Czech Technical University in Prague
Faculty of Electrical Engineering
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Offloading computing tasks to multi-access edge computing via multiple relaying nodes

Diploma thesis

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Master programme: Electronics and Communication
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Supervisor: Ing. Pavel Mach, Ph.D.

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Declaration

I hereby declare I have written this doctoral thesis independently and quoted all the sources of information used in accordance with methodological instructions on ethical principles for writing an academic thesis. Moreover, I state that this thesis has neither been submitted nor accepted for any other degree.

In Prague, May 2023

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MASTER'S THESIS ASSIGNMENT

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II. Master's thesis details

Master's thesis title in English:

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Přenášení výpočtu na hranu sítě prostřednictví vice retranslačních stanic

Guidelines:

The Diploma thesis is focusing on the problem of computation offloading to the multi-access edge computing (MEC) servers. First, study a problem of offloading decision provided that the computing task(s) can be processed locally by the device, offloaded directly to the MEC server, or offloaded to the MEC server via on or multiple relaying nodes. Assume that the relaying nodes can work either in half-duplex or full duplex mode. Then, propose a simple algorithm selecting jointly the relaying node(s) and relaying mode with the goal to minimize overall energy consumption of the offloading device and any potential relays while guaranteeing the constraint on maximal processing time is met. Investigate the performance of the proposes algorithm depending on number of relaying nodes, maximum allowed processing time, or other.

Bibliography / sources:

[1] P. Mach and Z. Becvar, „Mobile Edge Computing: A Survey on Architecture and Computation Offloading," IEEE Communications Surveys & Tutorials, vol. 19, no. 3, 2017.

[2] Molin Li, at al., „Multi-Relay Assisted Computation Offloading for Multi-Access Edge Computing Systems With Energy Harvesting," IEEE Transactions on Vehicular Technology, vol. 70, no. 10, 2021.

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Assignment valid until: **16.02.2025**

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Abstract

This diploma thesis focus is to analyze the performance and problems on computation offloading of high-demanding tasks to multi-access edge computing (MEC) servers. Two offloading models are analyzed; the first is direct offloading, where the tasks are directly sent to the MEC server, and the second is relay offloading, in which a task is initially offloaded to one or more relays before being forwarded to the MEC server. In the case of the second model, we also analyze half duplex relaying mode and full duplex relaying mode. Then, we formulate the problem targeting the minimization of the sum energy consumption of the user equipment (UE) and relay UEs under the maximum delay constraint. Further, we derive the transmission power for individual offloading modes depending on the maximum delay. Then, we propose a simple algorithm for joint selection of relay(s) and relaying options. We demonstrate the benefits of offloading over multiple relay UEs by means of energy consumption or by the probability that the offloaded task is processed within the required deadline.

Keywords: multi-access edge computing, direct offloading, relaying, half-duplex, full-duplex, energy consumption.

Abstrakt

Tato diplomová práce se zaměřuje na analýzu a problémy spojené s přenosem výpočetně náročných úloh na hranu sítě využívající koncept známý pod pojmem “multi-access edge comuting“. Práce analyzuje dva základní typy přenosu; první typ spočívá v přímém přenosu výpočetních úloh na základnovou stanici zatímco druhý typ přenosu využívá jedné nebo i více retranslačních stanic. V případě druhého typu přenosu jsou uvažovány dále poloviční a plný duplex přenosu. V dalším kroku je formulovaný problém zaměřující se na minimalizaci spotřeby energie uživatelského zařízení a retranslačních stanic při zaručení maximální doby zpracování úlohy. Poté je navržen jednoduchý algoritmus současně vybírající jak retranslační stanice tak i nejvhodnější typ přenosu. Následně jsou demonstrovány benefity přeposílání výpočetních úkolů přes několik retranslačních stanic pomocí spotřebované energie či pravděpodobnosti, že daná výpočetní úloha je zpracována v požadovaném čase.

Klíčová slova: výpočty na hraně sítě, přenos výpočtů, retranslace, poloviční duplex, plný duplex, spotřeba energie.

List of Tables

List of Algorithms

List of Figures

List of Acronyms

BS base station. 1

BW bandwidth. 10

D2D device-to-device. 2

DO direct offloading. v, 34

EC energy consumption. 1, 34, 35

FD full duplex. v, 2, 34, 35

HD half duplex. v, 2, 9, 34

MEC multi-acces edge computing. 1, 34, 35

SI self-interference. 8

UE user equipment. 1

Contents

Chapter 1

Introduction

Nowadays, there is ever increasing trend with a user equipment (UE) having highly demanding applications to be executed. Thus, there is a requirement on the UE to follow this trend and to be able to process the required computing. Examples of highly demanding applications include augmented reality [1], real-time data processing [2], virtual reality [3], or others. Since the UE's cannot keep up with the demands of highly demanding applications and since they are energy- and computationally-limited devices, local computing is not frequently an option.

Hence, to avoid a high energy consumption (EC), a computing concept called "Cloud computing" was introduced into the networks [4]. This concept offers to the UEs to offload highly demanding computation to a centralized powerful cloud farms, located geographically far away from the UEs. It means no energy will be consumed during task processing on the UE side; the sole consumption on the UE side will be caused by forwarding the task to the cloud. With cloud computing, we can significantly minimize the EC, but its main problem of high latency is still there.

To avoid high latency problems of cloud computing, there is a new concept called mobile edge computing (MEC) [5], later relabeled to multi-acces edge computing. Compared to cloud computing, MEC provides computing at the edge of the network, e.g., at the base station (BS). As computing services are at the edge of the network, the UE is now closer to them, and that is resulting in lower latency. Still, it can happen that UE can not reach BS easily due to long distances or obstacles resulting in high attenuation of the signal. Then, it could result in computation not meeting the predicted deadline for task processing, or offloading will require an undesirably large amount of energy [6].

When it comes to the point that BS is not within a reasonable range of the UE to offload the computing task, it is not a feasible option to perform an offloading as it would result in high EC. This problem can be solved by introducing offloading over the relays, which will help UE to reach the desired endpoint (e.g., BS). Introducing relays in the offloading process can significantly improve the performance of the overall process. When the one offloading relay is used, communication is contained in the two hops, the first from the UE to the relay and the second from the relay to the BS. Relaying solutions helps to minimize the overall process [7], [8] or increase the number of completed tasks within the specified deadline [9], [10]. Sometimes, relays can be an expensive part of the network for mobile operators. Still, the evolution of Device-to-Device (D2D) communication made it possible for UE to act as a relay as well [10], [11], [12]. The offloading of data over relay [6] is beneficial for both savings for mobile operators (like savings of radio resources allocated for offloading) and for the UEs as well as they can offload highly demanding computation to close BS.

To further capitalize on benefits coming from the relaying, more than one offloading relay can be exploited for the UE to reach the BS and, thus, to fulfill requirements by offloading tasks (i.e., offloading delay) and/or requirements on energy spent by the UE to offload its task(s). Offloading over multi-relays plays a vital role in vehicular communication as the high speed of UE changes the topology of the mobile network very fast. In that case, the vehicle acts as UE and will be used as a relay. Also, the UE that act as a relay will charge a fee for its relaying service, which is reasonable and practicable in the visible future [13]. One of the main drawbacks of multi-relay offloading is the optimal algorithm to find the most suitable relays for the offloading, as the positions of the relays or UE can change over time. Each particular node that acts as a relay has to choose the proper path in dynamic topology to the MEC server [6]. Despite the aforementioned issue, multi-relay offloading still could be the most viable option once the optimal algorithm is identified [12]. Besides, many papers exploring relay offloading problems fail to address the allocation of time power at both the UE and relays. Additionally, the majority of these papers only consider offloading using half duplex (HD) [7], [9], [11] while the advantages provided by the full duplex (FD) are not analyzed as of yet.

To this end, this thesis aims to enhance research on multi-hop relaying exploited for the offloading of computationally demanding tasks to the MEC while, at the same time, the main objective is to minimize the sum energy consumption of energy-constrained devices (i.e., the UE and relay UEs) during the offloading process while meeting the deadline for the task's computing. The thesis will consider two implementations of multi-relay offloading: *i)* HD offloading, where we divide the total available time into time intervals and assign one of them to each hop and *ii)* FD offloading, where the transmission is done all the time simultaneously. Hence, we analyze the performance of individual relaying modes and demonstrate the benefits of offloading via multi-hop relay UE(s).

The rest of the thesis is organized as follows. The next chapter (Chapter 2) will describe the system models, including models for direct offloading and offloading via relaying.

Further, Chapter 3 formulates the optimization problem with the goal of minimizing sum energy consumption while meeting the deadline imposed on computing tasks. Chapter 4 covers the analytical derivation of the transmission power for direct offloading and offloading via relay UE(s). The algorithm for selecting the offloading relay(s) and relaying model is described in Chapter 5. In Chapter 6, we will delve into the analysis and explanation of the simulation results. The final chapter of the thesis (Chapter 7) presents a comprehensive summary of the advantages and disadvantages of the entire research work and outline potential future research directions.

Chapter 2

System model

This chapter discusses the direct offloading model and models for offloading via one or more relay UE(s). Notice that we do not describe model for local computing as the main focus of this thesis is on offloading itself. Additionally, calculations of the necessary parameters, such as the channel capacity, processing delay of task during offloading, and resulting energy consumption, will be described.

2.1 Direct offloading model

This model describes offloading of the task from the UE to the BS. The offloading procedure and calculation of all necessary variables will be covered in the following sections.

2.1.1 Channel capacity

To determine processing delay, first, we must obtain the channel capacity corresponding to the maximum data throughput through the channel per unit of time. We assume that bandwidth B is split by the BS into N channels, where bandwidth B_n is assigned to the n-th UE [6]. We'll examine our model as though there is only one existing UE offloading, as the goal is to analyze the performance of the single user. If the n-th UE is directly offloading the task to the BS, the uplink channel capacity using Shannon Theorem can be calculated as:

$$C_{n,b} = B_n log_2 \left(1 + \frac{p_{n,b} g_{n,b}}{B_n(\sigma + I_b)}\right) \tag{2.1}$$

where $p_{n,b}$ correspond to the transmission power of the n-th UE, $g_{n,b}$ represents the channel gain between the n-th UE and BS, σ is the noise spectral density, and I_b is the background interface from the UEs located in the adjacent cells. One of the required parameters for the computation of the channel capacity is channel gain. More about channel gain is described in Chapter 6, but for now, it will be enough to mention how to calculate it:

$$g_{n,b} = 1/10^{\frac{PL_{n,b}}{10}} \tag{2.2}$$

where $PL_{n,b}$ corresponds to path loss in dB between n-th UE and BS.

2.1.2 Processing delay

In case of direct offloading to the BS, the processing delay is constituted from several time intervals. One of those intervals is the offloading time to the BS (denoted as t_n^o), which must be taken into consideration, and the other one is the time spent downloading the computation results from the BS. But, as downloading time is much smaller than the offloading time, it cat be neglected [6]. Then, time spent on direct offloading (t_n^D) can be calculated as:

$$t_n^D = t_n^o + t_n^c = \frac{D_n}{C_{n,b}} + \frac{c_n D_n}{F_b} \tag{2.3}$$

where t_n^c stands for computing time at the BS, c_n represents the average number of CPU cycles required to process one bit of the n-th task, D_n represents the size of the n-th task, and F_b corresponds to the number of CPU cycles processed by the BS per second.

2.1.3 Energy consumption

Consumed energy during the direct offloading of the task from the n-th UE to the BS is:

$$E_n^D = \frac{D_n}{C_{n,b}} p_{n,b} \tag{2.4}$$

Notice that a derivation of $p_{n,b}$ will be covered in Section 4.1.

2.2 Models for offloading via one relay UE

As was previously indicated, there are situations when the direct offloading is insufficient to fulfill the requirements, either in terms of time or energy consumption. This is the reason behind the introduction of offloading via relay UE, which will be discussed in this section. The relay's goal is to improve the system's overall performance by enabling UE to offload the task over the relay UE. In addition, three distinct models of this model will be considered:

- Half duplex model
- Full duplex model 1

- Full duplex model 2

2.2.1 Half duplex model

If the transmission is done in a half-duplex mode, it is not performed simultaneously at both transmission hops. That means the time predicted for the offloading time is divided into two time intervals. One interval with a duration of $t^o_{n,m}$ is for the transmission of the data from the n-th UE to the m-th relay UE, and the other one with duration of $t_{m,b}$ is for the relaying of the data from the m-th relay UE to the BS. An illustration of time division is presented in Figure 2.1, where T_{max} stands for the maximum time within which task should be processed. To obtain EC for this model, it is necessary to change the EC equation described in direct offloading model since total energy consumption is equal to the sum of the energies for each hop, which implies that we should start with the variables needed to calculate the EC.

Channel capacity

First of all, the capacity for each hop is calculated as:

$$C_{n,m} = B_n log_2 \left(1 + \frac{p_{n,m} g_{n,m}}{B_n(\sigma + I_b)}\right) \tag{2.5}$$

$$C_{m,b} = B_n log_2 \left(1 + \frac{p_{m,b} g_{m,b}}{B_n(\sigma + I_b)}\right) \tag{2.6}$$

where $p_{n,m}$ and $p_{m,b}$ are transmission powers of n-th UE and m-th relay UE, respectively, $g_{n,m}$ is channel gain between n-th UE and m-th relay UE, finally $g_{m,b}$ is channel gain between m-th relay UE and BS. The respective channel gains are calculated as:

$$g_{n,m} = 1/10^{\frac{PL_{n,m}}{10}} \tag{2.7}$$

$$g_{m,b} = 1/10^{\frac{PL_{m,b}}{10}} \tag{2.8}$$

Processing delay

The processing delay if the offloading task of n-th UE is done over the relay UE is composed of three parts, expressed as:

$$t_n^{O,HD} = t^o_{n,m} + t^o_{m,b} + t^c_n = \frac{D_n}{C_{n,m}} + \frac{D_n}{C_{m,b}} + t^c_n \tag{2.9}$$

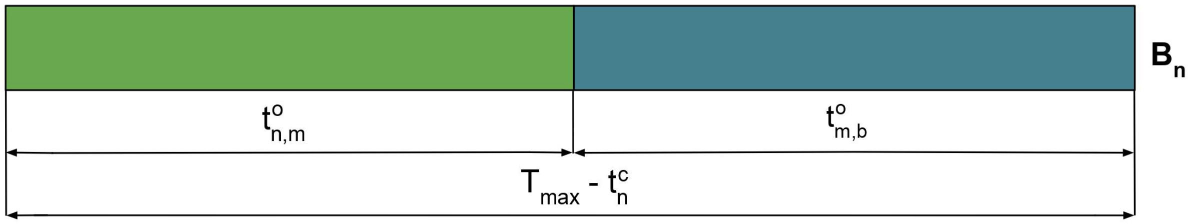


Figure 2.1: Illustration of time division for HD model with one relay UE

Energy consumption

The total energy consumption by the offloading task of n-th UE to the BS can be expressed as:

$$E_n^{O,HD} = E_{n,m} + E_{m,b} = t_{n,m}^o p_{n,m} + t_{m,b}^o p_{m,b} \tag{2.10}$$

where $E_{n,m}$ is energy consumed by transmission of data from n-th UE to m-th relay UE and $E_{m,b}$ corresponds to the energy required to transmit data from m-th relay UE to the BS.

2.2.2 Full duplex model 1

Compared to the previous model, this model allows full-duplex mode transmission. More specifically, the relay UE can send and receive data simultaneously in FD transmission mode but for the price of splitting the available channel bandwidth B to two orthogonal channels with bandwidth B_1 and B_2, respectively (see Figure 2.2). The former is used for the first hop transmission while the latter is exploited for the second hop. Note that by splitting of bandwidth, there is no interference between each hop.

The processing delay for this model is expressed as follows:

$$t_n^{O,FD_1} = \max(t_{n,m}^o, t_{m,b}^o) + t_n^c = \max\left(\frac{D_n}{C_{n,m}}, \frac{D_n}{C_{m,b}}\right) + t_n^c \tag{2.11}$$

where the time of transmission is limited by the capacity of the worse channel, notice that individual capacities (i.e., $C_{n,m}$ and $C_{m,b}$) are calculated as in the previous section but consider B_1 and B_2 instead of B_n.

The energy consumption for this mode is calculated similarly as for HD, expressed as:

$$E_n^{FD_1} = E_{n,m} + E_{m,b} = t_{n,m}^o p_{n,m} + t_{m,b}^o p_{m,b} \tag{2.12}$$

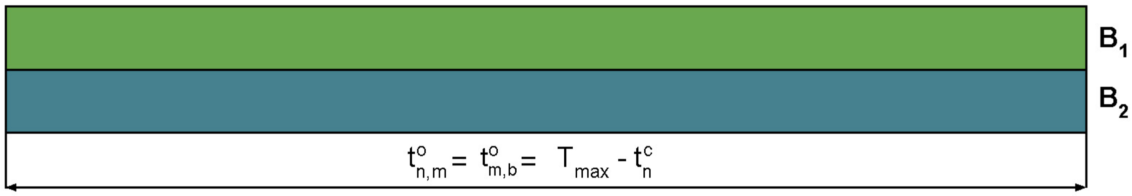


Figure 2.2: Illustration of bandwidth allocation for FD model 1 with one relay UE

2.2.3 Full duplex model 2

This model uses the whole available bandwidth at both hops compared to the previous model, as it is shown in the Figure 2.3.

Channel capacity

The capacity between n-th UE and m-th relay UE can be calculated as follows:

$$C_{n,m} = B_n log_2 \left(1 + \frac{p_{n,m} g_{n.m}}{B_n(\sigma + I_b) + p_{m,b} g_{m,m}}\right) \tag{2.13}$$

where all parameters within the equation can be calculated as for the FD model 1 with the exception of $g_{m,m}$ that represents the gain between the transmitter and receiver of the m-th relay UE to model self-interference (SI) due to the utilization of the same channel bandwidth at both hops [6]. Notice the SI in (2.13) is represented by term $p_{m,b}g_{m,m}$

Similarly, the capacity between m-th relay UE and BS is expressed as:

$$C_{m,b} = B_n log_2 \left(1 + \frac{p_{m,b} g_{m,b}}{B_n(\sigma + I_b) + p_{n,m} g_{n,b}}\right) \tag{2.14}$$

where $g_{n,b}$ is channel gain from n-th UE and BS and $p_{n,m}g_{n,b}$ corresponds to interference from the n-th UE to the BS occurred due to the same radio resources used at both transmission hops.

Note that we do not express processing delay ($t_n^{FD_2}$) and energy consumption ($E_n^{FD_2}$) for this mode as it can be calculated analogously to full duplex mode 1 but considering $C_{n,m}$ and $C_{m,b}$ expressed in (2.13) and (2.14), respectively.

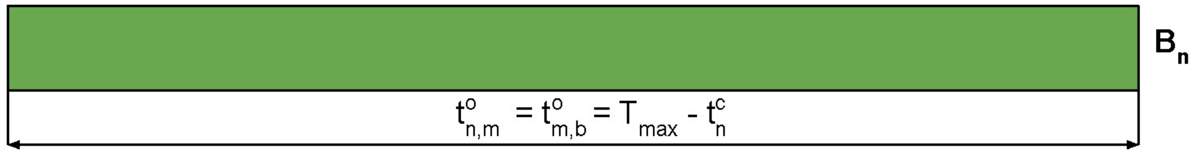


Figure 2.3: Illustration of bandwidth allocation for FD model 2 with one relay UE

2.3 Extension to Multi hop relaying

While the previous section described the models for general two-hop relaying system, we discus in this section the implications if more than two-hops are assumed as well. Note that we limit our analyses to three hops as this gives sufficient picture on benefits of multi-hop relaying. Again, we will describe three types of models:

- Half duplex model
- Full duplex model 1
- Full duplex model 2

2.3.1 Half duplex model

Again, the time division will be presented within the HD model. The total time allocated for the offloading (i.e., $T_{max} - t_n^c$) depends on the number of hops. In the case of J hops , the offloading time should be divided to J number of intervals, as it is shown in the Figure 2.4, each interval is assigned to one hop. The channel capacity can be calculated as in Section 2.2.1 for HD relaying model; the only difference is the processing delay $t_n^{O,HD}$ and total energy consumption $E_n^{O,HD}$.

In particular, the total processing delay is expressed as:

$$t_n^{O,HD} = t_{n,m}^o + t_{m,k}^o + t_{k,b}^o + t_n^c = \frac{D_n}{C_{n,m}} + \frac{D_n}{C_{m,k}} + \frac{D_n}{C_{k,b}} + t_n^c \tag{2.15}$$

where k is index of the second relay UE, $t_{m,k}^o$ is offloading time between m-th relay UE and k-th relay UE, $t_{k,b}^o$ is offloading time between k-th relay UE and BS, $C_{m,k}$ represents channel capacity between m-th and k-th relay UE, and $C_{k,b}$ represents channel capacity between k-th relay UE and BS.

The total energy consumption by the offloading task of n-th UE to the BS via m-th and k-th relay UEs can be expressed as:

$$E_n^{O,HD} = E_{n,m} + E_{m,k} + E_{k,b} = t_{n,m}^o p_{n,m} + t_{m,k}^o p_{m,k} + t_{k,b}^o p_{k,b} \tag{2.16}$$

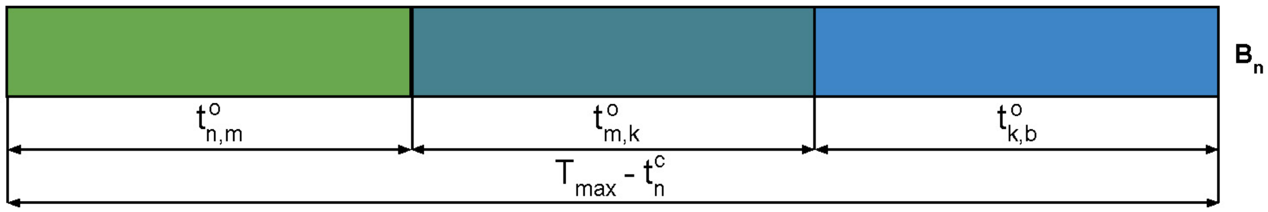


Figure 2.4: Illustration of time division for HD model with multi relay UEs

2.3.2 Full duplex model 1

This model modifies the previous one in a way that BW is split instead of time like in the Figure 2.5. BW is split to the J number of hops. Note that the channel capacity for each two communicating nodes can be calculated using equation (2.6), but the proper appropriate channel parameters must be used.

The processing delay for this model is expressed as follows:

$$t_n^{O,FD_1} = \max(t_{n,m}^o, t_{m,k}^o, t_{k,b}^o) + t_n^c = \max\left(\frac{D_n}{C_{n,m}}, \frac{D_n}{C_{m,k}}, \frac{D_n}{C_{k,b}}\right) + t_n^c \tag{2.17}$$

The total energy consumed by the offloading task of the n-th UE to the BS via m-th and k-th relay UEs is equal to:

$$E_n^{O,FD1} = E_{n,m} + E_{m,k} + E_{k,b} = t_{n,m}^o p_{n,m} + t_{m,k}^o p_{m,k} + t_{k,b}^o p_{k,b} \tag{2.18}$$

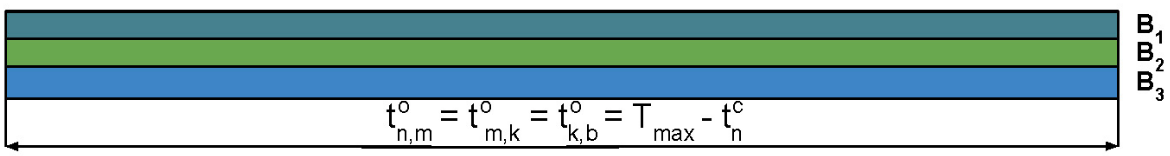


Figure 2.5: Illustration of bandwidth allocation for FD model 1 with multi-relay UEs

2.3.3 Full duplex model 2

Unlike HD and FD model 1, the extension of FD model 2 to multi-hop relaying is no that straightforward. The reason is that we cannot simply use the whole BW at all hops due to very high interference by m-th relay UE to the k-th relay UE as the channel between those two should be of high quality. Thus, we combine FD mode 1 with FD mode 2 in a sense that the former is used by m-th relay UE while the latter is exploited by the k-th relay UE, as it is shown in the Figure 2.6. Then, the channel capacity for the first hop can be calculated from the equation (2.6), while the capacities of the channels for the second and third hop can be calculated from the equations (2.13) and (2.14). Moreover, the processing delay and energy consumption can be calculated analogously to FD model 1 described in the previous section.

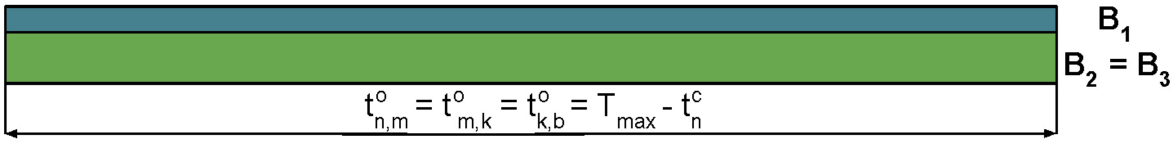


Figure 2.6: Illustration of bandwidth allocation for FD model 2 with multi relay UEs

Chapter 3

Problem formulation

A challenge of this thesis is to identify an ideal offloading model that minimizes energy consumed by energy-constrained devices via joint selection of the relay UEs and respective relaying modes in task offloading form the UE to the BS. Due to the dynamic environment, the model must also meet the requirements for transmission power and offloading time in addition to having the lowest EC. The lower EC will be reflected in the fulfillment of the aforementioned requirements, and the lowest EC with all requirements completed can be represented as the optimization's target. Hence, the problem can be formulated as:

$$
\begin{aligned}
\underset{EC}{\text{minimize}} \quad & EC = \sum_{j=1}^{J} E_j \\
\text{subject to} \quad & \text{(a) } p_j \leq P_{max}, \forall j, \\
& \text{(b) } t_n^O \leq T_{max}, \\
& \text{(c) } \delta^{HD} + \delta^{FD_1} + \delta^{FD_2} = 1, \forall \text{ Relay UEs}, \\
& \text{(d) } \delta^{HD} = \{0,1\}, \delta^{FD_1} = \{0,1\}, \delta^{FD_2} = \{0,1\}, \\
& \text{(e) } J \leq 3
\end{aligned}
\tag{3.1}
$$

where p_j represents the transmission power of the UE or relay UE at j-th hop, P_{max} is the maximum allowed transmission power of energy-constrained devices, δ^{HD}, δ^{FD_1}, and δ^{FD_2} are control variables deciding whether relay UE use HD model, FD model 1, or FD model 2, respectively. Then, the constraint (3.1a) ensures that the transmission power of any UE does not exceed P_{max}, the constraint (3.1b) guarantees that the processing delay of the task is done within T_{max}, constraints (3.1c) and (3.1d) guarantees that each relay UE can employ just one relaying model, and finally constraint (3.1d) assures that only three hops can be used at most in the offloading to limit the complexity of the problem.

Chapter 4

Analytical derivation of transmission power

4.1 Direct offloading

Transmission power is a crucial parameter for offloading as it directly affects whether offloading and processing of tasks can meet the deadline on the task's maximum processing time T_{max}. Processing delay consists of the time required for the offloading and the time needed for the calculation at the BS. The transmission power for direct offloading is derived in the following Lemma.

Lemma 4.1.1. *If the n-th UE is offloading n-th task to the BS, the transmission power of the n-th UE is derived as:*

$$p_{n,b} = \frac{B_n(\sigma + I_b)}{g_{n,b}} \left(2^{\frac{D_n}{t_n^o B_n}} - 1 \right) \tag{4.1}$$

Proof. This can be proved starting from the equation for the channel capacity (2.1):

$$C_{n,b} = B_n log_2 \left(1 + \frac{p_{n,b} g_{n,b}}{B_n(\sigma + I_b)} \right) \tag{4.2}$$

Dividing equation (4.2) with B_n, result with equation:

$$\frac{C_{n,b}}{B_n} = log_2 \left(1 + \frac{p_{n,b} g_{n,b}}{B_n(\sigma + I_b)} \right) \tag{4.3}$$

Then by getting rid off the *log* we get:

$$2^{\frac{C_{n,b}}{B_n}} = 1 + \frac{p_{n,b}g_{n,b}}{B_n(\sigma + I_b)} \tag{4.4}$$

$$2^{\frac{C_{n,b}}{B_n}} - 1 = \frac{p_{n,b}g_{n,b}}{B_n(\sigma + I_b)} \tag{4.5}$$

As $C_{n,b}$ can be replaced with D_n/t_n^o, then the equation (4.5) will look like:

$$2^{\frac{D_n}{B_n t_n^o}} - 1 = \frac{p_{n,b}g_{n,b}}{B_n(\sigma + I_b)} \tag{4.6}$$

Multiplying equation (4.6) by the denominator $B_n(\sigma + I_b)$ results in:

$$\left(2^{\frac{D_n}{B_n t_n^o}} - 1\right)(B_n(\sigma + I_b)) = p_{n,b}g_{n,b} \tag{4.7}$$

Finally, dividing the equation (4.7) with $g_{n,b}$ result with the equation for the $p_{n,b}$:

$$p_{n,b} = \frac{B_n(\sigma + I_b)}{g_{n,b}}\left(2^{\frac{D_n}{B_n t_n^o}} - 1\right) \tag{4.8}$$

This concludes the proof. □

Remark: Notice that the time elapsed during the offloading t_n^o should not exceed T_{max}. Since it can be easily proved that the longer offloading time results in less energy consumption, which is in line with the problem defined in (3.1), we set t_n^o in Lemma 4.1.1 to maximum allowed value while meeting T_{max} as:

$$t_n^o = T_{max} - t_n^c \tag{4.9}$$

In case derived $p_{n,b}$ is higher than P_{max}, T_{max} cannot be met. In this case, we set $p_{n,b} = P_{max}$, calculate $C_{n,b}$ in (2.1) and, subsequently we calculate the required processing time to manage the task according to (2.3).

4.2 Relaying models

This chapter focuses on the derivations of transmission powers for the case if offloading is managed via one or multiple relay UEs.

4.2.1 Half duplex model

In fact, the transmission power derived in Section 4.1 for direct offloading can also be adopted for two-hops and multi-hops relaying. Thus assuming that n-th UE sends data to m-th relay UE, the transmission power is expressed as (see the proof of Lemma 4.1.1):

$$p_{n,m} = \frac{B_n(\sigma + I_b)}{g_{n,m}} \left(2^{\frac{D_n}{t^o_{n,m} B_n}} - 1 \right) \tag{4.10}$$

where $g_{n,b}$ is substituted by $g_{n,m}$ to reflect the channel gain between n-th UE and m-th relay UE and $t^o_{n,m}$ is substituting t^o_n to reflect the fact that offloading time for each hop needs to be inevitably shortened. We follow general way for allocation of offloading time at each hop so that if the offloading process occurs over J number of hops, then offloading time for any hop between n-th and m-th UE (i.e., $t^o_{n,m}$) is:

$$t^o_{n,m} = \frac{T_{max} - t^c_n}{J} \tag{4.11}$$

Equation (4.10) can be used as a general equation for transmission power between hops in HD models, but we should keep in mind that for different hops, we have different channels, and it is necessary to recalculate all parameters related to channels.

4.2.2 Full duplex model 1

The transmission power for this model can be derived in the same way as for direct offloading and half duplex relaying. Since the transmission at both hops occur simultaneously (as described in Section 2.2.2), the transmission over each hop can be set analogously to direct offloading (i.e., $t^o_{n,m} = t^o_n$). On the contrary, due to splitting of bandwidth, divided by the number of hops, bandwidth used for transmission of data from n-th UE to relay UE is calculated as:

$$B_n = \frac{B_n}{J} \tag{4.12}$$

Then, the transmission power used, e.g., at first hop by sending data from n-th UE to m-th relay UE is calculated as:

$$p_{n,m} = \frac{B_1(\sigma + I_b)}{g_{n,m}} \left(2^{\frac{D_n}{t^o_{n,m} B_1}} - 1 \right) \tag{4.13}$$

Also, it is not just about changing the value of the BW for different hops. Every hop uses a distinct channel, a distinct channel means different channel parameters, and that should be kept in mind.

4.2.3 Full duplex model 2

In the case of full duplex model 2, the setting of transmission power is more complicated as transmission powers affect each other. The transmission power at both hops is derived in the following Lemma.

Lemma 4.2.1. *If n-th UE is using FD model 2 transmission and n-th UE is offloading n-th task to the m-th UE relay, transmission power between n-th UE and m-th relay UE is represented as :*

$$p_{n,m} = \frac{(2^{\frac{D_n}{B_n t^o_{n,m}}} - 1) + B_n(\sigma + I_b)}{g_{n,m}} + \frac{B_n\left(\sigma + I_b\right)\left(\left(2^{\frac{D_n}{B_n t^o_{m,b}}} - 1\right) + \left(2^{\frac{D_n}{B_n t^o_{m,b}}} - 1\right)^2 \frac{g_{n,m}}{g_{n,b}}\right) g_{m,m}}{\left(g_{m,b} - \left(2^{\frac{D_n}{B_n t^o_{m,b}}} - 1\right)^2 \frac{g_{n,m} g_{m,m}}{g_{n,b}}\right) g_{n,m}} \tag{4.14}$$

If the m-th UE relay is relaying the n-th task to the BS, then transmission power between the m-th relay and BS corresponds to:

$$p_{m,b} = \frac{B_n(\sigma + I_b)\left(2^{\frac{D_n}{B_n t^o_{m,b}}} - 1\right)\left(1 + \left(2^{\frac{D_n}{B_n t^o_{n,m}}} - 1\right)\frac{g_{n,m}}{g_{n,b}}\right)}{g_{m,b} - \left(2^{\frac{D_n}{B_n t^o_{n,m}}} - 1\right)^2 \frac{g_{n,m} g_{m,m}}{g_{n,b}}} \tag{4.15}$$

Proof. To prove this, starting point needs to be the equation for the uplink channel capacity (2.13):

$$C_{n,m} = B_n log_2(1 + \frac{p_{n,m} g_{n,m}}{B_n(\sigma + I_b) + p_{m,b} g_{m,m}}) \tag{4.16}$$

$$\frac{C_{n,m}}{B_n} = log_2\left(1 + \frac{p_{n,m}g_{n,m}}{B_n(\sigma + I_b) + p_{m,b}g_{m,m}}\right) \tag{4.17}$$

$$2^{\frac{C_{n,m}}{B_n}} = 1 + \frac{p_{n,m}g_{n,m}}{B_n(\sigma + I_b) + p_{m,b} \cdot g_{m,m}} \tag{4.18}$$

$$2^{\frac{C_{n,m}}{B_n}} - 1 = \frac{p_{n,m}g_{n,m}}{B_n(\sigma + I_b) + p_{m,b}g_{m,m}} \tag{4.19}$$

$$(2^{\frac{C_{n,m}}{B_n}} - 1)(B_n(\sigma + I_b) + p_{m,b}g_{m,m}) = p_{n,m}g_{n,m} \tag{4.20}$$

Replacing $C_{n,m}$ by the $D_n/t^o_{n,m}$, results in the equation for the transmission power of the first hop from the n-th UE to the m-th relay UE:

$$p_{n,m} = \frac{(2^{D_n/B_n t^o_{n,m}} - 1)(B_n(\sigma + I_b) + p_{m,b}g_{m,m})}{g_{n,m}} \tag{4.21}$$

Now we got the expression for the $p_{n,m}$, but to get rid of $p_{m,b}$ in the equation (4.21), derivation of the second hop transmission power $p_{m,b}$ needs to be done. To derive transmission power for the second hop, the start point should be again equation for the uplink channel capacity (2.14) of the second hop.

$$C_{m,b} = B_n log_2\left(1 + \frac{p_{m,b}g_{m,b}}{B_n(\sigma + I_b) + p_{n,m}g_{n,b}}\right) \tag{4.22}$$

$$\frac{C_{m,b}}{B_n} = log_2\left(1 + \frac{p_{m,b}g_{m,b}}{B_n(\sigma + I_b) + p_{n,m}g_{n,b}}\right) \tag{4.23}$$

$$2^{\frac{C_{m,b}}{B_n}} = 1 + \frac{p_{m,b}g_{m,b}}{B_n(\sigma + I_b) + p_{n,m}g_{n,b}} \tag{4.24}$$

$$2^{\frac{C_{m,b}}{B_n}} - 1 = \frac{p_{m,b}g_{m,b}}{B_n(\sigma + I_b) + p_{n,m}g_{n,b}} \tag{4.25}$$

$$(2^{\frac{C_{m,b}}{B_n}} - 1)(B_n(\sigma + I_b) + p_{n,m}g_{n,b}) = p_{m,b}g_{m,b} \tag{4.26}$$

$C_{m,b}$ can be replaced with $D_n/t^o_{m,b}$, and the equation for transmission power of the second hop is :

$$p_{m,b} = \frac{(2^{D_n/B_n t^o_{m,b}} - 1)(B_n(\sigma + I_b) + p_{n,m}g_{n,b})}{g_{m,b}} \tag{4.27}$$

To get independent equations of transmission power for both hops, it is necessary to solve a system of linear equations.

$$\begin{cases} p_{m,b} = \frac{(2^{D_n/B_n t^o_{m,b}}-1)(B_n(\sigma+I_b)+p_{n,m}g_{n,b})}{g_{m,b}} \\ p_{n,m} = \frac{(2^{D_n/B_n t^o_{n,m}}-1)(B_n(\sigma+I_b)+p_{m,b}g_{m,m})}{g_{n,m}} \end{cases}$$

Inserting the equation for the transmission power of the first hop (4.21) in (4.27) results in the equation:

$$p_{m,b} = \frac{(2^{D_n/B_n t^o_{m,b}} - 1)(B_n(\sigma + I_b) + (\frac{(2^{D_n/B_n t^o_{n,b}}-1)(B_n(\sigma+I_b)+p_{m,b}g_{m,m})}{g_{n,m}})g_{n,b})}{g_{m,b}} \tag{4.28}$$

The predicted offloading time is equal for both hops in this case, then $t^o_{n,m} = t^o_{m,b} = t^n_o$, and to make the expression less complicated, it is good to introduce substitution:

$$x = 2^{\frac{D_n}{B_n t^o_{n,m}}} - 1 = 2^{\frac{D_n}{B_n t^o_{m,b}}} - 1 \tag{4.29}$$

Then equation (4.28) becomes:

$$p_{m,b} = \frac{x(B_n(\sigma + I_b) + \frac{g_{n,m}}{g_{n,b}}\{[x(B_n(\sigma + I_b))] + [(x(p_{m,b}g_{m,m})]\})}{g_{m,b}} \tag{4.30}$$

Applying basic math operations, it is possible to derive $p_{m,b}$ from the equation (4.30).

$$p_{m,b}g_{m,b} = x(B_n(\sigma + I_b) + \frac{g_{n,m}}{g_{n,b}}\{[x(B_n(\sigma + I_b))] + [(x(p_{m,b}g_{m,m})]\}) \tag{4.31}$$

$$p_{m,b}g_{m,b} = xB_n(\sigma + I_b) + \frac{g_{n,m}}{g_{n,b}}x^2 B_n(\sigma + I_b) + \frac{g_{n,m}}{g_{n,b}}x^2 p_{m,b}g_{m,m} \tag{4.32}$$

$$p_{m,b}g_{m,b} - \frac{g_{n,m}}{g_{n,b}}x^2 p_{m,b}g_{m,m} = xB_n(\sigma + I_b)\left(1 + x\frac{g_{n,m}}{g_{n,b}}\right) \tag{4.33}$$

$$p_{m,b}\left(g_{m,b} - x^2\frac{g_{n,m}g_{m,m}}{g_{n,b}}\right) = xB_n(\sigma + I_b)\left(1 + x\frac{g_{n,m}}{g_{n,b}}\right) \tag{4.34}$$

$$p_{m,b} = \frac{xB_n(\sigma + I_b)\left(1 + x\frac{g_{n,m}}{g_{n,b}}\right)}{g_{m,b} - x^2\frac{g_{n,m}g_{m,m}}{g_{n,b}}} \tag{4.35}$$

After reverting the substitution, the result is the transmission power of the second hop expressed with equation (4.15).

So derived transmission power of the second hop (4.15) can be used in the equation for the first hop (4.21), and the result with the final equation for the transmission power of the first hop (4.14).

□

Note that if derived transmission power $p_{n,m}$ and/or $p_{m,b}$ is lower than 0 or higher than P_{max} (e.g., if introduced interference is too high), the full duplex model 2 is not feasible and other relaying model has to be utilized.

Chapter 5

Proposed relay and relaying model selection algorithm

This chapter explains the algorithm used for the joint relaying model and relay selection. A provided Algorithm 1 is for the offloading with one relay UE. At the beginning, Algorithm 1 sets initial parameters such as the distance between the UE and the BS (d), channel bandwidth B, number of potential relay UEs (N_r), task parameters, etc. (see first line in Algorithm 1). Then, also the resulting energy consumption, that is the energy consumption we are minimizing, is initially set to infinity. Next, for each relay Algorithm 1 repeats the following steps: *i)* control parameters for relaying model selection are set to 0, *ii)* energy consumption for each relaying model defined in previous chapters is calculated, *iii)* relaying model resulting in the lowest energy consumption is selected for each relay UE, and *iv)* if the energy consumption is lower than current EC, this particular relay UE is assumed to be used. Of course, if some other relay UE would result in even lower energy consumption than current EC, it is selected instead and EC is updated accordingly.

Algorithm 1 Proposed algorithm

```
Set initial parameters (e.g., d, B, f, σ, I_b, N_r, task parameters, etc.)
Set EC = inf
for r=1:N_R do
    Set δ^{HD} = 0, δ^{FD_1} = 0, δ^{FD_2} = 0
    Calculate E_n^{HD}, E_n^{FD_1}, E_n^{FD_2}
    Select min(E_n^{HD}, E_n^{FD_1}, E_n^{FD_2})
    Set appropriate δ to 1 (relaying model selection)
    if min(E_n^{HD}, E_n^{FD_1}, E_n^{FD_2}) < EC then
        EC=min(E_n^{HD}, E_n^{FD_1}, E_n^{FD_2}) (relay UE selected)
    end if
end for
```

An algorithm for offloading over two relay UEs can be implemented with a simple modification. That modification requires adding one more while loop, the same as the first one in the provided algorithm. With the added loop, we can test all possible combinations of relay UEs and based on that, we can select two relay UEs that will result in the lowest EC.

Chapter 6

Simulation results

This chapter first describes the simulation scenario including the generations of potential relay UEs positions, the path loss model, and the simulation parameters. Later in the following part, the simulation results are presented and discussed.

6.1 Simulation scenario

In the simulation scenario, we assume that there is one UE offloading the computing task to the BS, where the MEC server is located. The parameters of the task to be processed, such as its size (D_n) and required number of CPU cycle processed per bit (c_n) is generated by uniform distribution within $0.2-5$ Mbit and $1.5-2\times10^3$ CPU cycles per bit, respectively. The distance of the BS from the UE changes from 1 to 300 meters with the step of one meter in the direction of x-axis while the position of y-coordinate remains constant for both the UE and BS (i.e., $y=0$).

Besides direct offloading to the BS, we assume also offloading via one or two relay UEs. In this regard, two configurations of the relays UE's position is considered for the purpose of the simulations. In the first configuration, the relays' positions are supposed to be in the optimal positions, where the distance between individual communicating nodes is the shortest one (see Figure 6.1). Notice that the y-coordinate is the same as the UE's or BS's. Hence, the distance between any m-th and n-th node is calculated, by omitting the y-coordinate, simply as:

$$d=\sqrt{(x_m-x_n)^2} \tag{6.1}$$

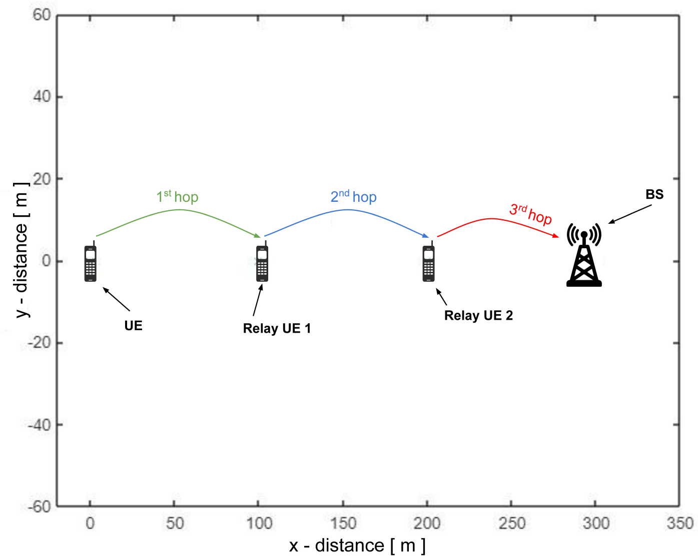


Figure 6.1: Relays position - optimal position configuration

In contrast, in the second configuration, the positions of relay UEs are not optimal and are determined randomly in a way that each relay UE is in between the UE and the BS disregarding their mutual distance while y-coordinate is randomly generated between ± 60 m (see Figure 6.2). We assume that for the non-optimal position configuration, five potential offloading relay UEs are in a game.

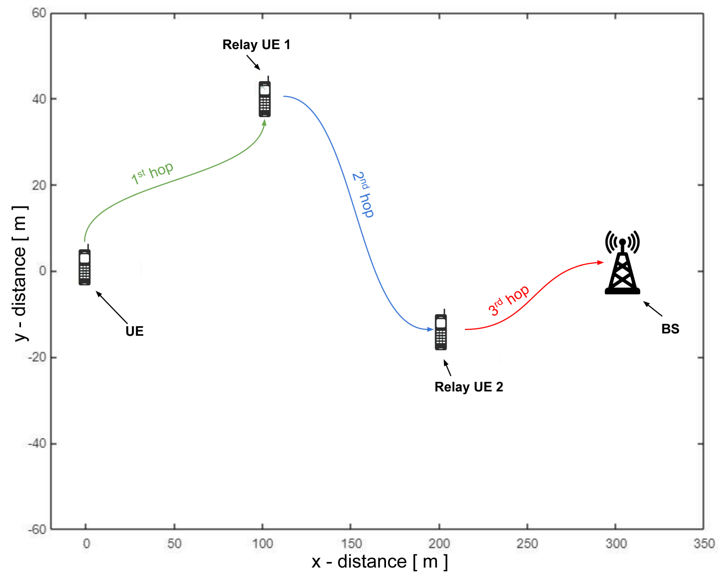


Figure 6.2: Relays position - non-optimal position configuration

For the non-optimal position of the relays, the distance between two nodes can be calculated as:

$$d = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \tag{6.2}$$

To obtain channel gain, it is necessary to specify the path loss model. The model used in the simulation for calculation of the path loss calculation is based on the IEEE 802.16m evaluation methodology. According to mentioned methodology, the path loss is calculated as follows:

$$PL = 35.2 + 35log_{10}(d) + 26log_{10}(\frac{f}{2}) \tag{6.3}$$

where d represents the distance in meters between the BS and the UE in case of direct offloading or between the UE and the relay UE in case of relay offloading, and f is carrier frequency in GHz [14]. Notice that any path loss model can be adopted as this not affect the principle of derived transmission powers or proposed algorithm.

In addition, we assume that the communication path between the transmitter and the receiver can be attenuated by some obstacles. To this end, we first calculate the probability of line of sight p(LoS) according to 3GPP [15] as:

$$p(LoS) = \min(\frac{18}{d}, 1)(1 - e^{\frac{-d}{63}}) + e^{\frac{-d}{63}}. \tag{6.4}$$

Then, random variable x within the range [0,1] is generated. If $x \geq p(LoS)$, additional attenuation τ is added to the path loss, which represents attenuation due to various obstacles (i.e., $PL = PL + \tau$). Notice that τ is generated by uniform distribution between 5 and 20 [dB].

Finally, the channel gain between n-th UE and m-th relay UE is:

$$g_{n,m} = \frac{1}{10^{\frac{PL}{10}}} \tag{6.5}$$

Notice that Equation (6.5) can be used for the calculation of channel gain between any two nodes.

The simulations are done over 1000 simulation drops. Within each simulation drop, we generate the task's parameters, positions of relay UEs (in case of non-optimal configuration), and path loss incorporating the possibility of signal attenuation due to various obstacles. Finally, the results are averaged out over all simulation drops to obtained statistically valid results.

Values and ranges of the individual simulation parameters can be found in the Table 6.1.

Parameter	**Value**	**Parameter**	Value
Carrier freq	2 GHz	T_{max}	[1 3.5] s
Bandwidth	1 MHz	F_b	40·10^9 cyc/s [11]
D_n	[0.2 5] Mbits	c_n	[1.5 2]10^3 cyc/bit [11]
τ	[5 20] dB	J	[1 3] hops
$(\sigma + I_b)$	-150 dBm/Hz	sim. drops	1000 drops
$SIgain$ ($\mathrm{g}_{m,m} in (2.13)$)	10^{-13}	num. of potential relays	5
P_{max}	100mW	-	-

Table 6.1: Simulation parameters

6.2 Results

The section covers the results of the direct offloading model (abbreviated in the figures as DO), single relay model, and multi-relay model. Each previously mentioned relaying mode that is appropriate for the offloading model is implemented in the simulation. First, we focus on the scenario with optimal relay UEs positions and then also illustrate the results for non-optimal relay UEs positions.

6.2.1 Optimal relay configuration

Energy consumption

Energy consumption as a function of the distance for the configuration from Figure 6.1 is presented in Figure 6.3. If not stated differently, we assume the maximal delay of each task to be set to $T_{max} = 3.5$ s.

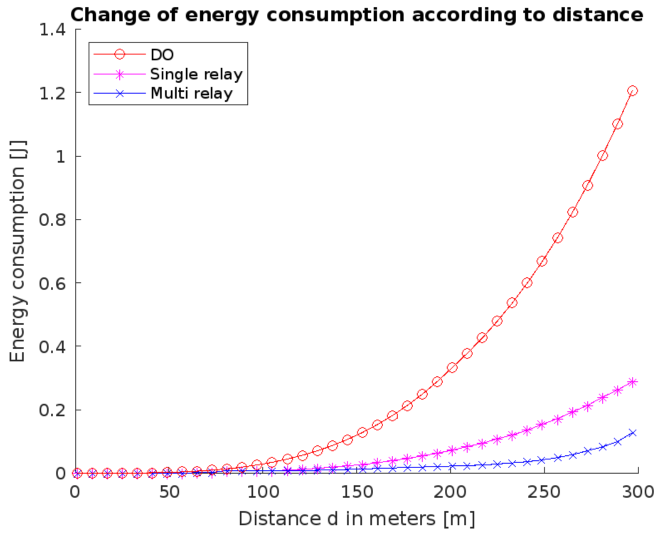


Figure 6.3: Energy consumption over the distance for optimal relay configuration

Figure 6.3 shows that there is a minor difference between DO and relay offloading for distances up to approximately 60 meters. From 60 to 150 meters, a single relay and multi-relay configuration consumes almost the same amount of energy, and from 120 to 300 meters, the best results from an EC point of view cause the multi-relay configuration. For longer distances, high EC for DO configuration is caused by requirements on higher transmission power to reach BS. Also, for the single relay model, consumption is quite higher on larger distances because reaching BS requires more transmission power. For example, for a distance equal to 300m, a multi-relay scenario is able to decrease energy consumption up to 90% and up to 60% when compared to DO and Single relay case.

Offloading time

For the purpose of the simulation, we assumed that the maximum time during which the task had to be processed T_{max} is 3.5 seconds, and it was mentioned earlier that the lowest EC could be obtained if the offloading time t_n^o is equal to that value.

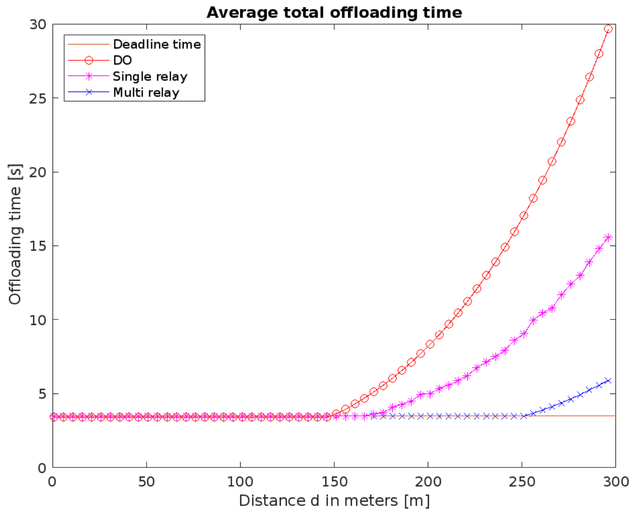


Figure 6.4: Average offloading time for optimal relay configuration

From Figure 6.4, we can see that the DO model offloads within the deadline for distances less than 145 meters approximately, then the single relay model meets the deadline for the distance up to 175 meters, and the multi-relay model meets the deadline for distances up to 250 meters approximately, extending the possible offloading distance by roughly another 75 meters. Again, here we can see a significant advantage of using the multi-relay model because it provides offloading within the deadline for around 83% if the distance between the UE and BS is set to 300 meters, while the DO model provides around 50% and single relay model around 53%.

Offloading probability

From the obtained EC results, we can calculate the probability of offloading the task within the deadline.

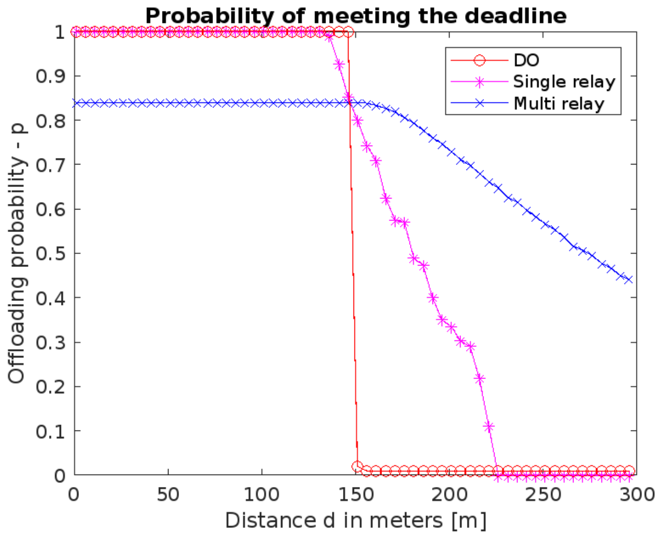


Figure 6.5: Probability of meeting the deadline for optimal relay configuration

It is noticeable that at short distances, up to 150 meters, the DO model and a single relay model have the highest probability of offloading the task within the deadline. After 150 meters, the probability of meeting the deadline with the DO model reaches almost 0 due to the high distance. The probability of the single relay model slowly decreases from 150 meters to approximately 225 meters, where it also reaches nearly 0. On the other side, the multi-relay model provides a high probability for distances up to 150 meters, and behind that point, the probability is slightly decreased. However, the probability is still much better than the other two models.

Energy consumption for fixed distance with variable offloading time

Another interesting thing is to analyze the impact on EC if the different offloading times are used while the distance between UE and BS is constant. Allocated offloading time changes in simulation from 1 second to 3.5 seconds with a step of 0.1 seconds. The results of EC change for distances of 75 and 250 meters are presented in the next two figures.

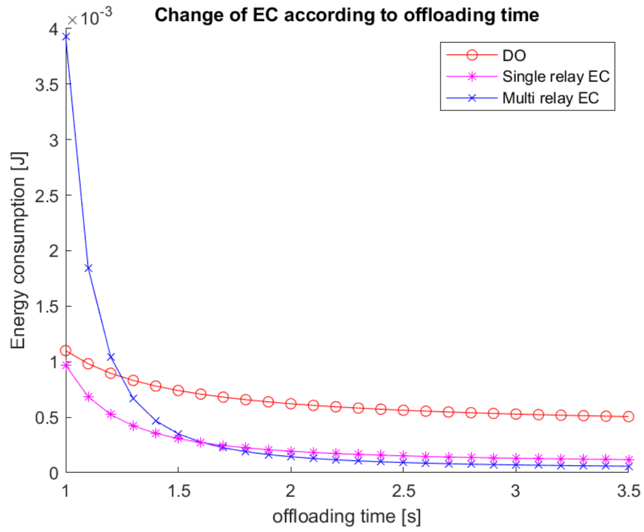


Figure 6.6: Optimal configuration with distance to BS of 75m

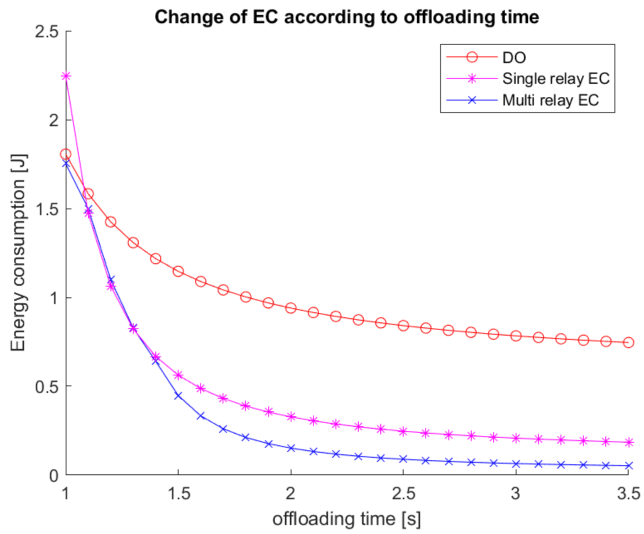


Figure 6.7: Optimal configuration with distance to BS of 250m

In Figure 6.6, it is essential to notice that the EC of the DO model is very close to the consumption of the relaying offloading model due to the lower distance between UE and BS, and more downward distance requiring lower transmission power. Figure 6.7 shows that for a 250m distance between UE and BS, DO is not a good option because it results in a much higher EC than the relaying offloading. For the offloading time lower than around 1.4 seconds, relay offloading models consumption is very similar. But later, for the values of offloading time greater than 1.4 seconds, a multi-relay configuration results in the lowest EC.

6.2.2 Non-optimal relay configuration

Energy consumption

Again, observing energy consumption according to the change in the distance, but this time for non-optimal relay configuration is shown in the figure below.

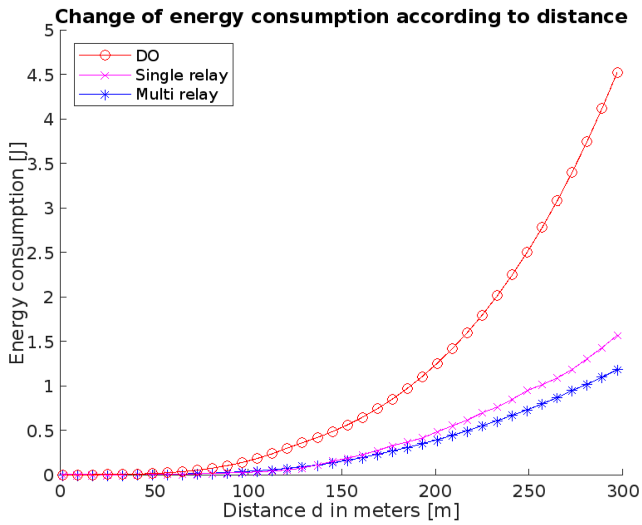


Figure 6.8: Energy consumption over the distance for non-optimal relay configuration

For non-optimal configuration, on a distance of 300 meters, the multi-relaying model consumes around 75% less energy than the DO model and around 25% less than the single relay model. Then, if we compare these results with Figure 6.3, it is noticeable that in the single relay model, for the non-optimal configuration, with distance increase, consumption increases quite faster in comparison with optimal configuration. Also, a single relay model consumes about four times more energy than the model with the optimal configuration. The situation with a multi-relay model is even worse. This model with non-optimal configuration consumes up to 10 times more energy than the same model with optimal configuration.

Offloading time

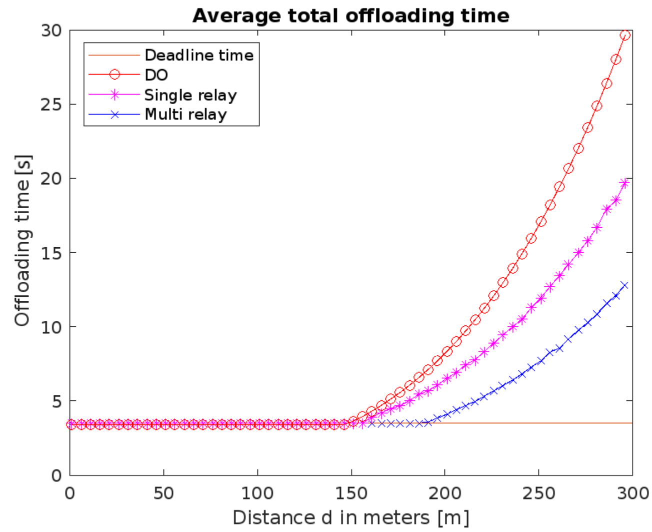


Figure 6.9: Average offloading time for non-optimal relay configuration

Again, we are interested in comparing the results of two relay configurations. If we compare Figures 6.9 and 6.4, we can see that optimal relay configuration provides the lower offloading time for relay offloading models. For example, if we compare multi-relay offloading, it is noticeable that the average offloading time for non-optimal configuration becomes higher than T_{max} on distances above approximately 185 meters, while for optimal configuration, it starts to become higher only after 250 meters.

Offloading probability

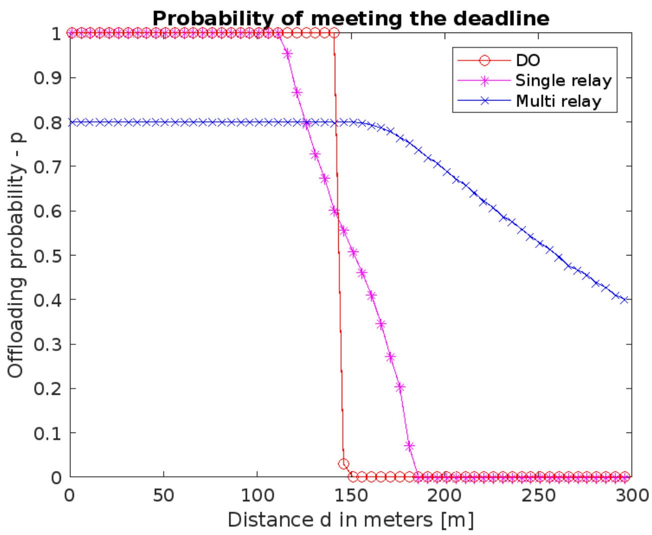
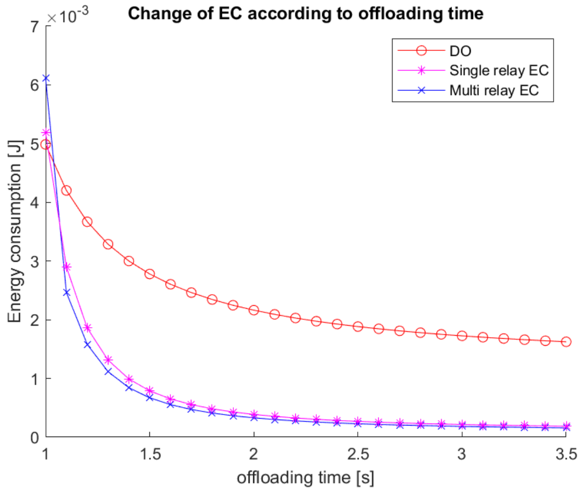


Figure 6.10: Probability of meeting the deadline for non-optimal relay configuration

Comparing Figure 6.10 with Figure 6.5, it is evident that optimal configuration provides higher offloading probability on longer ranges. For single relay configuration, the probability is lowest from about 175 meters in non-optimal configuration, while for optimal, it is around 225 meters. The probability for the multi-relay model doesn't reach near zero in any configuration. Still, from the figures, we can see that optimal configuration provides quite a higher probability of offloading on higher distances.

Energy consumption for fixed distance with variable offloading time

The same scenario, where we consider the change in energy due to the influence of different offloading times while the distance between UE and BS is constant, has also been applied for the non-optimal relay configuration. Again, the considered distances are 75 meters and 250 meters, while offloading time changes from 1 second to 3.5 seconds with a step of 0.1 seconds.



Note

Figure 6.11: Non-optimal configuration with distance to BS of 75m

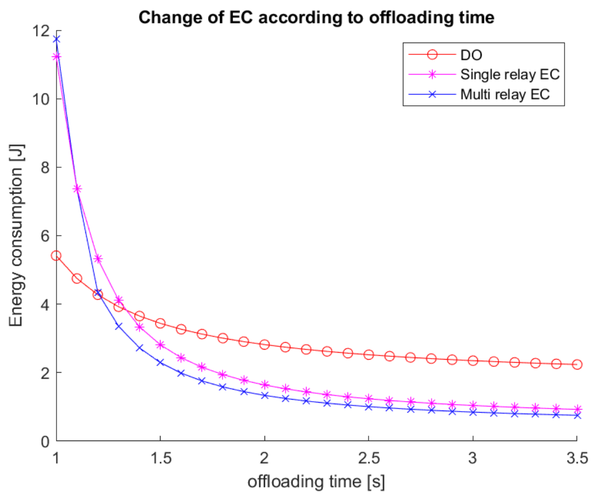


Figure 6.12: Non-optimal configuration with distance to BS of 250m

As a result, from Figures 6.11 and 6.12 we can say that although the energy usage for non-optimal configuration changes quite similarly to the optimal configuration, it is important to notice that EC is noticeably higher for this configuration. Also it is noticeable that if relay UEs are not in the optimal positions, the gain of multi-hop relaying over single relay UE is not that significant. Hence, the optimization of multi-hop relaying, such as setting optimal relaying time slots, is crucial here.

Chapter 7

Conclusion

7.1 Summary of thesis

The main goal of this thesis was to analyze the impact on EC by offloading the computing tasks of highly demanding applications via multi relays to the multi-acces edge computing server located at the edge of the network. First, we had to examine direct offloading and offloading across a single relay to be able to compare and see the actual effects of multi-relay offloading. Analyzing various relaying modes was another objective. In addition to HD relaying, we also needed to get findings for FD relaying; thus, two types of FD relaying were examined. In the FD model 1, simply BW splitting for the hops was applied, and in the FD model 2, there was no BW or offloading time split. The same resources were utilized at the same time but for the price of the additional interference. Another analyzed aspect was the impact of the offloading time to EC for a constant distance between UE and BS. Some difficulties that appeared during the creation of the thesis were the long execution time of the simulations because of the high number of repetitions and the complexity of finding optimal parameters for the configuration of our simulations. Notice that the MEC itself is still not standardized in mobile networks, and much research is still going on it.

7.2 Fulfilments of targets

Numerous Matlab simulations were performed to reach the goals of the thesis assignment from the previous section. Initially, we have simulated and compared EC for a scenario of local computing and DO. The simulation results showed that, from the perspective of the EC, DO is a far better option, and that was the reason not to consider local computing in the further simulations. We demonstrate that for the shorter distances, DO is not such a viable option and could also be helpful for offloading computation tasks. Still, for longer distances it is frequently more beneficial offloading via relay of significant benefit in terms of EC. Another step was to introduce multi-relay offloading, and again, from the results, we could see notable improvements in terms of EC. These mentioned results were obtained without FD relaying modes. Introducing FD relaying modes offloading process consumed even less energy. At this point, we proved the advantage of introducing multiple relays in the offloading process. First, we have investigate the performance if the relay UEs are in the optimal positions to demonstrate the theoretical upper bound we can obtained by multi-hop relaying. Then, we have also analyzed the scenario with relay UEs positioned randomly more often than not the relay UEs will not be ideal positions .

In another simulation, we analyzed the impact of allocated offloading time on EC for a constant distance between UE and BS. From the results, we've concluded that in some cases, the DO model can replace offloading models on shorter distances, especially on smaller offloading time values. Still, offloading models are much more efficient for higher distances, especially if multi-relay offloading is considered.

By managing to run all the simulations, we proved that introducing multi-relay offloading of computing tasks to MEC server has quite a significant impact on energy savings, and that was the goal of the thesis.

7.3 Further extensibility and recommendations

In the future, interesting improvements for this thesis could be the improvement of the algorithm in the way of minimizing the time for selecting offloading relay UEs. As for now, a decision is based just on the EC, but it is necessary to calculate it for each relay UE. Optimization of multi-hop relaying, in a way of setting optimal relaying time slots would also be a nice improvement. Even some machine learning algorithms can be applied which can help with the solution of very hard problems, like NP-hard or NP-complete problems with very low complexity. This approach will minimize the duration of the overall process, but it will require a lot of research to find the optimal one because of the often dynamic environment configurations. It can happen also that, relay UEs may not be willing to help others relay with their tasks and some incentivization mechanisms should be developed in the future to motivate the relay UEs to do it . This should result in more precise results. In the end, all finished work is still the concept; to prove it, it is necessary to implement models and transform simulations into a real scenario in a real environment with real devices.

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