content for a long duration to content servers,
however, is expected to lead to an even more rapid depletion
of its battery. Therefore, energy consumption reduction at such
mobile terminals/devices is a challenging research avenue.

Broadly speaking, in the conventional wireless communi-
cation systems, a UE would ideally want to communicate
with a content server with an end-to-end connection. Due to
the end-to-end nature of the connection between the content
server and the UE, the distance between them becomes an
important factor in the transmission delay. This implies that
the transmission delay is significantly higher in case of the UE
communicating with a distant content server in contrast with a
nearby eNB owing to the long distance propagation, queuing,
and routing issues between the server and the UE. Given
that the UE consumes much energy during transmitting its
data, the longer transmission time to a distant eNB and/or the
distant content server results in even more energy consump-
tion at the UE. Furthermore, the wireless links employed by the
UEs may experience instability issues due to the radio/channel
interference and high density of UEs connected to the same
eNB. In IEEE 802.11, the Carrier Sense Multiple Access
with Collision Avoidance (CSMA/CA) is used to avoid colli-
sions. For example, if the UEs employing CSMA/CA have a
concentrated distribution (i.e., high density deployment), the
time required for their collision avoidance becomes larger. As
a consequence, the transmission time becomes significantly
larger in a crowded UEs scenario that leads to much energy
consumption of the UEs. Therefore, energy consumption re-
duction at the UEs is, indeed, a critical problem, which is
formally formulated as follows.

Due to the fact that every UE wants to connect to the
nearest eNB to download the content stored in the eNB’s
storage, the likelihood of the scenario whereby too many UEs
connect to the same eNB increases. In such a scenario, the
capacity of the eNBs and the number of UEs under each eNB
affect the throughput of the UEs. Because the UEs connected
to the same eNB share its bandwidth, when the number of
UEs under that eNB increases, their throughput is likely to
drop. Note that this throughput drop is inter-linked with the
increased energy consumption of the UEs due to a relatively
long transmission time to download the content from an eNB,
which is currently accessed by a large population of UEs. This
increase in the transmission time happens because many UEs
share the communication bandwidth as well as the content
access speed (i.e., the read/write speed of the storage) of
the eNB. As the UEs require longer transmission time, their
screen is open for a longer time to buffer and stream the
content that results in a significant increase in their energy
consumption. Therefore, the research challenge consists in
how to minimize the total energy consumption of the UEs
in the considered heterogeneous network with the constraint
that the UEs’ throughput is guaranteed. In other words, the
research challenge is to achieve shorter transmission time and
balanced number of UEs under each eNB so as to reduce the
overall energy consumption of the UEs while maintaining their
throughput requirement.

IV. PROPOSED SOLUTION

In this section, we propose a solution to the earlier stated
problem by reassigning the UEs to different eNBs in such
a fashion that the total energy consumption of the UEs
is minimized while guaranteeing the UEs’ throughput. Our
proposal can be summarized through Algorithm 1. The inputs
to the algorithm are the topology of the eNBs and UEs,
capacities of eNBs, and the transmission ranges of the eNBs.
When a congestion happens at an eNB (i.e., when the number
of UEs connected to the eNB exceeds a threshold), the eNB
sends a request message to the macro eNB. Upon receiving
this request from the eNB, which is experiencing congestion,
the macro eNB reassigns the UEs so that the total energy
consumption of the UEs is minimized. Since checking and
testing all the combinations for reassigning all the UEs to
different eNBs would result in a significantly high overhead,
the macro eNB only reassigns a fraction of the UEs. Also,
the algorithm verifies if the new topology of eNBs and UEs
would lead to congestion at the eNBs so as to avoid going
back to the originally congested topology profile. In step 1,
the algorithm computes the low threshold for the number
of UEs under each of the femto, pico, micro, and macro
eNBs. The corresponding eNB can accept more UEs up to
the low threshold. On the other hand, the high threshold for
each of the eNBs is calculated in step 2 beyond which the
corresponding eNB is not able to accept more UEs. From
steps 3 to 8 in the algorithm, for each femto eNB, a check
is performed whether the number of users under the femto
eNB is more than the high threshold of that femto eNB. In
such a case, a predecessor eNB of that femto eNB is found
Reassigning UEs by using Algorithm 1

The thresholds are calculated beforehand based on communication and storage capacities of eNBs, transmission ranges of eNBs, and read/write speeds of embedded storages in eNBs.

**Example:** \( \ell_{\text{femto}} = 3, \ell_{\text{pico}} = 6, \ell_{\text{micro}} = 100, \ell_{\text{macro}} = 300, \)

\( H_{\text{femto}} = 6, H_{\text{pico}} = 10, H_{\text{micro}} = 200, H_{\text{macro}} = 2000. \)

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**Scenario 1**

Many UEs in femto cell and few UEs in pico cell

4 UEs in the range of the femto eNB download the same content from the storage of pico eNB.

**Scenario 2**

Many UEs in femto cell and few UEs in micro cell

3 UEs in the range of the femto eNB download the same content from the storage of micro eNB.

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**Fig. 2.** Two example scenarios illustrating the reassignment of the UEs by using Algorithm 1.

Please refer to Fig. 2 comprising two example scenarios that illustrate the operation of Algorithm 1. In example 1 portrayed in the figure, there are many UEs in one of the femto cells while there are only a few UEs connected to its predecessor pico eNB. By using Algorithm 1, the macro eNB decides to reassign 4 UEs from the femto cell to the pico eNB so as to minimize the total energy consumption of the UEs while improving their throughput. Similarly, in example 2, a large number of UEs in the femto cell experience degraded throughput and increased energy consumption. However, the predecessor pico eNB, in this case, is unable to serve more UEs. On the contrary, the predecessor micro eNB is still capable of serving additional UEs. Therefore, in example 2, the macro eNB decides to reassign 3 UEs from the femto cell to the micro eNB for improving the overall energy consumption and throughput of the UEs.

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**V. PERFORMANCE EVALUATION**

In this section, we present the evaluation of our proposal through computer-based simulations, which are conducted using C++. The assumed simulation topology of the considered heterogeneous network is illustrated in Fig. 3. As shown in the figure, hexagonal cells are constructed by the deployed eNBs. The eNBs are considered to be fixed. The eNBs are assumed to be connected with their immediately upper level eNBs using optical fiber connections. In the considered topology, a total 763 eNBs are assumed. Only a macro eNB is supposed for simplicity, which is considered to cover an area of four square kilometers. Six micro eNBs are assumed, each of which has 18 pico eNBs. Each pico eNB in the simulated topology is
assumed to have 6 femto eNBs. The macro eNB is assumed to be equipped with 10TB Solid State Drive (SSD) type embedded storage while each of the micro, pico, and femto eNBs is considered to be equipped with 1TB SSD type, 128GB flash/SD type, and 32GB flash/SD type embedded storage, respectively. The total number of users is varied from a small pool of UEs (i.e., 1000) to a significantly large number of users in an urban area (i.e., up to 70000). The conducted simulations are repeated for 200 times, and average values are used as results.

In Fig. 4, the improvement in the average throughput of the UEs is plotted against the average number of UEs per eNB for two extreme cases, namely extremely low and high numbers of UEs (on average) per eNB, respectively. The improvement of the average UE throughput refers to the difference between the throughput achieved by our proposal and that in the random deployment scenario. Fig. 4(a) demonstrates the case of extremely low number of UEs, varied from just one to seven UEs (on average) per eNB. Notice that there is no

Algorithm 1 UE Reassignment for Minimizing Energy Consumption in Storage-Embedded Heterogeneous Networks

**Input:** Topology of eNBs and UEs, capacities of eNBs, and transmission ranges of eNBs.

**Output:** New topology of eNBs and UEs in which total energy consumption and average throughput of UEs are improved.

1: Calculate the low threshold for number of UEs under each eNB, \( L_{\text{femto}}, L_{\text{pico}}, L_{\text{micro}}, \) and \( L_{\text{macro}} \) for femto, pico, micro, and macro eNBs, respectively. Below that, the eNB is available to accept more UEs.
2: Calculate the high threshold for number of UEs under each eNB, \( H_{\text{femto}}, H_{\text{pico}}, H_{\text{micro}}, \) and \( H_{\text{macro}} \) for femto, pico, micro, and macro eNBs, respectively. Beyond that, the eNB cannot accept more UEs.
3: for each femto eNB \( \text{Femto}[i] \) do
4: 
5: \text{if} \( \text{Femto}[i].\text{numUsers} > H_{\text{femto}} \) then
6: 
7: Reassign the overload UEs to the predecessor.
8: \text{end if}
9: \text{end for}
10: for each pico eNB \( \text{Pico}[j] \) do
11: 
12: \text{if} \( \text{Pico}[j].\text{numUsers} > H_{\text{pico}} \) then
13: 
14: Find an available predecessor eNB of \( \text{Pico}[j] \) that has the same content in its storage.
15: 
16: \text{Reassign the overload UEs to the predecessor.}
17: \text{end if}
18: \text{end for}
19: for each micro eNB \( \text{Micro}[k] \) do
20: 
21: \text{if} \( \text{Micro}[k].\text{numUsers} > H_{\text{micro}} \) then
22: 
23: \text{if} the macro eNB can accept more UEs then
24: 
25: Reassign overload UEs to the macro eNB.
26: \text{end if}
27: \text{end if}
28: \text{end for}
29: \text{return} the new topology.
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