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

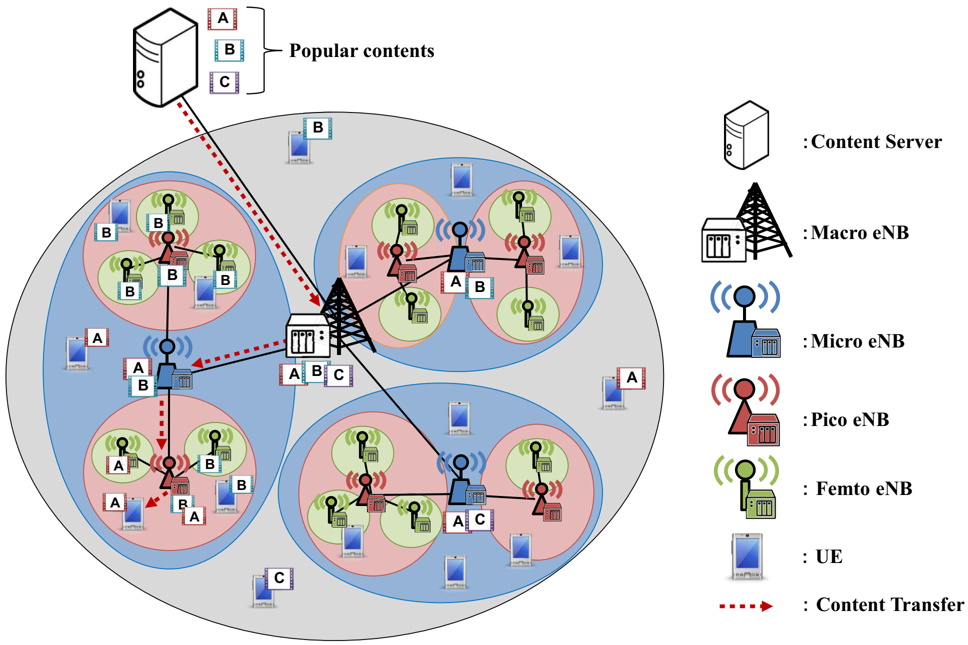

Fig. 1. The architecture of our considered heterogeneous network environment where each of the eNBs have embedded storage for caching popular multimedia contents for offloading to the UEs.

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 tecHnologies (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 consumption 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 communication 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 consumption 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 collisions. 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 reduction 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

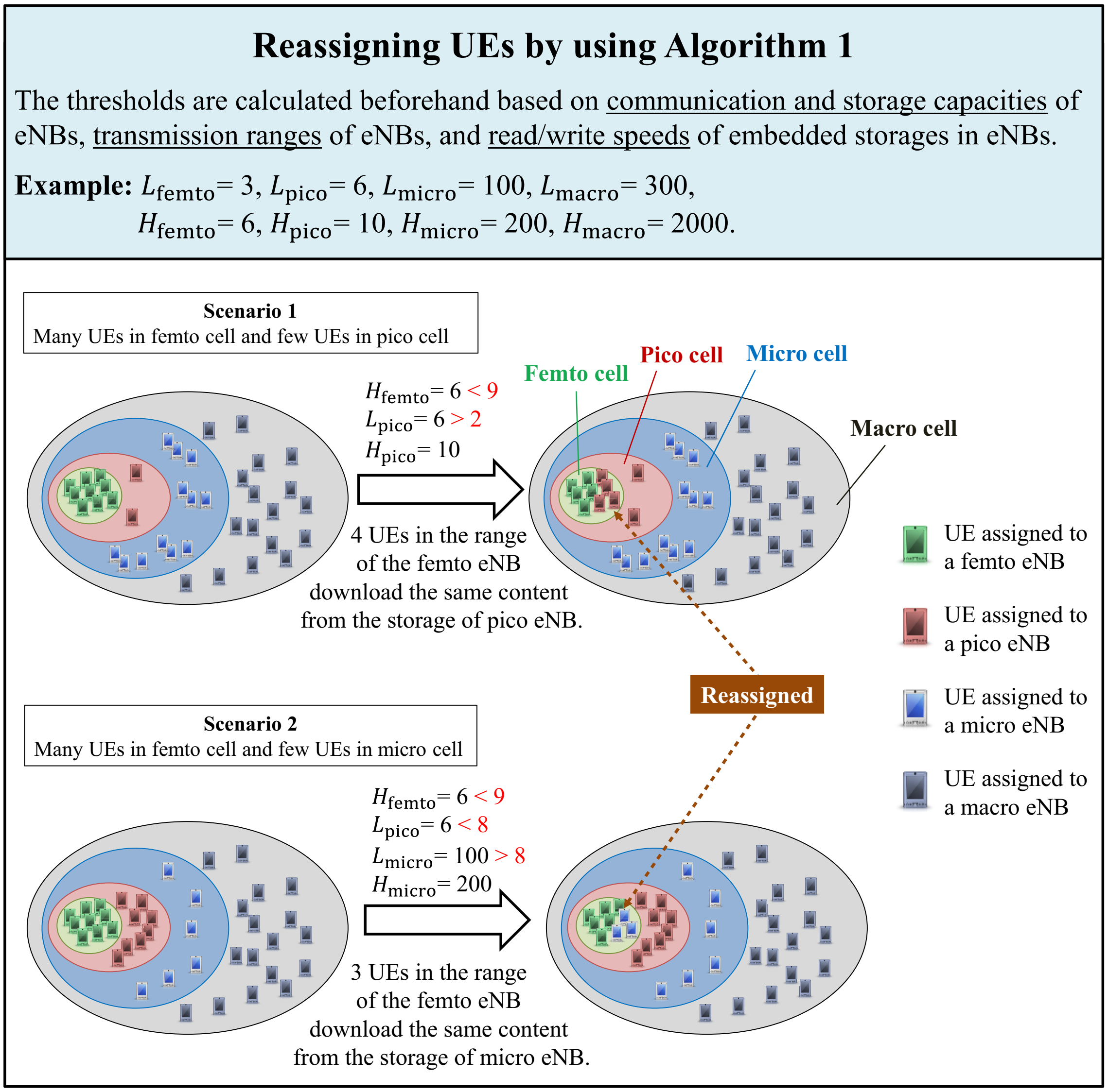

Fig. 2. Two example scenarios illustrating the reassignment of the UEs by using Algorithm 1.

that can accept more UEs. Then, the redundant UEs of the femto eNB are reassigned to that predecessor eNB. Similarly, in steps 9 to 14 of the algorithm, if required, redundant UEs of each pico eNB are reassigned to a predecessor eNB capable of accepting more users. Finally, steps 15 to 21 in the algorithm describe the process of reallocating overload UEs to the macro eNB from the micro eNBs. Finally, in step 22, the algorithm outputs the new topology of eNBs and UEs in which the total energy consumption and the average throughput of the UEs are improved.

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.

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 improvement in the average UE throughput for very low number of users (i.e., 1 to 2 UEs per eNB) while for increasing number of UEs, the throughput improvement is much more significant. On the other hand, Fig. 4(b) demonstrates the other extreme case, namely significantly high number of UEs per eNB. In this figure, it is worth noting how the improvement linearly decreases with the increasing number of UEs per eNB. Since these two scenarios depicted in Figs. 4(a) and 4(b) represent the extreme numbers of UEs, they are not used for computing the energy consumption improvement.

Fig. 5 illustrates the improvement in the total energy con-

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.

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Calculate the low threshold for number of UEs under each eNB, L_femto, L_pico, L_micro, and L_macro for femto, pico, micro, and macro eNBs, respectively. Below that, the eNB is available to accept more UEs.
Calculate the high threshold for number of UEs under each eNB, H_femto, H_pico, H_micro, and H_macro for femto, pico, micro, and macro eNBs, respectively. Beyond that, the eNB cannot accept more UEs.
for each femto eNB Femto[i] do
    if Femto[i].numUsers > H_femto then
        Find an available predecessor eNB of Femto[i] that has the same content in its storage.
        Reassign the overload UEs to the predecessor.
    end if
end for
for each pico eNB Pico[j] do
    if Pico[j].numUsers > H_pico then
        Find an available predecessor eNB of Pico[j] that has the same content in its storage.
        Reassign the overload UEs to the predecessor.
    end if
end for
for each micro eNB Micro[k] do
    if Micro[k].numUsers > H_micro then
        if the macro eNB can accept more UEs then
            Reassign overload UEs to the macro eNB.
        end if
    end if
end for
return the new topology.
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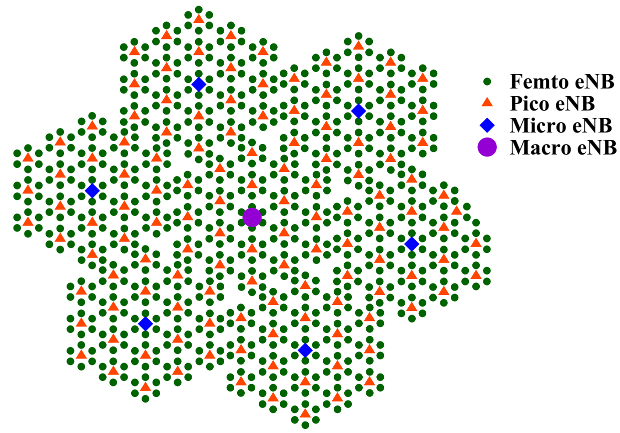
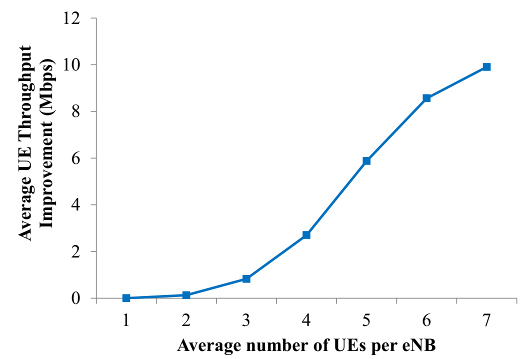
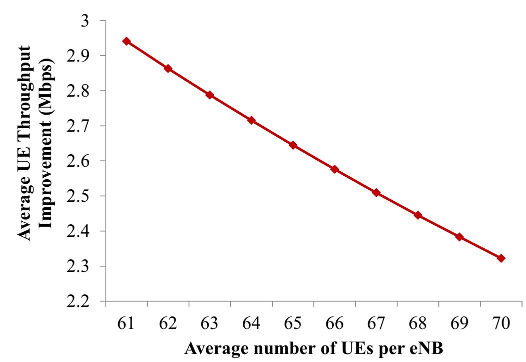


Fig. 3. Assumed simulation topology of the considered heterogeneous network.



(a) The case of few number of UEs (on average) per eNB.



(b) The case of very high number of UEs (on average) per eNB.

Fig. 4. Improvement in average UE throughput for average number of UEs per eNB for two extreme cases, namely extremely low and high numbers of UEs (on average) per eNB.

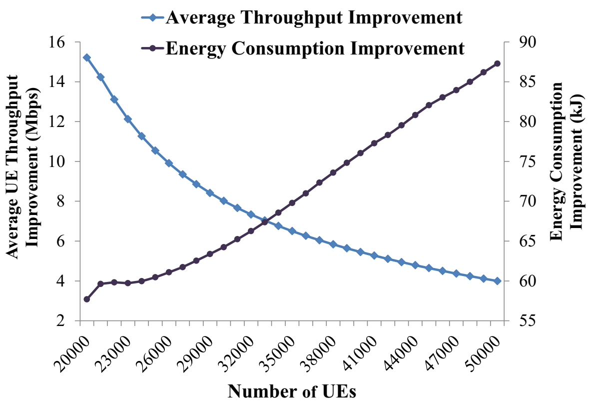


Fig. 5. Improvements in average UE throughput and total energy consumption for varying numbers of UEs.

sumption for varying numbers of UEs by using our proposed algorithm, and also demonstrates its tradeoff with the improvement in the average UE throughput for the various populations of UEs. The results clearly elucidate that the average throughput gain linearly decreases with the increasing number of UEs. However, the performance of our proposed algorithm is still encouraging for larger population of users (i.e., 50000 UEs) whereby the improvement in terms of the average UE throughput is still over 2Mbps. On the other hand, in terms of the improvement of the total energy consumption, the larger the pool of UEs, the more UEs can be reassigned to various eNBs by adopting our proposed algorithm so as to minimize the energy consumption in the considered network. This attributes to the significant performance gain in terms of improved total energy consumption for increasing number of UEs.

VI. Conclusion

Recently, data volumes in wireless multimedia transmission have tremendously increased because of many factors, such as explosion of rich multimedia contents exchanges, dramatically increasing number of UEs, and so forth. Also, the energy consumption of the UEs has also significantly increased. However, the battery power available at the UEs is still somewhat limited. In this article, we considered a heterogeneous network environment comprising eNBs with embedded storage, and focused on reducing the energy consumption of the UEs that offload contents from the various eNBs. As many UEs connect to the same eNB, their downlink communication speed as well as the read/write speed of the eNB's storage significantly degrade. This affects the UEs' throughput and increases their transmission time required for downloading the content from the eNB. As a result of few eNBs serving a large population of UEs, the energy consumption of the UEs significantly increases. To deal with this challenge, we proposed 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. Through computer-based simulations, we demonstrated the effectiveness of our proposal.

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Biographies

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Nei Kato [F'13] is a full Professor and a Strategic Adviser to the President of Tohoku University. He has been engaged in research on computer networking; wireless mobile communications; satellite communications; ad hoc, sensor, and mesh networks; smart grid; and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as a Member-at-Large on the Board of Governors, IEEE Communications Society, the Chair of IEEE Ad Hoc and Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the Associate Editor-in-Chief of IEEE Internet of Things Journal, an Area Editor of IEEE Transactions on Vehicular Technology, an editor of IEEE Wireless Communications Magazine and IEEE Network Magazine.