Energy-Efficient Device-to-Device Edge Computing Network: An Approach Offloading Both Traffic and Computation

Jinming Wen, Chao Ren, and Arun Kumar Sangaiah

The authors attempt to further improve the energy-efficient communication in mobile edge computing by proposing a device-to-device offloading architecture. The D2D technique, in line with mobile edge computing, is responsible for offloading wireless traffic as well as computational tasks. Cooperative relay-aided transmission is also used in this architecture to pursue further improvements in a multi-cell scenario.

Abstract

Edge computing is expected to enable the cloud computing services in proximity and leverage the computational capacities at the edge of a network. Driven by massive data-hungry and energy-hungry applications, future wireless networks will need to provide various cloud-based multimedia services in a "greener" manner. However, limited computing capacity, wireless resources, and power supply prevent edge computing from evolving and maturing in terms of high sustainability and energy efficiency. In this article, we attempt to further improve the energy-efficient communication in mobile edge computing by proposing a device-to-device (D2D) offloading architecture. The D2D technique, in line with mobile edge computing, is responsible for offloading wireless traffic as well as computational tasks. Cooperative relay-aided transmission is also used in this architecture to pursue further improvements in a multi-cell scenario. Finally, offloading and balancing technologies are introduced to increase the total energy efficiency, decrease the inter/intra-cell interference, deal with traffic/computational congestion, and provide better services to end users.

Introduction

The applications of virtual reality, augmented reality (AR), wearable technology, and artificial intelligence are driving mobile users into a frenzy of excitement, while demanding dramatically reduced response time and rapidly upgraded user equipment. Currently, mobile subscribers require high storage capacity, swift data exchange, long battery life, and fast computational ability, which are extremely difficult to propel by pocket-sized hardware. Meanwhile, the development of storage, battery capacity, wireless broadband, and CPU design is relatively slow in the face of the accelerating increase in the number of user requests for rich multimedia and big data services [1–3]. Therefore, new concepts need to be developed to pave the way for large-scale mobile applications. Among the emerging paradigms, "migrating" and "offloading" are viewed as efficient concepts that transfer local computing and storage tasks to remote cloud and edge computing servers, respectively.

Migrating and Offloading Concepts

Cloud Computing: This is an exploitation of the migrating concept. This concept is typically achieved by cloud computing, and allows users to store and process data on servers located in remote data centers. The existing mobile users can thus enjoy most of the emerging services with minimal upgrade of their pocket-sized hardware [4]. The migrating concept also avoids high energy consumption by local mobile devices, which immediately increases the serviceability ratio. However, a cloud-based radio access network has to fight against new challenges associated with long distance, exponential data traffic growth, service congestion, and unpredictable wireless channels [5]. Hence, the overall quality of service may be affected by the following two factors:

- **High total latency** for massive applications due to the long transmission distance, peak hour, and server congestion
- **Extra energy consumption** to compensate the possible negative effects of unstable traffic and combat interference

Unless these problems are addressed, mobile devices that depend considerably on local resources or cloud computing may suspend their services in the case of a low resource level or high latency (i.e., when experiencing an unexpected outage).

Edge Computing: This is an offloading service at the network edge. In contrast to cloud computing, mobile edge computing (MEC) utilizes the offloading concept to optimize cloud-based systems by performing data processing near the mobile subscriber [6]. MEC can also be classified as local computing that dramatically decreases the consequent traffic and distance. Compared to the mitigating concept, offloading expedites and highlights the advantages of lower latency and energy consumption. Thus, the MEC can provide better cloud services "per energy," or higher performance in terms of energy efficiency (EE). Nevertheless, a huge amount of mobile data will continuously proliferate, which will in turn result in an ever growing data-driven and energy-hungry situation. As on-demand green communication

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becomes one of the key issues of future wireless systems, further improvement of energy-efficient MEC is a challenging essential step in conservation-oriented "anywhere" cloud services [7].

Energy Consumption and Offloading in MEC

From the perspective of information communications technology, most of the energy consumption in MEC systems should be attributed to:

- The requested computation tasks
- The end-to-end data traffic

It is straightforward to achieve both enhanced performance and decreased energy consumption if these energy-extensive processes are sufficiently energy-efficient.

Certain computational tasks can be taken over from the remote cloud to the MEC platform in the vicinity, which could result in a sharp reduction in energy consumption. Currently, MEC has managed to achieve high EE on the computational side, where computational offloading contributes to this improvement. The next energy-extensive side in the MEC system is the data transmission over wireless channels [8]. However, very few studies have been conducted on energy-efficient edge data transmission in MEC (i.e., traffic offloading). Further details of the energy-efficient offloading in MEC and related works can be found later.

Therefore, we can still achieve greener MEC by exploiting energy-efficient edge data delivery. As MEC requests radio access networks, the background noise, shadowing effect, path loss, and interference in cellular networks hinder improvement in EE. Thus, the offloading of the cellular traffic at the edge of wireless networks has become a key issue. In the fifth generation (5G) era, this offloading is facilitated by a peer-to-peer paradigm referred to as device-to-device (D2D) communication. D2D communication can be recognized as direct short-range communication between mobile devices, which offloads the intermediate transmission by the base station (BS) to a proximity service (ProSe). In addition to traffic offloading, it has been proven that D2D eliminates coverage holes, improves the spatial reuse ratio, reduces battery consumption, and alleviates the data congestion caused by the explosive mobile growth [9, 10].

Motivation and Contribution

It is a coincidence that both D2D and MEC work at the edge of wireless networks and use the concepts of offloading and ProSe. The incorporation of D2D to further offload MEC's traffic is thus possible. Considering that D2D is currently specified by the Third Generation Partnership Project (3GPP) in LTE Rel-12 and is recognized as one of the technological components of the evolving 5G architecture, we believe that the "MEC plus D2D" (MEC D2D) technique can achieve widespread public adoption and help mobile users enjoy ubiquitous edge computing anywhere and anytime. In addition, cooperative relaying, another low-complexity wireless technique, can be applied in cloud-based networks with convenient deployment, flexible adjustment, coverage extension, quick recovery, and intelligent routing. It has also been proven that relaying can enhance both the EE and the spectral efficiency in wireless communication systems [11].

Thus, we have designed an energy-efficient D2D MEC network architecture, which extended the offloading concept from edge computing to wireless traffic. This D2D edge computing architecture is proposed with energy-efficient traffic offloading and balancing technologies. In the architecture, multiple access and cooperative relaying methods are provided to mobile users, which create choices to access MEC servers in an energy-efficient manner. The experimental results show that the proposed one-hop MEC-D2D model and the two-hop MEC-D2D-Relay model reduce the per-operation energy cost by 36 and 54 percent, respectively, and both provide a rapid response to a specific computational task. To improve the total EE of edge computing, load balancing schemes have been designed for this architecture and deal with the main problems of inter/intra-cell interference, traffic/computation congestion, and uneven EE distribution.

The rest of this article is organized as follows. We describe the energy-efficient D2D edge computing architecture and the main problems to be solved. The energy-efficient load balancing scheme for D2D edge computing is introduced later. The conclusion is presented, along with directions for possible future work.

Energy-Efficient Device-to-Device Edge Computing Architecture

Energy Efficiency and General Offloading in Edge Computing

In cloud-based networks, the conservation of the energy consumed by the communication devices becomes a challenging and critical issue, which needs to be exploited using flexible approaches [12]. The goal of energy-efficient edge computing is to reduce the amount of energy required to complete or improve the quality of the requested computation/storage services. The EE in edge computing can be defined as follows:

$$\text{Energy Efficiency} = \frac{\text{Quality/Satisfaction of Services}}{\text{Energy Consumption}}.$$

Offloading is defined as the use of complementary network technologies to transfer tasks from the original devices to the targeted devices, such that the resources consumed by the original devices can be freed. In scenarios with limited local resources and massive interference, offloading allows users to enjoy better services with better connectivity. Edge computing is an application of the offloading concept, which transfers the cloud-based services from a congested remote cloud to the MEC servers deployed within a macrocell. Computation offloading in the proximity is the basic method of edge computing. As both computational tasks and wireless traffic consume most of the energy, we can extend the offloading method in edge computing to a more general one: offloading both the computational tasks from the remote cloud to the local edge servers, and the offloaded traffic from the cellular base station to cost-effective direct connectivity.

In scenarios with limited local resources and massive interference, offloading allows users to enjoy better services with better connectivity. Edge computing is an application of the offloading concept, which transfers the cloud-based services from a congested remote cloud to the MEC servers deployed within a macrocell.

Related Works

Few works have addressed the energy-efficient offloading problems in edge computing. We compare and summarize the related works on

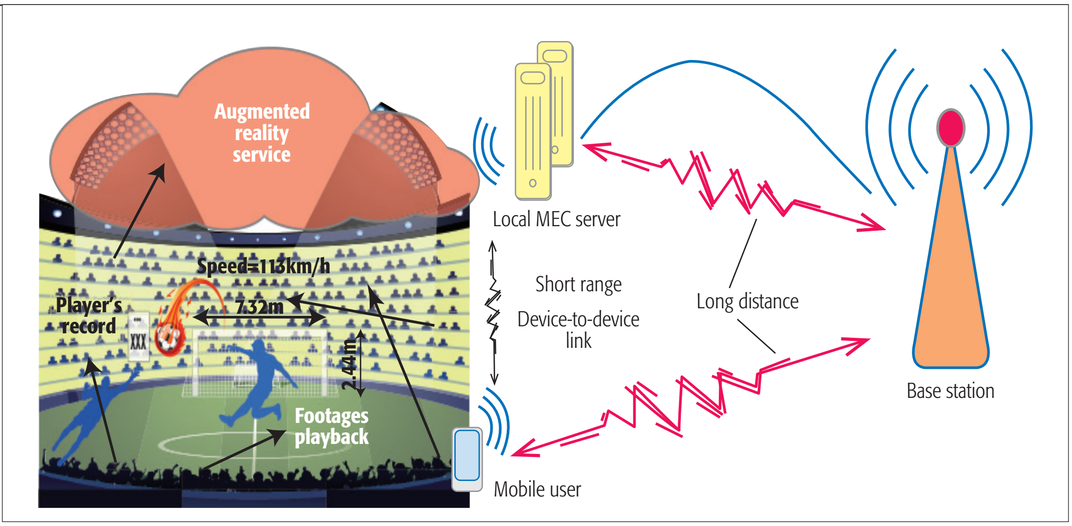

Figure 1. Basic scenario of augmented reality supported by MEC services during a soccer match, where a basic link of device-to-device communication is black, and conventional communication links via the base station are red.

Related works	Offloading aspects		Energy-efficient aspects		Wireless technologies	
	Computation	Traffic	Computation	Traffic	D2D	Cooperative relay
[13]	✓		✓			
[8]	✓		✓	✓		
[14]	✓	✓			✓	
Proposed	✓	✓	✓	✓	✓	✓

Table 1. Comparison of related works on energy-efficient MEC.

energy-efficient MEC (i.e., [8, 13, 14]; Table 1). Among these works, a distributed computation offloading game was considered in [13]. In [13], the researchers proposed and solved the EE optimization problem in a multi-channel wireless interference environment, and the solution was mutually beneficial in terms of satisfactory offloading. However, the efficient transmission and usage of wireless resource was not the major concern of [13]; thus, higher EE could be achieved if the wireless communication was greener.

To the best of our knowledge, thus far, no studies have been conducted on energy-efficient traffic offloading in edge computing systems. Setting aside the concern of dedicated traffic offloading, a problem related to energy-efficient wireless transmission was investigated in [8]. Although in [8] the researchers mainly studied energy-efficient computation offloading, the system model considered most of the multi-access characteristics of the 5G wireless network. Then the energy cost of both the computational tasks and the file transmission was reduced in the computational offloading system [8], which also provided a good example of optimizing the energy-efficient data traffic in MEC. However, the network structure for wireless traffic was unchanged, and traffic was still not offloaded. Further improvement may exist if the traffic at the edge of the mobile network can be considered in a true traffic offloading mechanism.

As an ongoing exploration of the energy-efficient communication concept, the D2D mechanism can be utilized to offload the traffic in MEC, where the transmission can be handled by the low-power direct links from the edge servers to the mobile users. In this spirit, in [14], the researchers proposed a D2D-based MEC local cloud architecture, where the communication between devices was realized by the D2D relay gateways. Nevertheless, the concept of energy-efficient traffic offloading was not considered in [14]; thus, our work has the following distinctive features:

- Offloading the traffic of a relay gateway. If a direct D2D link between the mobile users and the MEC servers exists, these nodes do not require connections from the relay gateway, thus reducing the one-hop communication.
- Targeting EE. The architecture and schemes aim at increasing the EE of the edge computing networks.
- Supporting multiple cells. The schemes are designed for a large-scale network including multiple cells.

Main Problems and Proposed Architecture

Aimed at improving EE, our D2D edge computing architecture mainly solves the following three problems.

Unnecessary detour: As shown in Fig. 1, the conventional MEC transmission has to utilize two hops to complete each unidirectional transmission from the MEC server to the mobile user.

Considering the case where some mobile users may be closer to the MEC server than the macro base station, an unnecessary detour is required and unexpected energy is consumed.

Massive interference: In 5G, interference at the edge is still a major concern, particularly for densely deployed spectrum-sharing small cells, calling for efficient and flexible solutions in MEC.

Regional congestion: The requests for edge computing may be generated concurrently in a specific small region, such as football fans applying AR in a football stadium (Fig. 1), which exerts high pressure on both the MEC server and the base station. In this situation, most of the devices frequently refresh their requests and are anxious for feedback, deteriorating the level of energy dissipation.

The new D2D-based MEC architecture (Fig. 2) is designed to ameliorate the negative effects

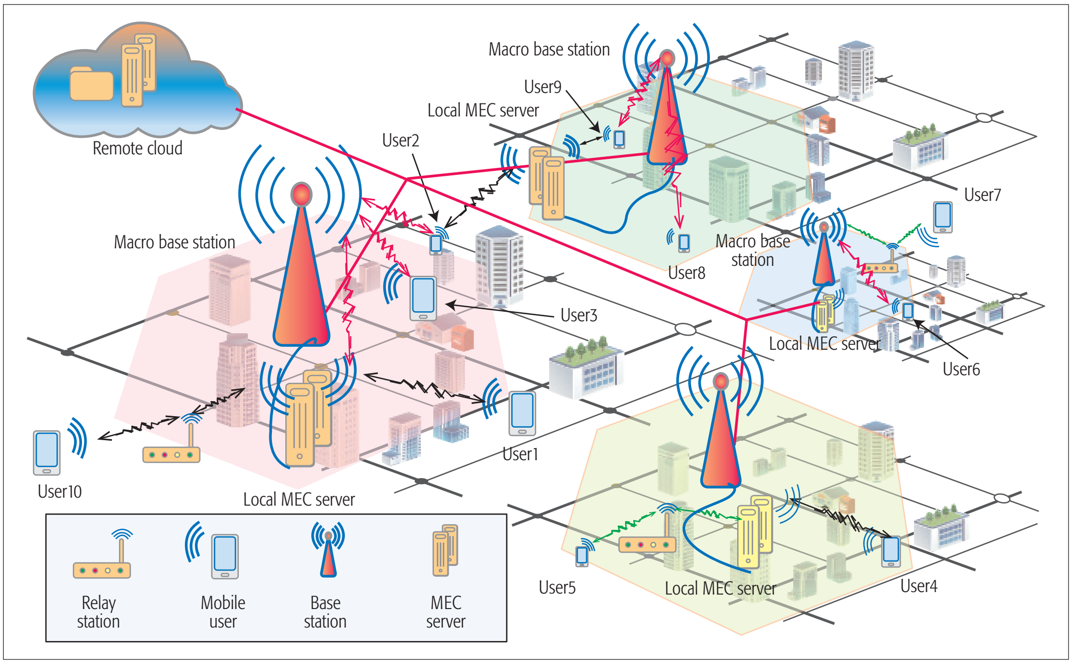

Figure 2. Architecture of device-to-device edge computing. Typical links can be found as follows: device-to-device wireless links (black), conventional MEC links (red), and relay-aided transmissions (green). "Local MEC server" refers to the MEC server located within the coverage area of one macro base station, and "remote cloud" refers to the cloud service provided by the conventional cloud service provider, such as Amazon Web Services (AWS).

The proposed architecture can provide the mobile devices with D2D access, cooperative D2D access, and conventional base station access at the same time to both the proximal and neighboring MEC servers. Thus, all of the applications previously processed by the local CPU or the remote cloud server can either be offloaded to the closest MEC servers or be shared with the neighboring MEC server.

caused by the aforementioned problems. In Fig. 2, the traffic from mobile devices to an MEC server is offloaded by D2D wireless links or relay-aided D2D links. In the system, we consider multiple D2D links connecting the end mobile devices to the MEC server deployed at the edge of radio access networks. All of the wireless nodes have the D2D functionalities, such as a refined 5G transceiver, WiFi-Direct, Bluetooth, and millimeter-wave transceivers.

As an example of the proposed architecture, the architecture in Fig. 2 illustrates 10 mobile users to demonstrate the basic links and the possible choices to access the MEC services. The basic computational and communication technologies in this architecture include the following:

D2D MEC: Mobile users can directly establish the D2D links or the D2D relay-assisted links to connect to the MEC server, which can be recognized as proximal cloud computing without accessing the base station links.

In Fig. 2, User1 is not covered by the macro base station. Now, using D2D communications, User1 connects a proximal MEC server without accessing the cellular network. If User4, located at the edge of the cellular network, attempts to receive MEC services via conventional cellular links, it will encounter an unreliable wireless transmission or a heavy shadowing effect, and thus involve low EE consequences. Fortunately, enabling the D2D transmission for User4 can offload the traffic of the macro base station and shift the wireless transmission to the direct links, which increases the EE. User5, also located at the edge of the cellular network, uses a D2D link to get the help of cooperative relay, which accesses the MEC server with high EE. User9 has two choices to access the MEC services, which are offered by MEC-D2D and conventional MEC (i.e., using cellular links). Depending on the EE of each choice, User9 can choose and enjoy the optimal quality of service with low energy consumption. User10 is out of the cellular service but can use the cooperative MEC-D2D-Relay technique to enjoy edge computing.

Neighboring D2D: If the mobile users are not satisfied with the local MEC service, they can connect to the nearest D2D edge computing server "across" the cell boundary. User2, located at the edge of its serving cell, may use the MEC server inside its serving cell at a high energy cost (because of the long distance and the weak cellular signal). With the technology of the neighboring D2D, User2 can communicate with the neighboring MEC server across the boundary and thus improve its EE.

Cooperative relay: With the help of the relay nodes, the computation and communication service range can be extended, and the mobile users will have more choices to access the MEC services. User5 and User6 have two choices to access the MEC servers. For User5 and User6, whether to choose the relay or the base station to connect to MEC depends on the EE of the associated links. With the help of cooperative relay, User7, the mobile user outside the cell boundary, can access the conventional MEC services, remote cloud services, and D2D MEC services. User10, located outside the boundary of the macrocell, is out of service, but it can use the D2D MEC technique to enjoy edge computing with the help of a relay node.

Conventional MEC: The following is the conventional manner in which mobile users use the base station to connect to the MEC server deployed in the same cell. If a macrocell uses an MEC server, any mobile user connected to the base station can enjoy the conventional MEC services. User2, located at the edge of the serving

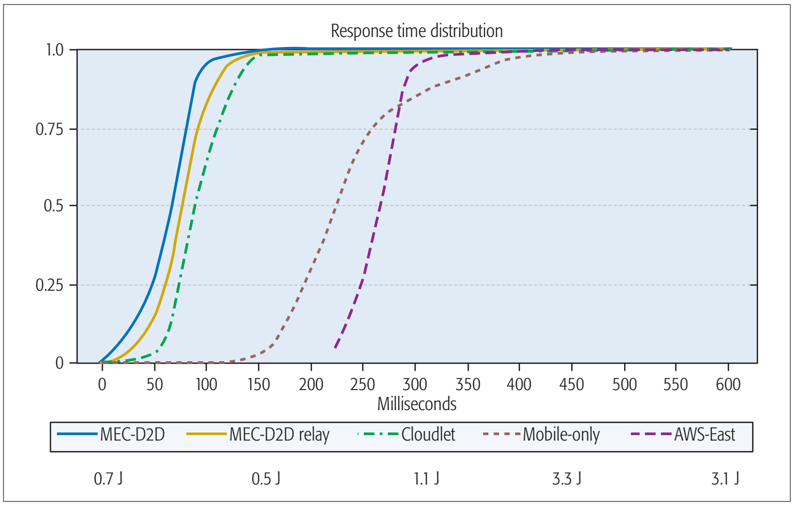

Figure 3. Response time distribution and per-operation energy cost of augmented reality [2, 3].

cell and far away from local MEC, can choose the neighboring D2D or conventional MEC. User3 is served by the base station and can access the conventional MEC services. User5, although it has a weak cellular signal, has a chance to increase the EE of conventional MEC by requesting a relay service. User4 can choose conventional MEC or D2D MEC on the basis of its EE. Although User6 is closer to the MEC server than to the macro base station, MEC-D2D is not the best choice because of the high energy consumption (because the MEC server is not sufficiently close). User7 is outside the boundary of the macrocell, but it can enjoy conventional MEC or remote cloud computing with the help of the cooperative relay nodes. User8 only connects to the base station because of its high EE (channel condition is sufficiently good).

Remote cloud: This is the conventional cloud computing technique that needs a macro base station to provide wireless access and a backhaul link to exchange data with the remote cloud. All of the mobile users accessing the Internet, such as User2, User3, User4, User5, User6, User7, User8, and User9, can use this technology. Although User7 is outside the cell boundary, it can enjoy conventional MEC or remote cloud computing because of the help of the relay node.

The proposed architecture can provide the mobile devices with D2D access, cooperative D2D access, and conventional base station access at the same time to both the proximal and neighboring MEC servers. Thus, all of the applications previously processed by the local CPU or the remote cloud server can either be offloaded to the closest MEC servers or be shared with the neighboring MEC servers, thereby enabling the proposed architecture to increase the EE.

Advantages

The three abovementioned problems, namely unnecessary detour, massive interference, and regional congestion, can be solved by the proposed energy-efficient D2D edge computing architecture:

- In Fig. 2, the D2D transmission shortens the long distance of the cellular transmission in conventional MEC. Moreover, energy can be saved because of the low-power short-range transmission.
- Local transmission or short-range transmission can utilize low-power transceivers, in return reducing the interference from other devices at a distance. For example, the signal sent by a WiFi or Bluetooth transmitter cannot interfere with the receivers located 100 m away.
- Congestion in the MEC server or traffic may result in low EE, which needs the cooperative relaying method to offer users more choices to access the MEC services and balance the load.

Furthermore, the schemes of spectrum sharing, resource allocation, relay selection, and interference coordination can be utilized to maximize the EE.

One of the major advantages over conventional MEC is that MEC-D2D can serve the mobile users with any proximity server, irrespective of the macrocell to which the user belongs. This feature may be included in wireless resource virtualization in our future works. The other advantage of D2D edge computing and MEC is that the balancing and switching schemes can offer enhanced sustainability for users with unpredicted mobility.

Compared to cloud computing, cloudlet, and mobile-only (i.e., keeping all calculations running on the mobile device), the proposed D2D edge computing architecture (consisting of MEC-D2D and MEC-D2D-Relay) consumes less energy. Figure 3 shows the importance of computational and traffic offloading for augmented reality on a mobile device; the full details of the experiments can be found in [2, 3]. An AR request from the end user is transmitted over a D2D link to an MEC server, over a WiFi link to a cloudlet, or over conventional backhaul to Amazon Cloud. After processing, the AR data are transmitted back to the end user, whose cumulative distributed function (CDF) of the observed response time distribution is shown in Fig. 3. MEC-D2D has the best performance because of the one-hop design, while MEC-D2D-Relay needs two hops and longer latency. However, the relaying technique helps to reduce end-to-end energy consumption, which explains why MEC-D2D consumes more energy than MEC-D2D-Relay (an energy consumption increase of approximately 0.2 J). Although a cloudlet using a one-hop link may lead to high EE, this case needs a very high density of deployment. In a real-word deployment, a cloudlet needs more hops on average than MEC-D2D and MEC-D2D-Relay, which explains why it spends slightly more time and consumes more energy to complete the operation. More distance should be traveled to access the AWS cloud, thereby increasing the response time and the per-operation energy consumption (3.1 J). The label “mobile-only” in Fig. 3 corresponds to a case where the entire computational code is run on the mobile device. For avoiding low EE, the data show that mobile-only performs worse than any of the offloading options.

Energy-Efficient Offloading and Balancing Technologies

The MEC-D2D facilitates both computing offloading and traffic offloading, which provides energy-efficient and sustainable cloud services to end users. In the proposed architecture (Fig. 2),

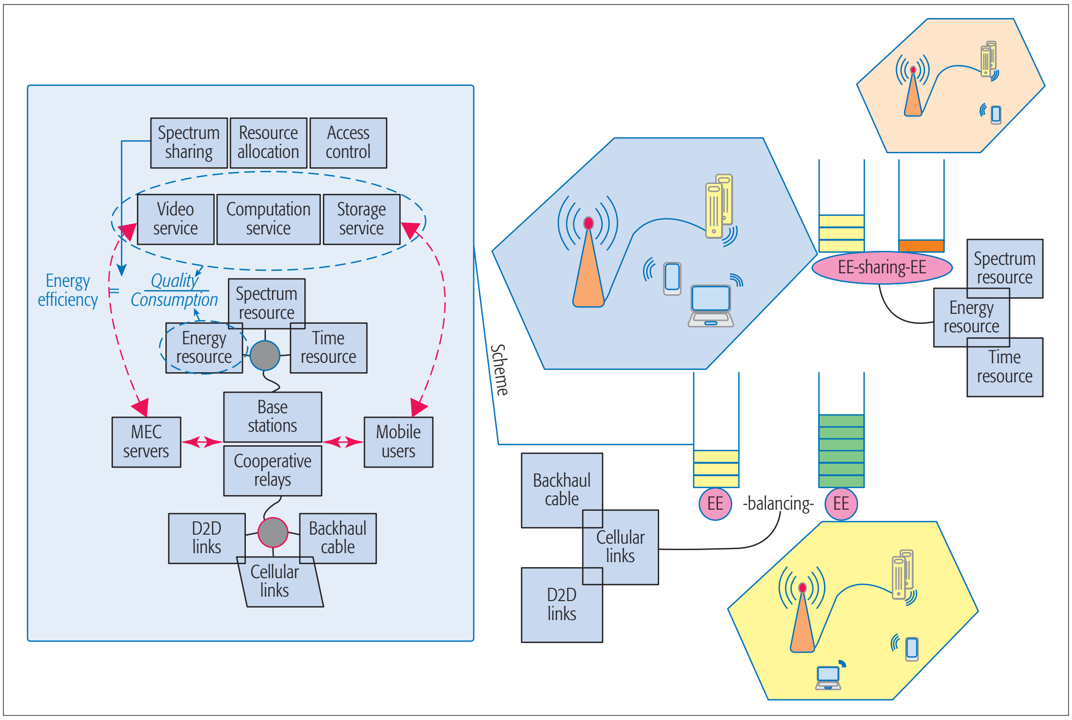

Figure 4. Energy-efficient offloading, balancing, and resource-sharing technologies. EE: energy efficiency.

The spectrum sharing technique may help to reduce the energy consumption by cooperatively coordinating the mutual interference, particularly in ultra-dense 5G networks. The access control directly determines which user should be served and thus, affects the queuing time (affects the quality of service) for the edge computing services.

multiple links can be found to access the local/neighboring MEC servers. Among these links, the D2D-based approach is appropriate for offloading both the computational and communication tasks as well as for saving the associated energy. However, the D2D-based approach may not be the optimal choice if the mobile users have the following features:

- Location outside the radio coverage area of the wireless MEC server
- Encountering high interference over the D2D channel
- Low EE in a specific region or time period

As shown in Fig. 4, the mobile users can access the services (e.g., video services, computation services, and storage services) provided by the MEC server via the base station or the cooperative relays. The available links (e.g., D2D links, cellular links, and backhaul cable) can be used to balance the tasks by transferring them from one cell to its neighboring cell. It is easy to obtain the optimal balancing result by formulating the link scheduling problems.

However, resource management affects the result of link scheduling. For example, if one aims to maximize the performance of link scheduling, the transmission power, band, and time slot should be determined in advance or simultaneously. Thus, resources (e.g., the energy, spectrum, and time slots in Fig. 4) should be managed in a joint optimization problem with the link scheduling. If one aims at increasing the

$$\text{Energy Efficiency}=\frac{\text{Quality/Satisfication of Services}}{\text{Energy Consumption}},$$

energy consumption and quality of service (or quality of experience) are the most important factors to be considered. Furthermore, the spectrum sharing technique may help to reduce the energy consumption by cooperatively coordinating the mutual interference, particularly in ultra-dense 5G networks. The access control directly determines which user should be served and thus affects the queuing time (the quality of service) for the edge computing services.

In this scenario, spectrum sharing, resource allocation, and access control can be jointly utilized to facilitate a resource sharing scheme (Fig. 4), which is a supplementary technique of the balancing scheme. Thus, all of the resources of the "hot spot" (with low EE) and the "cold spot" (with high EE) can be shared and reused, thus offloading and balancing the computation and traffic in the edge computing networks. Figure 5 shows the expected results of the offloading and balancing schemes in the MEC-D2D architecture. Figure 5 also shows that the goals of the offloading and balancing schemes are twofold:

1. Increasing the total EE
2. Reducing the pressure of low EE areas

Conclusion

In this article, we present the basic architecture of energy-efficient device-to-device edge computing and discuss examples of different links and access patterns. With respect to offloading, the architecture incorporates both device-to-device communication and the cooperative relaying technique. Moreover, traffic offloading and balancing technologies were discussed, which exhibited twofold advantages:

1. A further improvement of the total energy efficiency and the quality of services to the edge users
2. Certain alleviation of both the inter/intra-cell interference and the traffic/computation congestion

In the future, we intend to focus on:

1. Utilizing artificial intelligence and big data techniques to obtain satisfactory solutions to offloading, balancing, and allocation problems

In the future, we intend to focus on utilizing artificial intelligence and big data techniques to obtain satisfactory solutions to offloading, balancing, and allocation problems, and wireless resource virtualization to simplify the process of the entire network.

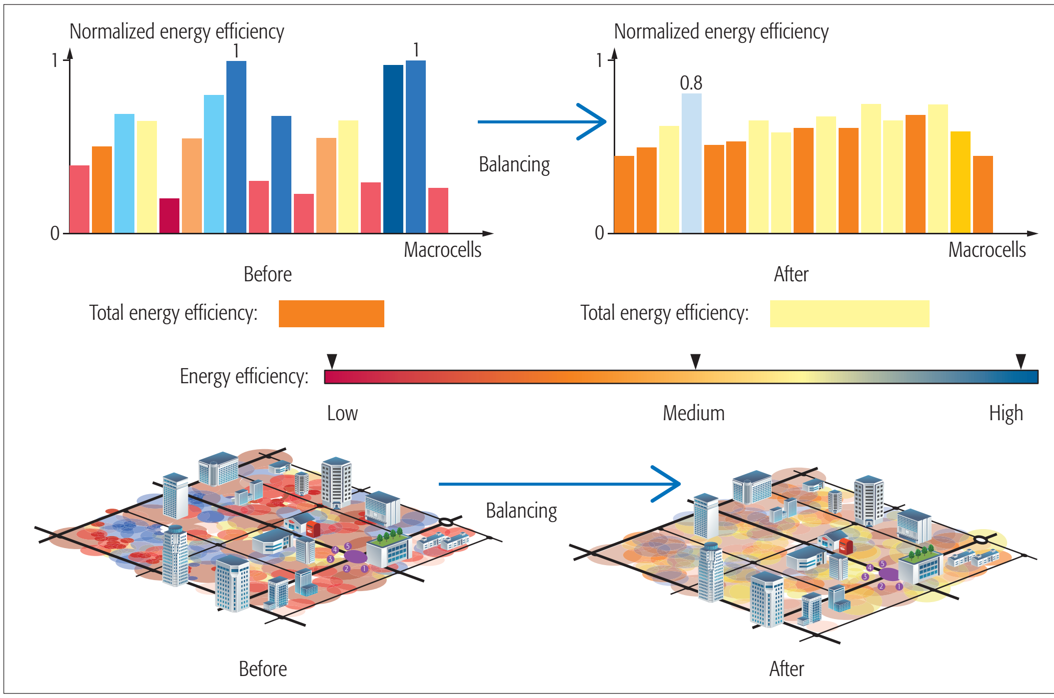

Figure 5. Expected results of the offloading and balancing schemes in device-to-device edge computing. Normalized energy efficiency: Each energy efficiency value should be divided by the maximum energy efficiency.

2. Wireless resource virtualization to simplify the process of the entire network

Acknowledgments

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