Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Telecommunication Engineering

Diploma Thesis

Mobility Management for D2D Communication in Combined Radio Frequency and Visible Light Communications Bands

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Study Programme:	Electronics and Communication
Field of Study:	Communication Systems and Networks

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MASTER'S THESIS ASSIGNMENT

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II. Master's thesis details

Master's thesis title in English:

Mobility Management for D2D Communication in Combined Radio Frequency and Visible Light Communications Bands

Master's thesis title in Czech:

Řízení mobility pro D2D komunikaci s využitím radiového pásma a pásma pro komunikaci ve viditelném spektru

Guidelines:

Study the concept of device-to-device (D2D) communication combining conventional radio frequency (RF) and visible light communication (VLC) bands. Analyze aspects potentially limiting exploitation of this concept in scenario with moving users in cellular networks. Then, define a suitable method for handover of the user equipment between RF and VLC bands. By means of simulations, assess the performance and efficiency of the proposed method for handover in an indoor scenario with mobile user equipments. Select suitable performance metrics to demonstrate efficiency of the proposed handover.

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[1] P. Mach, Z. Becvar, M. Najla, S. Zvanovec, "Combination of Visible Light and Radio Frequency Bands for Device-to-Device Communication," IEEE PIMRC 2017 workshops, Montreal, Canada, October 2017.
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Date of master's thesis assignment: **07.02.2018** Deadline for master's thesis submission: ___________

Assignment valid until: **30.09.2019**

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Abstrakt

Požadavky na propustnost se značně zvyšují s každou novou generací mobilních sítí. Proto je zapotřebí zlepšovat spektrální efektivitu existujících rádio frekvenčních (RF) systémů a zároveň implementovat nové doplňující technologie. V této práci je zkoumám koncept kombinace RF a komunikace s využitím spektra viditelného světla (VLC) pro Device-to-Device (D2D) komunikaci. VLC je schopno poskytnout vyšší propustnost než RF, zároveň je ovšem VLC velice citlivé na blokování signálu a rušení. Proto je zapotřebí vyvinout rychlý a efektivní vertikální handover (VHO) algoritmus pro přepínaní mezi RF a VLC módy komunikace. Tento VHO algoritmus rozhoduje, zda je pro uživatelské zařízení výhodné přepnout z VLC do RF a naopak. Pokud se zařízení rozhodne zůstat ve VLC, je zapotřebí určit čas, který v tomto blokovaném stavu stráví. V této práci je tento čas počítán na základě počtu D2D párů přítomných v systému. Analytický hierarchický proces, kooperativní hra a stupeň racionality jsou využity pro rozhodnutí o VHO. Dále jsou v této práci diskutovány aplikace, výzvy a problémy, které je nutné vyřešit pro plnohodnotné využití zvažovaného systému. Navržený VHO algoritmus je porovnán se dvěma základními přístupy a dvěma dalšími řešeními VHO, které nezvažovali využití D2D komunikace. Výsledky provedených simulací prokázali, že navržený algoritmus navyšuje průměrné přenosové rychlosti ve většině testovaných scénářů.

Klíčová slova: Device-to-device; Komunikace s viditelným světlem; Rádiová frekvence; Vertikální handover

Abstract

The requirements on throughput are increased significantly with every new generation of mobile networks. Therefore it is necessary to improve the spectral efficiency of existing radio frequency (RF) systems as well as implement new complementary technologies. The concept of combining RF and Visible Light Communication (VLC) in Device-to-Device (D2D) scenario is investigated in this work. VLC can provide much higher throughput than RF, but VLC is also very sensitive to signal blockage and shadowing events. Therefore, it is important to develop fast and effective vertical handover (VHO) algorithm in RF/VLC network. This VHO algorithm decides whether or not it is beneficial for a user equipment (UE) to switch from VLC to RF, or vice versa. If the UE decides to stay in VLC it needs to set a dwell timer which will determine the time UE waits in a blocked state. In this work, the dwell timer is calculated in relation to the number of D2D pairs in the system. The Analytic Hierarchy Process, Cooperative Game and Rationality Degree are then combined to make a decision about VHO. Further, the challenges for a practical application of the proposed communication system are discussed in this work. The VHO algorithm proposed in this work is compared to basic approaches and two other solutions that did not consider D2D. The results of the performed simulations show that the proposed algorithm increases the average bit-rate in the majority of tested environments.

Keywords: Device-to-device; Visible Light Communication; Radio frequency; Vertical Handover

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I would like to thank my thesis supervisor doc. Ing. Zdeněk Bečvář, Ph.D. from the Faculty of Electrical Engineering at Czech Technical University in Prague. I am grateful for efficient communication during many consultations. I very appreciate his professional and valuable guiding opinions for the thesis that has led me through the entire research process. Further, I would like to thank prof. Ray-Guang Cheng from the Department of Electronic and Computer Engineering at National Taiwan University of Science and Technology. His supervision during my stay at NTUST helped me to improve the quality of this thesis.

Contents

List of Figures

List of Tables

List of Acronyms

AHP	Analytic Hierarchy Process.
AP	Access Point.
AR	Augmented reality.
CG	Cooperative Game.
CSK	Color Shift Modulation.
CUE	Cellular User Equipment.
D2D	Device-to-Device.
DUE	Device-to-Device User Equipment.
DVHO	Dwell Vertical Handover.
IVHO	Immediate Vertical Handover.
LOM	Largest-of-Maximum.
LOS	Line-of-sight.
OFDM	Orthogonal Frequency Division Modulation.
PVHO	Prediction Vertical Handover.
RD	Rationality Degree.
RF	Radio Frequency.
RSS	Received Signal Strength.
SINR	Signal-to-Interference-plus-Noise Ratio.
TD	Transfer Delay.
UE	User Equipment.
UVHO	United Vertical Handover.
VHO	Vertical Handover.
VLC	Visible Light Communication.
VR	Virtual reality.

Chapter 1

Introduction

The demands for mobile data consumption of a user increase continuously. There is plenty of reasons why the data consumption is higher every year. The number of smartphones is predicted to be 6.2 billion in 2021, which is almost double compared to 2016 [1]. Video streaming services have the main contribution to data traffic usage. Video related services are predicted to increase 870% from 2016 to 2021 and will make up 78% of all mobile data traffic[1]. In 2016, the data traffic was 7 exabytes per month. The estimated data traffic for 2021 is 49 exabytes [2]. Further, the growth of data consumption will be influenced by rising adoption of Virtual reality (VR) and Augmented reality (AR) [1].

To handle this amount of data, new more efficient approaches to data delivery for the user must be developed. The Radio Frequency (RF) spectral efficiency improvement is necessary, but other complementary technologies should be developed to relieve the pressure on RF systems. One possible technology is Visible Light Communication (VLC) [3]. The VLC provides a large unlicensed spectrum, which can be utilized for high-speed data transfers [4]. The fact that visible light cannot penetrate walls and other obstacles makes VLC technology a good candidate for indoors use. While the introduction of VLC into the network brings many positives it also introduces new challenges that have to be addressed. It is crucial to develop efficient Vertical Handover (VHO) between RF and VLC bands. Without a proper decision on which band should be used the user experience might not improve with the introduction of VLC. It might be even worse if a decision to perform the handover is made poorly and users experience long interruptions in communication. The challenge of a handover decision is caused by many factors. Similarly to RF communication, the bit-rate of VLC is highly dependent on Signal-to-Interference-plus-Noise Ratio (SINR). The challenge is that the level of SINR is changing much faster than in the case of RF-based communication. One of the reasons is VLC's dependence on Line-of-sight (LOS). If clear LOS communication scenario is not available the level of SINR is low [5].

Moreover, compared to VLC communication systems utilizing transmitters in the ceiling, the Device-to-Device (D2D) communication scenario is facing much higher interference if D2D pairs operate in the same frequency band. With a rising number of D2D pairs operating in a single location, the stability of communication in the visible light spectrum is further decreased. The simplest solution is to utilize VLC mode whenever it is available and in case of VLC channel interruption, User Equipment (UE) should fall back to RF communication. This approach is possible however due to high instability of VLC channel it leads to frequent handovers. Therefore, the switch from VLC should be performed only if the interruption is so long that it would be more efficient to use RF. The problem is that at the moment of an interruption start the duration of the interruption is unknown.

Combination of VLC and RF is commonly addressed in a scenario with VLC Access Point (AP) deployed in the ceiling [6],[7],[8]. In these solutions, the use of VLC is assumed only for down-link. Therefore there is no need for VLC transmitter in UE and the VLC APs transmitters are static. The use of D2D communication is not considered in these papers. While RF D2D scenarios are well studied, and are surveyed in [9], the research of VLC in D2D is limited only to several papers [10],[11],[12],[13]. In [10] and [11], only the VLC mode is studied for D2D communication. In [10], the most suitable VLC mode from three proposed option is selected based on game theory. The UE can communicate directly, indirectly via AP or by combination of these two. In [11], the optical repeater scheme is studied to extend the available distance of VLC D2D. The only papers considering combination of both VLC and RF bands in D2D is to best of my knowledge [12] and [13]. The [12] showcase the possible increase in system capacity by combining the RF and VLC in D2D scenario. The most significant gain from the proposed combination of communication bands is identified for low distances (up to 10m). However, the problem of efficient VHO is not addressed. In [13] the selection of communication mode is studied, the interruption of communication and mobility of UEs is not considered.

In this work, aspects potentially limiting exploitation of VLC-RF based D2D communication system are further studied. This system has the potential to enable VLC even in areas without light system upgraded to support VLC. To the best of my knowledge, there is currently no solution that would address the problem of VHO between RF and VLC in D2D communication scenario. By means of simulations, the performance and efficiency of the proposed method of handover are assessed, in an indoor scenario with mobile UEs. Average bit-rate is selected as a performance metric, in order to assess the spectral efficiency of the proposed solution. Thanks to the conducted simulations, additional insight into the dynamics of VLC-RF D2D communication is gathered. The proposed solution is capable to increase the average bit-rate of UEs. The effect of the increasing number of D2D pairs in a single location is studied. Overall the plausibility of the proposed system is confirmed. The results suggest that the VLC can play a significant role in relieving the demands on future RF based systems. With the new generation of devices that would support D2D communication in both RF and VLC, efficient VHO between these modes is crucial to maximizing the efficiency of the available technology.

The rest of this work is structured as follows. Chapter 2 presents an overview of related work. Chapter 3 describes the system model of VLC-RF network utilizing D2D communication. Chapter 4 presents the proposed algorithm applied to a system model from Chapter 3. Chapter 5 presents the simulation parameters and simulation results. Finally, in Chapter 6, the conclusion and discussion of future work are provided.

Chapter 2

Literature Review

In this chapter, the literature review is conducted in order to cover the knowledge available in all areas related to the conducted work. First, the basics of radio frequency communication and visible light communication are introduced. The differences between these two access methods are described. Second, an overview of D2D communication is presented in order to understand the differences this type of communication has over the eNB based system. The key areas of mobility management are introduced. The existing solutions for VHO between RF and VLC are summarized next. Finally, the challenges of the proposed communication system are evaluated in the last section.

2.1 RF vs VLC Overview

While the RF communication is well researched since the beginning of the 20th century, the first efforts to utilize LED based system for VLC is proposed by researchers at Keio University in 2000 [14]. Since then, the research continued with rapid paste to develop this technology. Multiple surveys has been conducted to evaluate the applications, architecture and challenges of systems utilizing VLC [15],[16],[17],[18]. Fig. 2.1 shows the range of frequencies that are utilized by VLC. As the name suggests, the frequencies from the range of 430 to 790 THz are visible to the human eye. Thanks to that, the VLC based system can serve for illumination and communication at the same time. Similarly to RF, VLC can be modulated in various ways. Following four methods are discussed in [15]: On-Off Keying, Pulse modulation, Orthogonal Frequency Division Modulation (OFDM) and Color Shift Modulation (CSK). Compared to RF communication, the higher frequency used in VLC has several implications. Contrary to RF, the frequencies of visible light are easily blocked by walls or passing humans. While this does present a challenge in form of higher sensitivity to shadowing, it also results in higher privacy/security of the VLC [15]. Finally, the potential to achieve high bit-rates is very promising as shown in previous research [4], [19]. While most studies focus on the usage of VLC in a scenario with transmitter statically positioned in the ceiling. If UEs are modified accordingly, it is plausible to utilize the VLC communication in the D2D scenario as shown in [20].

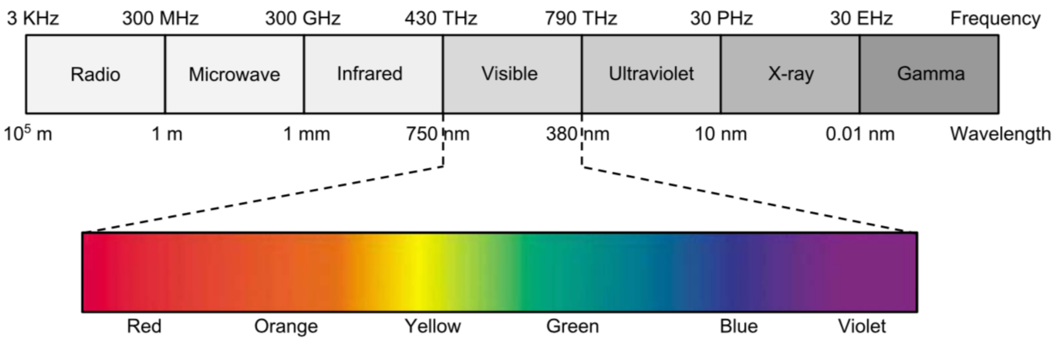


Figure 2.1: VLC spectrum [15]

2.2 D2D Communication

The D2D communication is identified as direct communication between two or more UEs without intervention from a base station. Fig. 2.2 illustrates this concept, Device-to-Device User Equipment (DUE) represent devices communicating in D2D mode and Cellular User Equipment (CUE) represent cellular communication. Four main advantages are identified in [21]. First, the close proximity of DUEs allows for the high bit-rate, while the energy consumption is reduced thanks to the good quality of communication channel. Second, the packet delay is reduced. Third, the radio resources are saved by utilizing one-hop communication instead of the traditional two hop model. Fourth, it is possible to reuse radio resources utilized by a cellular network. The D2D communication can be divided into Out-of-Band and In-Band. For In-Band case the frequencies of the licensed spectrum are utilized. In case of Out-of-Band, the unlicensed spectrum such as VLC is used for communication between DUEs. Further, the D2D communication can be divided into overlay and underlay. In overlay mode, the resources allocated to DUEs are not used by CUEs and vice versa. The D2D communication in RF is well researched and surveyed for example in [9],[22],[23]. On contrary the VLC D2D is mentioned only in a limited number of papers [10],[11],[12],[13]. However, the use of VLC can help to increase the mentioned advantages of D2D.

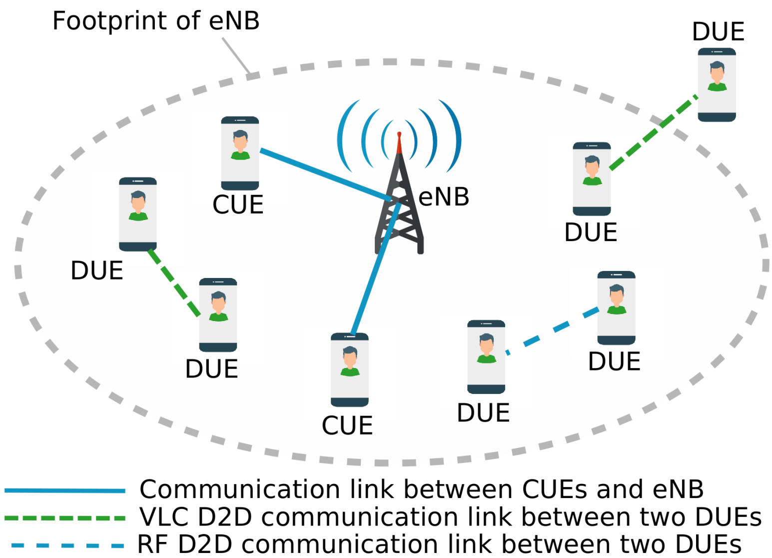


Figure 2.2: D2D concept

2.3 Mobility Management

The two main components of mobility management are location and handover management [24]. In this work, the main focus is on the handover management. The process of handover management is illustrated in Fig. 2.3. The handover process can be divided into three phases: Handover Information Gathering, Handover Decision and Handover Execution [25]. Information gathering phase is used to collect all the available information that is needed for the decision phase. In the decision phase, the most suitable communication mode is selected and the type of handover is chosen accordingly. Finally, based on instructions from the previous phase, the handover is executed. The mobility of UEs can be horizontal (between two cells in the same network) or vertical (between two different access methods). The focus of this work is on mobility management in RF/VLC based system, therefore the vertical handover is used. Further, the handover can be divided based on who has the control over handover. The handover can be controlled by network or UE. To evaluate the performance of the handover it is possible to use many different metrics, see Fig. 2.3. There is a selection of strategies that can be implemented for the decision process. From traditional approaches utilizing one or two criteria for instance Received Signal Strength (RSS), to more complex solutions, such as neural network or fuzzy logic based solutions. The disadvantage of more complex approaches is a computational complexity, which results in a slower decision process.

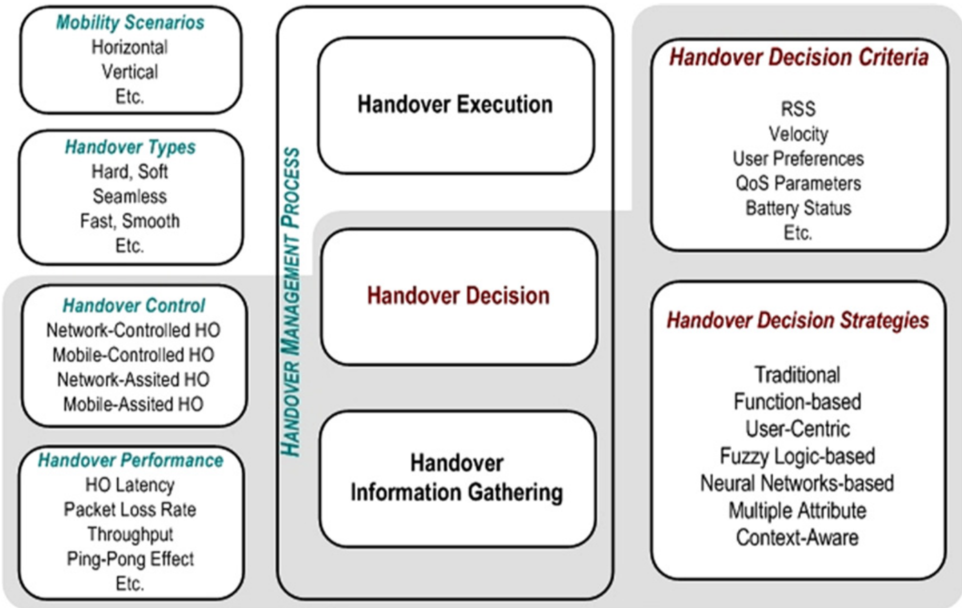


Figure 2.3: Handover managment concept [25]

2.4 Existing Solutions for VHO in RF-VLC System

There are several VHO algorithms addressing the problem of VHO between VLC and RF in access point based systems [7],[6]. These can be used as inspiration and are tested for D2D scenario in this work. There are two basic VHO algorithms mentioned in [8]: Perform the VHO immediately after an interruption (Immediate Vertical Handover (IVHO)) or: to set a dwell timer (Dwell Vertical Handover (DVHO)). Those are very basic solutions and each has its advantages in certain situations. For example, for long interruptions, IVHO has lower Transfer Delay (TD). Contrary, in case of a short interruption, the DVHO has the lower TD [6]. The problem is that both of these interruptions occur in VLC rather randomly, therefore more sophisticated VHO should be introduced. The fuzzy logic VHO algorithm [8] identifies three variables that are used for a decision between IVHO and DVHO. There is the probability of short interruption, the failure probability of handover to radio and the size of unsent messages. With these three variables as inputs, the algorithm utilizes singleton fuzzifier and a Largest-of-Maximum (LOM) defuzzifier [8] to generate a clear decision to use either IVHO or DVHO. By selection of the better option, it is possible to evade the undesired effects of IVHO or DVHO and utilize them only in scenarios where either of them performs better. Similarly to fuzzy logic VHO, the Prediction Vertical Handover (PVHO) [6] algorithm utilizes a set of variables to decide between performing IVHO or DVHO. The set of variables is slightly different (interruption durations, message sizes, and access delays) and the main focus is on the prediction of the delay caused by either IVHO or DVHO. Once predictions of delay for IVHO and DVHO are calculated the option with a lower value is selected. The Multi-attribute VHO [7] uses for the decision three parameters. Similarly to PVHO, the delay of the decision, message queue length, and bit-rate are used. To make a decision the Multi-attribute algorithm exploits Analytic Hierarchy Process (AHP), two-person Cooperative Game (CG) and the Rationality Degree (RD). To evaluate the weight of each parameter the AHP is used. The CG is used to assess the capability of the decision to either perform VHO or not. These results are finally combined by criterion called rationality degree. This process is triggered every time a VLC channel is interrupted. The algorithm compares the RD and selects the decision with higher value. This work does not consider a long interruption of VLC signal. Therefore it does not include any solution for dwell timer in case of long-term signal blockage. None of the mentioned solutions for VHO between RF and VLC consider the D2D type of communication.

2.5 Use Cases and Challenges for RF-VLC D2D

The combination of VLC and RF utilizing the D2D has a potential to increase the system capacity. However, due to the specifics of VLC communication, the use case with the high benefit is restricted by several factors. The VLC has been proven to be effective especially in short range scenarios [5], suggesting the main application in indoor environments. Further, the services which require high throughput and can tolerate occasional sudden degradation of the communication channel are targeted. With the mentioned limitations, we can imagine a scenario of users which needs to transfer files with significant size. If those users stay in the same room it will be more effective to utilize D2D links and by combining VLC with RF communication we can further increase the capacity available to all users in one location. During the transition of files the latency of communication is less important and therefore the maximization of communication throughput should be a priority. Four challenges for RF-VLC D2D communication are identified in [12]. The first challenge is a selection of a better alternative from RF and VLC, this is the main focus of the proposed work. Three other challenges that need to be further researched are handover control, resource scheduling and signaling. The handover control can be centralized or distributed. In the case of the centralized solution, the base station makes the decision to switch between different modes. The advantage of the distributed approach is a reduced delay of a decision by allowing UE to decide. The disadvantage is that the UE does not have information about the overall status of the network. Regarding scheduling, the scheduling metrics can be represented in the same way for both RF and VLC. Therefore, one scheduler should be able to serve both RF and VLC without any complications [12]. However, the inclusion of VLC brings larger variability in available resources and channel quality variations. New solutions that would utilize these specifics to improve the performance can be investigated. Finally, the question of the utilization of available communication channels for signaling has to be addressed. It is possible to use both RF and VLC for signalization. However, the amount of data transferred in signaling is low. Therefore, it should be sufficient to utilize only RF link as in case of VLC the quality of channel varies drastically.

Chapter 3

System model

In this chapter, a general system model is described. In this model, there are N*2 UEs divided into N D2D pairs. All users carry multi-mode UEs and move around. Each UE is therefore equipped with two transmitters and receivers each capable to communicate in VLC and RF mode, respectively. Each of N pairs represents communicating users. Transmitting user $\mathrm{UE}_{Tj} \in$ MT and receiving user $\mathrm{UE}_{Ri} \in$ MR. The MT represents the set of all transmitting users and the MR represents the set of all receiving users see Fig. 3.1. Each device operates in one of two possible modes of D2D communication: RF or VLC. In the first one, RF mode, the device communicates at a standard LTE frequency. In the second mode, VLC mode, the device operates in frequencies of the visible light spectrum. The channel gain of each D2D pair is denoted as g_{Tj-Ri} and is further divided in relation to used communication mode to g^{RF}_{Tj-Ri} and g^{VLC}_{Tj-Ri} for RF and VLC mode, respectively. The devices from MT and MR can also be further classified into two groups according to communication mode used by the pair. M^{VLC}_R and M^{RF}_R represent all receivers communicating in VLC or RF mode, respectively. While M^{VLC}_T and M^{RF}_T correspond to transmitters operating in VLC and RF mode, respectively. All M^{VLC}_T transmit VLC signal in the same frequency band and therefore cause interference to all M^{VLC}_R, except the receiver, which is in the same pair. Similarly, all M^{RF}_T cause interference to all M^{RF}_R except the receiver, which is in the same pair. Also, it is assumed that D2D pairs communicating in RF are interfered by D2D pairs in neighboring cells. This fixed interference is modeled as -70 dBm [13]. Between two D2D pairs, this system model has three possible combinations which could occur. First, each pair is communicating in a different mode and therefore there is no interference. Second, both pairs communicate in VLC and therefore both receivers are interfered by the transmitter from the other pair. Third, similarly to the previous case, both pairs communicate in RF mode and both receivers are interfered by the transmitter from the other pair. In general, we can say that each UE_{Rn}^{RF} from M_{R}^{RF} is interfered by M_{T}^{RF} except UE_{Tn}^{RF}. Similarly, each UE_{Rn}^{VLC} is interfered by M_{T}^{VLC} except UE_{Tn}^{VLC}.

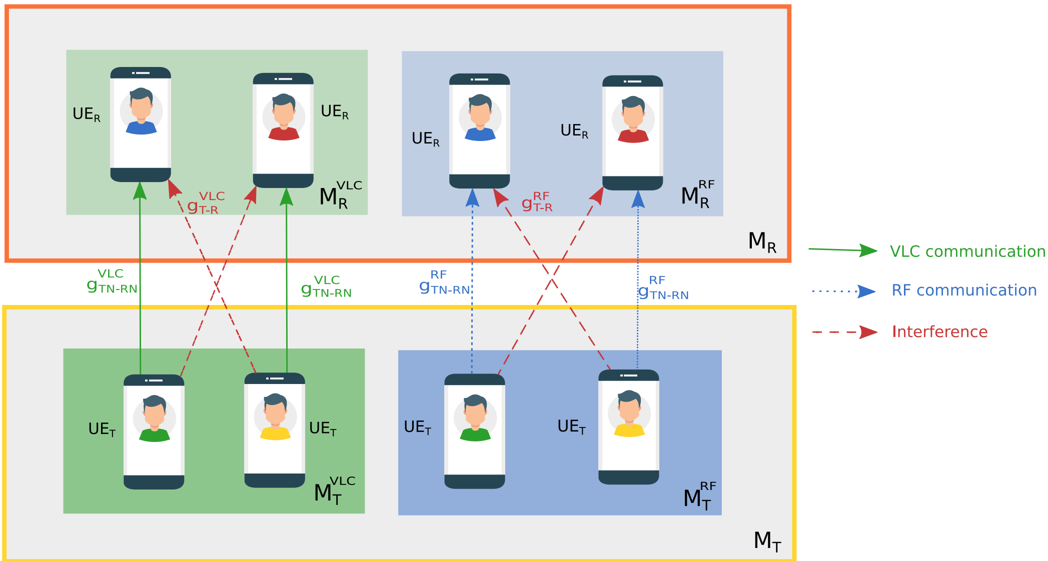


Figure 3.1: UE group classification

The Fig. 3.2 illustrates capability of UEs to communicate in both RF and VLC. In this thesis, we do not assume the option for one D2D pair to communicate in both proposed modes at the same time. The example shows UE_{T1} communicating with UE_{R1} while interfering to UE_{Ri}. Also, UE_{Tj} communicates with UE_{Ri} while interfering to UE_{R1}.

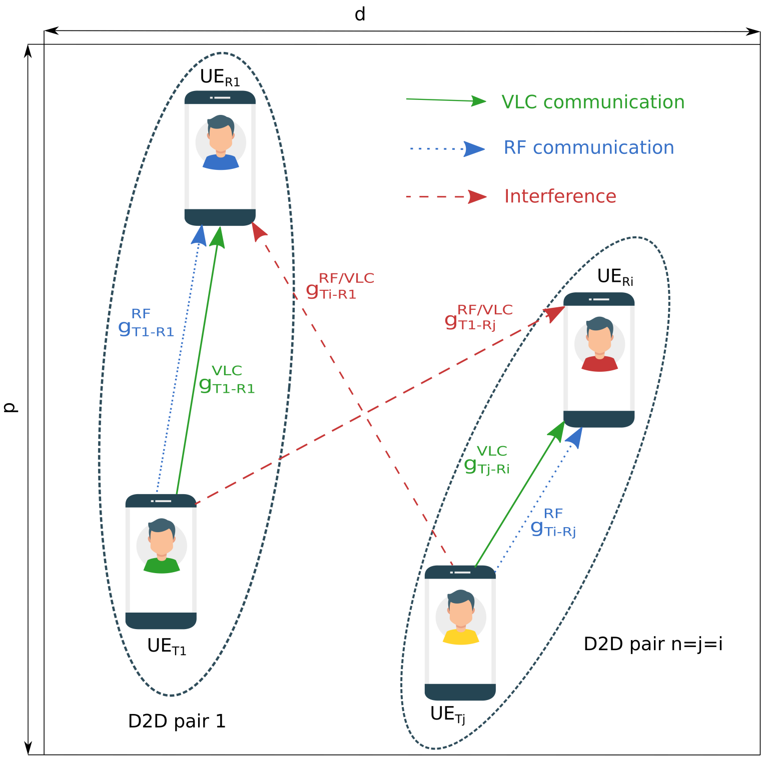


Figure 3.2: System Model concept

VLC is highly sensitive to the azimuthal orientation of the transmitter and the receiver. Variable azimuthal orientation is therefore assumed for all devices. In Fig. 3.3 the irradiance (ϕ) and incidence (ψ) angles are illustrated.

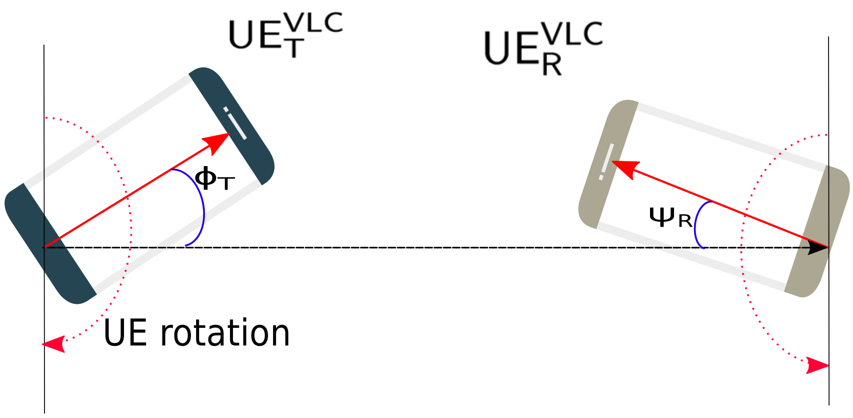


Figure 3.3: Illustration of irradiance and incidence angles

The default mode of communication is set to VLC in [7], in our system model the default mode is RF. However, this change is only a minor since after a certain period of time both approaches will behave the same way. The change of the default mode is made due to believe that VLC should be mainly a complementary technology to RF and not the other way around. The traffic between UE_{Tn} and UE_{Rn}, is assumed to follow the full buffer model, where all UE_{Tn} always have data available for transition to UE_{Rn}. The buffer structure of UE_{Tn} can be divided into input buffer queue and output buffer queue. In accordance with the traffic model the input data queue always has data that can be provided to output data queue. This results in a situation where the output data queue is always at its maximum level since new data from input buffer queue are always available. This model is used to assess the spectral efficiency of the communication channels without dependency on the traffic type used by the users in the system [26]. While the RF mode is assumed to be stable, the interruptions are assumed with duration D_b in VLC mode. These interruptions are caused either by signal blockage or interference from M_T^{VLC}.

The VHO from VLC to RF is triggered every time interruption of VLC signal occurs. This interruption is detected by a severe decline of SINR^{VLC}. To model SINR^{VLC} following equation is used [12]:

$$SINR_{R_n}^{VLC} = \frac{P_t^{VLC} g_{T_n-R_n}^{VLC} \gamma^2}{\sum\limits_{l \neq n} (P_t^{VLC} g_{T_l-R_n}^{VLC}) + \sigma_{t,VLC}^2 + \sigma_s^2} \tag{3.1}$$

where P_t^{VLC} represents the transmitting optical power of LED, $g_{T_n-R_n}^{VLC}$ is the VLC channel gain between the UEs of the n-th pair, γ represents the responsivity of a photodiode, the $\sigma_{t,VLC}^2$ and σ_s^2 corresponds to the thermal noise in VLC and shot noise respectively. Since the gain of VLC channel is strongly dependent on irradiance ϕ and incidence ψ angle, in addition to optical receiver parameters. The channel gain $g_{T_n-R_n}^{VLC}$ is represented by following equation:

$$g_{T_j-R_i}^{VLC} = \frac{(m+1)A cos^m(\phi) T_s g(\psi) cos(\psi)}{2\pi d_{TR}^2} \tag{3.2}$$

where for a designated D2D pair *i*=*j*=*n*. A is the physical area of photodetector, T_s represents the gain of an optical filter, d_{TR} is the distance between UE_{Ri} and UE_{Tj}, $g(\phi)$ is the gain of an optical concentrator, the m corresponds to the order of Lambertian emission which can is represented in the following equation:

$$m = \frac{-ln(2)}{ln(cos(\phi_c))} \tag{3.3}$$

where ϕ_c represents the transmitter semi-angle at half power [15].
Optical concentrator gain $g(\psi)$ is depended on photodetector's view angle ($\psi(c)$) and can be expressed as:

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2(\psi_c)} & if \quad 0 < \ \psi \leq \psi_c \\ 0 & otherwise \end{cases} \tag{3.4}$$

Following equations are used to calculate the thermal and shot noises [15]:

$$\sigma^2_{t,VLC} = \frac{8\pi k T_k \eta A I_2 B^2}{G} + \frac{16\pi^2 k T_k \Gamma \eta 2 A^2 I_3 B^3}{g_m} \tag{3.5}$$

$$\sigma^2_s = (2qI_{bg}I_2B) + (2q\gamma P^{VLC}_t g^{VLC}_{T_n-R_n}B) \tag{3.6}$$

where k is Boltzmann's constant, T_k corresponds to the absolute temperature, η is the fixed capacitance of the photodetector per unit are, I_2 and I_3 stand for the noise bandwidth factors, B is the equivalent noise bandwidth, G represents the open-loop voltage gain, Γ is FET channel noise factor, g_m corresponds to FET transconductance, q is the charge, and I_{bg} is the background current [15]. For this model the assumptions is that all UEs are equipped with RGB-based LED and photodetector [4],[11].
Further, the bit rate is derived according to Shannon-Hartley's theorem:

$$R^{VLC} = B^{VLC} log_2(1 + SINR^{VLC}) \tag{3.7}$$

where R^{VLC} is the bandwidth of VLC system, and $SINR^{VLC}$ represents SINR in VLC mode at UE_R.

Similarly, the R^{RF} and SINRRF are calculated as follows:

$$R^{RF} = B^{RF} log_2(1 + SINR^{RF}) \tag{3.8}$$

$$SINR^{RF}_{R_n} = \frac{P^{RF}_t g^{RF}_{T_n-R_n}}{\sum\limits_{l\neq n}(P^{RF}_t g^{RF}_{T_l-R_n}) + \sigma^2_{t,RF}} \tag{3.9}$$

where R^{RF} is the bandwidth of the RF system, and $SINR^{RF}$ represents SINR in RF mode at UE_R, P_t^{RF} is the RF transmitting power of UE_T, $g_{T_i-Ri}^{RF}$ is the RF channel gain between the UE_{Ti} and the UE_{Ri} of the i-th pair, and $\sigma_{t,RF}^2$ represents the thermal noise in RF with a spectral density of -174 dBm/Hz.

To evaluate the performance of proposed algorithm the average bit-rate is selected as a performance metric. The average bit-rate is calculated as follows:

$$R_{avg} = \frac{\sum_0^t S_{data}}{t} \tag{3.10}$$

where t represents the overall time elapsed during the communication of the devices and S_{data} stands for the total amount of transferred data. Further, to evaluate the behavior of the proposed system, two additional metrics are used. The average interruption of communication and the average number of performed VHO.

$$Int_{avg} = \frac{Int_{duration}}{Int_{count}} \tag{3.11}$$

$$VHO_{avg} = \frac{VHO_{count}}{N} \tag{3.12}$$

where $Int_{duration}$ represents the total time UEs spend in the interrupted state, and Int_{count} represents the total number of interruptions, VHO_{count} represents the total number of performed VHO and N is the number of D2D pairs.

Following assumptions are used in the presented system model:

- D2D communication has dedicated bands:
  D2D RF does not interfere with cellular communication, but all D2D pairs in RF band do interfere with each other [12] & [9]. For a high number of D2D pairs in RF mode, the interference caused by nearby pairs is significant.

- Pairs in D2D VLC mode cause interference to other pairs in VLC mode [12]:
  As all D2D pairs in VLC use the same frequency, the stability of communication is significantly reduced with increasing number of pairs in VLC.

- The VHO is triggered if VLC signal drops rapidly [6] & [7]:
  In VLC communication the SINR level drops rapidly in case of high interference or blockage, therefore the fast drop below designated value is assumed to indicate one of these states.

- Full buffer traffic model is used [26]:
  In order to analyze the spectral efficiency of communication channels, communication scenario with a heavy load of radio channels is assumed.

Chapter 4

Proposed algorithm

The aim is to design VHO algorithm that decides which link should be used by the UE whenever an interruption of VLC link occurs. The VLC links are sensitive to interruptions, which appear at random times. In addition to the randomness, the interruptions also come in two types of durations. Short interruptions are caused by shadowing, or short signal blockage by an obstacle. Long interruptions are caused by a long-term signal blockage. Further, both types of interruption are caused by strong interference from other pairs communicating in the VLC band. At the moment when the interruption starts, it is rather challenging to distinguish which of these two interruption types is the device dealing with. However, a different approach to VHO should be applied for each type of interruption. If the interruption is very short, it is more efficient to set some dwell time and not perform handover to RF. Contrary, if the interruption is long it is more efficient for UE to perform handover to RF immediately. This decision can have a significant impact on QoS provided to users. Multiple parameters have to be considered to select a proper VHO approach. First of all, the delay caused by each decision, even if we choose to perform handover immediately there is still delay from network access procedure. The second parameter is the message size, for small messages fast handover to RF will provide a better result since even slower bit-rate will be able to handle the transfer. The third parameter which plays a significant role in the decision is the bit rate R itself. By considering the actual value of available bit-rate in both transmission modes, it is possible to decide more accurately how big influence will the difference in bit-rate have on the transfer of user's data.

4.1 High-Level Overview of the Proposed Algorithm

The baseline for the proposed algorithm is [7] which presents the solution for Vertical handover in hybrid VLC-Femto system. Delay of the decision, message queue length, and bit-rate are used to decide if the device should perform the handover to RF or stay at VLC. To make a decision about VHO, three following steps are performed by the algorithm proposed in [7]. First, with the analytic hierarchy process (AHP) the weights of each criterion are calculated. The weight table is created in advance and does not contribute in any significant way to algorithm computation complexity. Next, the algorithm utilizes a two-person cooperative game (CG). The solution of the game is calculated by the Shapley Value method. This method is used due to its small computational complexity [7] which is a very important factor for handover decision. This decision has to be made fast to be useful. Finally, the results of CG are combined with AHP by criterion created in [7] called rationality degree (RD). The decision with higher RD is performed. Similarly, if VLC link with SINR above-defined value is available, the decision is made with adjusted parameters to evaluate the benefit of switching from RF to VLC. In the following section the AHP, CG, and RD are explained in more detail. The Fig. 4.1 shows the diagram with modifications highlighted in blue and new sections in green, in regards to [7]. In order to differentiate the proposed algorithm from the existing solutions, United Vertical Handover (UVHO) is used in the further chapters.

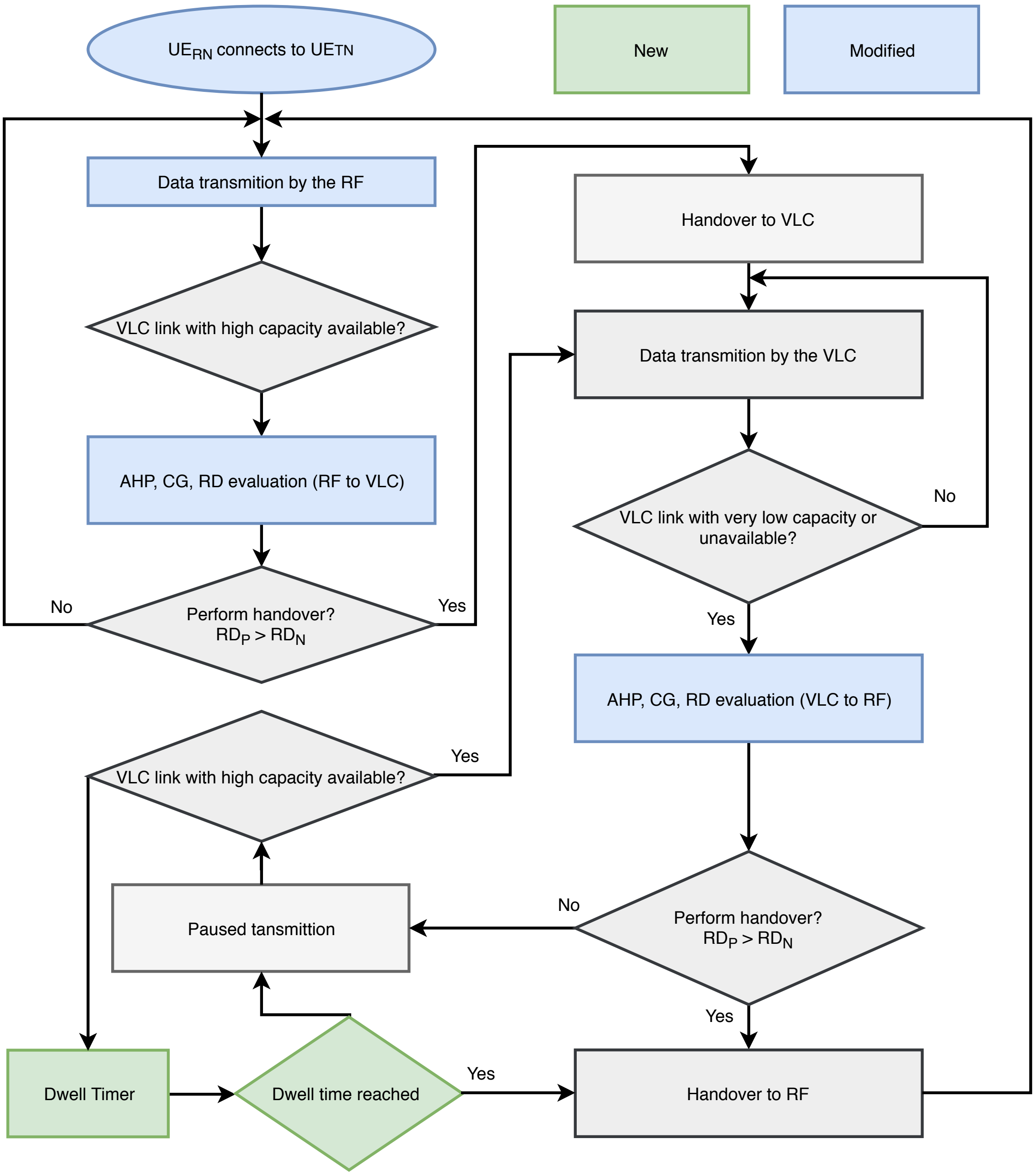


Figure 4.1: Proposed Algorithm Flow Chart

In [7] the algorithm does not consider the possibility of long interruption. In case the algorithm from [7] decides to not perform VHO, communication is interrupted until the VLC link is available again. This solution is possible only in scenarios without long interruptions. Since the long interruptions are possible in our system model, the algorithm must be modified accordingly. To handle long interruptions, we add the dwell timer. The value of dwell time is calculated every time interruption occurs. In order to set the dwell timer reasonably following equation is used:

$$D_{Timer} = D_{Access} + \alpha \times log(1 + \frac{R_{VLC}}{R_{RF}}) \tag{4.1}$$

where D_{Access} represents the average RF access time, R_{RF} and R_{VLC} represent the bit-rates available in RF and VLC mode. The value of α varies in dependence to number of D2D pairs. With a higher number of pairs, the value of R_{RF} decreases due to higher interference from other pairs in RF mode. Therefore, longer dwell times are desired. With the higher value of α the dwell time can be further increased. The value of the dwell timer will be low for R_{RF} similar to R_{VLC} and will get higher with decreasing R_{RF}.

4.2 Analytic Hierarchy Process

The Analytic Hierarchy Process is "general theory of measurement" [27], which helps with decision making in situations where multiple criteria have to be considered at the same time and it is not possible to compare two parameters directly. The weakness of AHP is the ability to compare the criteria values since the outcome of AHP is only the weight of each criterion. The tables with criterion importance comparisons need to be created in relation to a specific use case. To create the comparison matrix $A = [a_{ij}]_{3x3}$, the numerical scales from [27] are used. The a_{ij} represents the relative importance between criterion i and j. Where $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$. In order to calculate the largest eigenvalue λ_{max} and normalized eigenvector W of the matrix A the "root method" can be used as presented in the following equations:

$$\overline{w_i} = \sqrt[3]{\prod_{j=1}^{3} a_{ij}}, i = 1, 2, 3 \tag{4.2}$$

$$w_j = \frac{\overline{w_j}}{\sum\limits_{i=1}^{3} \overline{w_i}}, j = 1, 2, 3 \tag{4.3}$$

$$W = [w_1, w_2, w_3]^T \tag{4.4}$$

$$\lambda_{max} = \sum_{i=1}^{3} \sum_{j=1}^{3} \frac{a_{ij} w_j}{3 w_i} \tag{4.5}$$

Due to the subjective nature of AHP, it is necessary to check the consistency of matrix A. In order to calculate the consistency ratio (CR), we need to calculate the consistency index (CI) and divide it by the random consistency index (RI) [28]. The CI can be calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.6}$$

where n is the order of A which in this case is equal to 3. According to [28] the RI is 0.58 for $n = 3$. Since the perfect consistency occurs only rarely, the maximum acceptable value of CR is 0.1 [28] and the pair-wise comparison must be repeated in case this condition is not met.

In this work values from Tab. 4.1 are used to compare the individual criteria. The comparison of each criterion with all others is based on numerical scales listed in [27]. The consistency of the presented matrix does meet the condition from [28] as the value of CR is 0.03.

Criterion	Delay	Queue length	Bit rate
Delay	1	1/3	1/5
Queue length	3	1	1
Bit rate	5	1	1

Table 4.1: Criteria Importance Comparison [7]

4.3 Cooperative Game

The cooperative game is used to compensate the AHP weakness of considering criterion values and through cooperation, the contribution of each criterion on final decision is considered.

As input for CG, we use a set of data created by calculating the three criterion values for both performing and not performing the handover. This way $[b_{ij}]_{2x3}$ matrix is created. Consisting of i_{th} decision and j_{th} criterion.

$$B = \begin{bmatrix} D_P & L_P & R_P \\ D_N & L_N & R_N \end{bmatrix} \tag{4.7}$$

here D_P, L_P and R_P represent the "Delay" "Queue length" and "Bit rate" of the decision to perform the VHO. Similarly, D_N, L_N and R_N represent the same values for the decision to not perform the VHO. The R_P is set as R_N^{RF} and R_N is set as R_N^{VLC}. Further, L_P and L_N are set according to buffer size. Finally, D_N is equal to D_{Timer} and D_P is set as D_{Access}. The matrix B is further adjusted into matrix C to ensure that higher value is always better and normalized as presented in matrix D, to make each criterion range from zero to one.

$$C = \begin{bmatrix} 1/D_P & 1/L_P & R_P \\ 1/D_N & 1/L_N & R_N \end{bmatrix} \tag{4.8}$$

$$D = \begin{bmatrix} c_{11}/(c_{11}+c_{21}) & c_{12}/(c_{12}+c_{22}) & c_{13}/(c_{13}+c_{23}) \\ c_{21}/(c_{11}+c_{21}) & c_{22}/(c_{12}+c_{22}) & c_{23}/(c_{13}+c_{23}) \end{bmatrix} \tag{4.9}$$

The "perform" and "not perform" values create the cooperation set, which can either be in coalition S on its own or join the other set. This means there are three possible coalitions for each criterion. For every coalition and all criteria, the characteristic function v is needed. In case of the two-person model v is calculated as follows [29]:

$$v_j(S) = max(d_{1j}, d_{2j}) - \sum_{i=1, X_i \notin S}^{2} d_{ij}, j = 1, 2, 3 \tag{4.10}$$

Finally the Shapley value, representing the capability $\phi_{i,j}$ of decision i in criterion j is calculated. The Shapley Value represents "average marginal contribution to a coalition if the cooperators join in by a completely random order" [7]. This solution is used for its low computational complexity and relative fairness [30].

$$\phi_{i,j} = \sum_{S \subseteq X, X_i \in S} \frac{(m - |S|)!(|S| - 1)!}{m!}(v_j(S) - v_j(S - \{X_i\})) \tag{4.11}$$

here m represents the total cooperator number, in this case, $m = 2$, and $|S|$ stands for the cooperator's number in the coalition.

4.4 Rationality Degree

Finally, the $\phi_{i,j}$ is combined with w_i in following way:

$$RD_i = \sum_{j=1}^{3} w_j \phi_{i,j}, i = 1, 2 \tag{4.12}$$

the decision i with the higher value of RD is performed.

Chapter 5

Simulations

To compare the proposed algorithm with already existing solutions, this chapter outlines the simulation scenarios and parameters used to simulate the above-described system model. The simulation is performed in MATLAB. All algorithms are executed with the exact same set of location, UE orientation, and random channel blockages.

5.1 Simulation Scenario

Generally speaking, the use case of VLC technology is currently considered mainly for indoor environments. Therefore, the indoor scenario with a room of size d x d m is assumed. In the room, N pairs of UEs are placed in a random location. Random waypoint model is used to simulate the movement of UEs. The irradiance and incidence angle of each UE is generated by Gaussian selection. The mean is set to 0° and the standard deviation σ is set to 30°. This is used to simulate the situation when users point devices at each other, but it is not always possible to achieve a perfectly direct link between UEs. At the start of the simulation, all devices transmit data in RF mode and perform handover to VLC whenever it is available. In case of severe SINR decrease, VHO algorithm is triggered. As already mentioned all algorithms work with the same set of position and orientation values in the simulation. However, due to the different decision process, the usage of transmission technology varies. The RF channel is simulated in accordance with the 3GPP model for indoor D2D communication [31]. The VLC channel simulation follows the modeling described in [15]. The random waypoint model is simulated with parameters presented in Table 5.1. The detailed summary of parameters used to simulated both mentioned channels is presented in Table 5.2.

Random Waypoint model parameters	
Speed interval	0.9-1.1 [m/s]
Pause interval	4-10 [s]
Walk interval	1-100 [s]
Direction interval	-180-180 [°]

Table 5.1: Parameters Used for Random Waypoint Model

RF Parameters		
Parameters		Value
Carrier frequency	f_c	2 [MHz]
Bandwidth	B^{RF}	20 [MHz]
Transmission power of UE	P_t^{RF}	200 [mW]
VLC Parameters		
Parameters		Value
Bandwidth	B^{VLC}	10 [MHz]
Transmission power of UE	P_t^{VLC}	200 [mW]
Physical area of photodetector	A	1 $[cm]^2$
Background current	I_{bg}	10 [nA]
Noise Bandwidth factors	$I_2 - I_3$	0.562 - 0.0868
Fixed capacitance of the photodetector	η	112×10^{-8} [F/m]
FET channel noise factor	Γ	1.5
FET transconductance	g_m	0.03 [s]
Responsivity of the photo diode	γ	0.53 [A]
Open-loop voltage gain	G	10
Optical concentrator gain	$g(\psi)$	3
Optical filter gain	T_s	1
Absolute temperature	T_k	295 [k]
General Parameters		
Parameters		Value
Irradiance angle	ϕ	$-30 - 30[°]$
Incidence angle	ψ	$-30 - 30[°]$
Room dimension	d	10 [m]

Table 5.2: Simulation Parameters

The values from Table 5.1 are selected by continuous uniform random numbers function. Each UE is assigned with a value of speed, pause, walk time and direction from the interval in Table 2. Where speed defines how fast UEs move in the room, the pause defines the duration of movement interruption, the walk time corresponds to the duration of movement and direction defines the angle of movement of each UE. This process is repeated until the simulation time is reached. The simulation time is set to 400 seconds, with one step of simulation set to 0.01 second. The simulation is repeated in 20 drops to generate statistically significant results.

In order to compare the performance of a different number of UE pairs, Simulation is run for a range of 2-10 pairs. The interruption is triggered either by a drop of SINR due to interference from other pairs or by blockage of the LoS. The limit of minimal SINR is set as -10 dB. This value is based on simulation results which show that receivers with high interference have SINR below -10 dB and bitrates are very close to 0 in this situation. The duration of LoS blockages is tested in a range of 0.2 to 2 seconds. The occurrence of interruption is generated by Poisson process with mean 0.2 per second [7]. Finally, all simulations are performed with full queue traffic model [26] which ensures that all devices always have data to send or receive, to test the performance of a fully utilized communication channel's. Since all devices always have new data to send this buffer is always full.

For each interruption occurrence, the decision based on the selected algorithm is provided and in accordance with the result of this decision devices either wait or start to access the RF channel. In both cases, the channel between the transmitter and receiver is temporarily blocked and interruption duration is recorded. In case of a decision to perform the VHO immediately the interruption is always equal to RF access delay, which is for the simulation set to values in the range of 0.2-0.6 seconds. In case the decision of algorithm is to wait for dwell timer to expire, interruption varies in dependence on interruption length with maximum value of dwell time plus RF access delay.

To calculate the dwell timer the average RF access delay, the bit-rates in both communication modes and the parameter α are used. The value of α has been experimentally tested and the best performing results are used for the final result. It can be approximated as $\alpha = -0,0085 \times x^3 + 0,2326x^2 - 1,0241 \times x + 1,4778$, where x stands for number of

D2D pairs. The comparison of used values with the proposed approximation function is presented in Fig. 5.1.

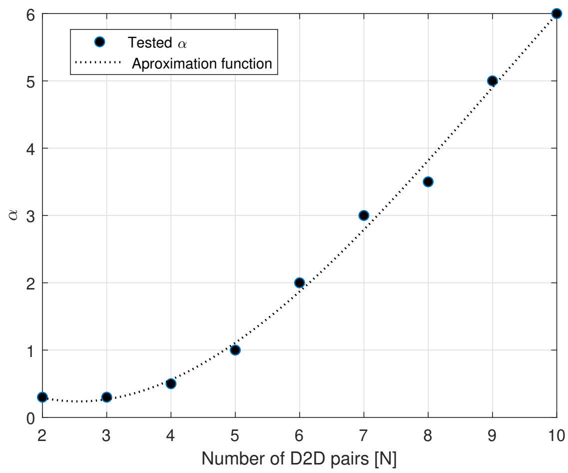


Figure 5.1: Approximation function of α

5.2 Simulation Results

In this subsection the average bit-rate, interruption and VHO count is evaluated under different network conditions. To demonstrate the efficiency of proposed algorithm, results are compared with two basic VHO schemes (DVHO & IVHO [8]) and VHOs inspired by [6] and [7], for description of these solutions see section 2.4.

Fig. 5.2 illustrates the average bit-rate of communication in RF and VLC mode without VHO. The sum of RF and VLC is further used as reference to illustrate the efficiency of performing VHO. We can see that with increasing number of D2D pairs the average bit-rate decreases significantly. This decrease is caused by a high level of interference. The goal of VHO approaches is to distribute D2D pairs between the two available modes to mitigate the interference caused by the higher number of pairs in the same mode. Further, we can see that for small number of D2D pairs, VLC mode bit-rates are more than double compared to RF. This advantage of VLC is however lost for high number of D2D pairs. This is caused by the fact that if UE in VLC mode is interfered its bit-rate is very close or equal to 0. On contrary in RF mode all D2D pairs are able to communicate. In other words, the interference in RF mode is influencing bit-rate less then in VLC mode. Therefore, for a higher number of D2D pairs, the average bit-rate is similar for scenarios where RF or VLC mode are used exclusively.

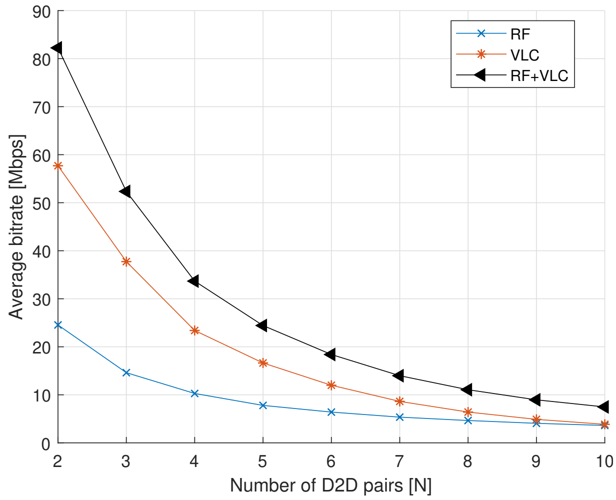


Figure 5.2: Comparison of average bit-rate for RF, VLC and RF+VLC modes

Fig. 5.3 shows the average bit-rate of all tested approaches in relation to number of D2D pairs. The purpose of this comparison is to show the overall trend of decreasing bit-rate with the higher number of D2D pairs. Also, the behavior of the algorithms for two different interruption durations is evaluated. Fig. 5.3a and 5.3b compare the average bit-rates for short and long interruption duration, respectively. With an increasing number of D2D pairs, the average bit-rate decreases for all tested algorithms. In the case of short interruption (0.2 s), the proposed algorithm does perform overall best. The IVHO and PVHO are closest for 2 and 3 D2D pairs. However, for the higher number of D2D pairs, DVHO and MVHO perform better. It is evident that all VHO solutions perform significantly better than approach without VHO, except for 2 D2D pairs. For 2 second interruption duration, we can see that UVHO is the best solution for 4 to 10 D2D pairs. In case of long interruption and a low number of D2D pairs, performing handover without any delay increases average bit-rate compared to solutions with dwell timer. This increase is higher compared to solutions with a dwell timer because the interference in RF mode is low. Therefore, the bit-rate available in RF mode is contributing to average bit-rate more than in cases with a higher number of D2D pairs and interference. The best performing for 2 and 3 pairs are IVHO and PVHO. Moreover, for 2 pairs it is overall the best to utilize both communication modes at the same time without performing VHO. The factors influencing the performance of all algorithms are further discussed in the following sections.

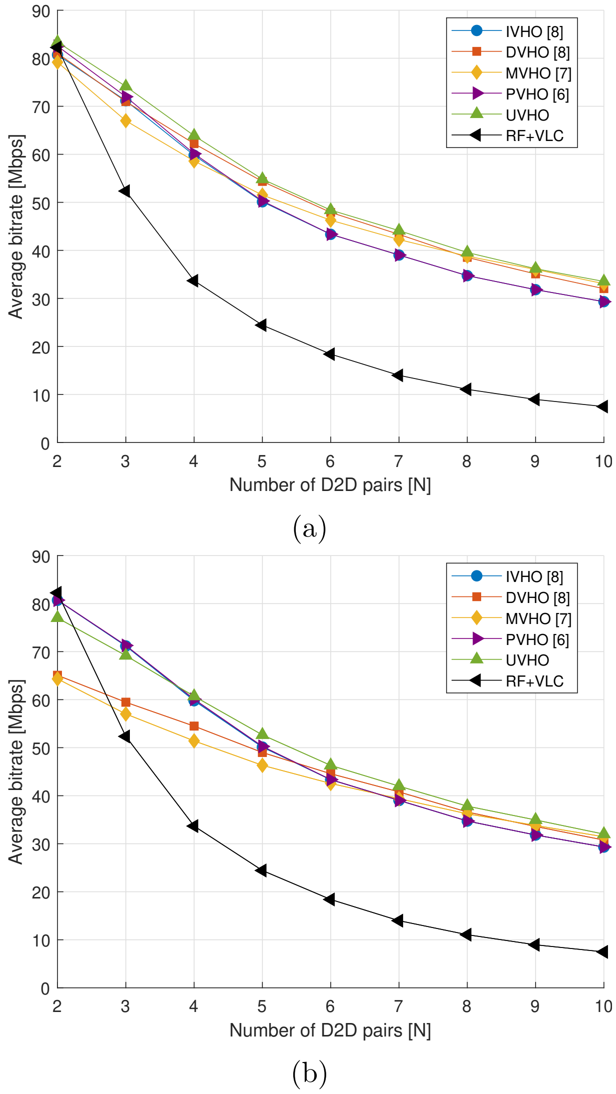
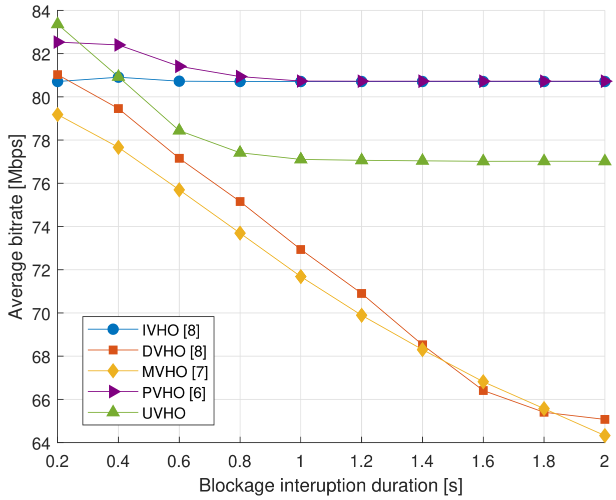


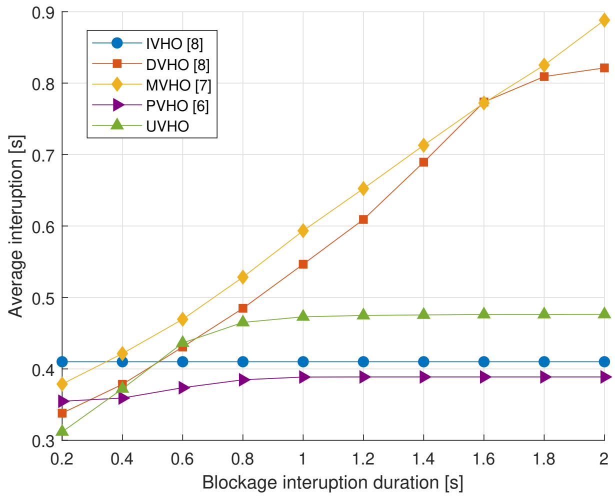
Figure 5.3: Average bit-rate for interruption duration (a) 0.2 seconds (b) 2 seconds

The results are further divided into three groups with similar trends of evaluated metrics. First group is 2 and 3 D2D pairs. In this group the best performance is achieved by IVHO and PVHO as it is more effective to switch to RF mode as soon as possible. Next is the group of 4 to 8 pairs where the best performing solution is UVHO followed by DVHO. The last group is 9 and 10 D2D pairs, UVHO still performs better. However, the second best solution is MVHO and the specific of this group is that it is more effective to stay in VLC for a longer time. The proposed algorithm is able to improve the capacity of communication up to 4.5 times compared to the approach which utilizes both communication modes at the same time. Solutions with VHO can be further divided into two group which perform similarly. IVHO and PVHO do perform better for a lower number of D2D pairs and their performance decreases with increasing number of D2D pairs. This is caused by higher levels of interference in RF mode which leads to the lower benefit of performing VHO quickly. The proposed UVHO increases the average bit-rate in scenarios with a higher number of D2D pairs up to 10% compared to IVHO and PVHO. DVHO and MVHO do perform better for a higher number of D2D pairs and their performance decreases with decreasing number of D2D pairs. As the interference gets higher for the increased number of D2D pairs it is more effective from the perspective of average bit-rate to stay in the interrupted state of VLC channel for a longer time. It is no longer beneficial to switch from VLC every time an interruption occurs. The proposed UVHO algorithm is able to increase the average bit-rate up to 20% compared to DVHO and MVHO

The Fig 5.4 shows the average bit-rate and interruption for case of two D2D pairs. These results have similar trends as the case with three D2D pairs and therefore only the case of two pairs is shown. In Fig 5.4a we can see best performance is achieved by PVHO followed by IVHO. However as shown further the number of VHO is much higher (double for the case of IVHO) than in the case of UVHO. The good performance of PVHO and IVHO is caused by the situation where both VLC and RF mode operates without the high level of interference. Therefore, it is the best option to switch from VLC as soon as possible. In Fig. 5.4b it is shown that the duration of the interruption is on average lowest for PVHO. The performance of UVHO is close to PVHO and IVHO as it tends to stay in VLC with short dwell timer. This approach is beneficial for very short interruptions however for longer interruptions it leads to the slight decrease in average bit-rate. The difference between VLC and RF is not significant enough to justify the periods of keeping the UE in VLC even when the communication is interfered. Compared to DVHO and MVHO the average bit-rate of UVHO is significantly higher, especially for longer durations of interruption.



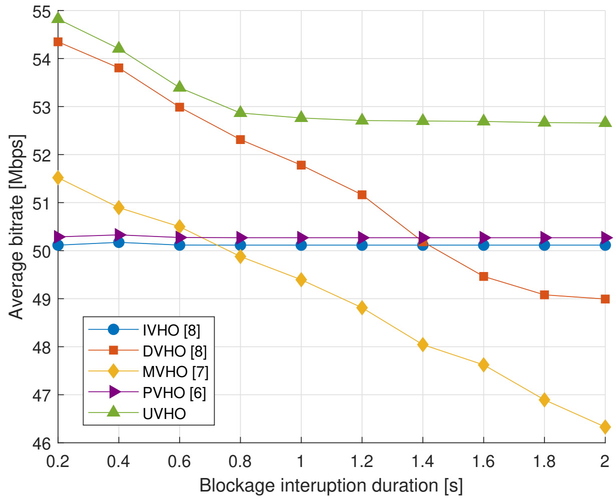
(a)



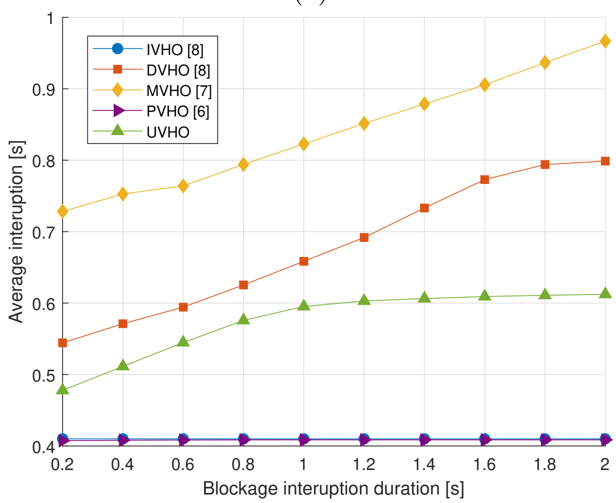
(b)

Figure 5.4: Impact of blockage interruption duration on (a) average bit-rate and (b) average interruption for 2 pairs

Fig. 5.5 plots the average bit-rate and interruption for scenario with five D2D pairs. This serves as an example for the group of four to eight D2D pairs which do have similar trends. We can see in Fig. 5.5a that UVHO average bit-rate is highest for all tested interruption durations. The closest to UVHO is DVHO which is able to perform similarly for short interruption duration. However, DVHO performance decreases drastically with increased interruption duration. We can see that for the last four tested blockage durations the DVHO perform either similar or worse than PVHO and IVHO. This is caused by DVHO reaching its timer limit and performing VHO which further increases its time in the blocked state. In Fig 5.5b the average interruption is shown. The average interruption of IVHO is lowest and corresponds with the values of average RF access delay. This however again leads to the high number of VHO performed by the IVHO algorithm. In the scenario with a higher number of D2D pairs it is no longer beneficial in terms of average bit-rate to reduce average interruption to the minimum. We can also see that DVHO has higher average interruption than UVHO yet its average bit-rate is lower. From this, we can conclude the efficiency of UVHO in the matter of setting the value of the dwell timer.



(a)

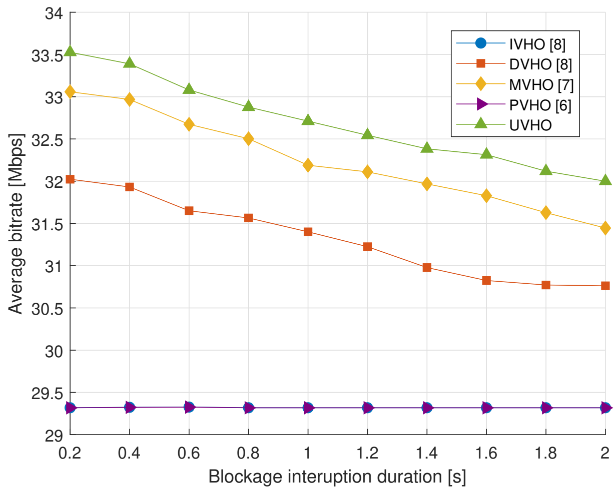


(b)

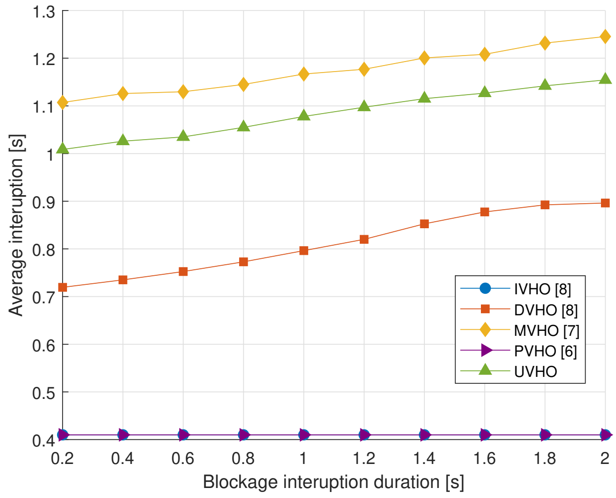
Figure 5.5: Impact of blockage interruption duration on (a) average bit-rate and (b) average interruption for 5 pairs

Fig. 5.6 shows the example from the last group of results, the scenario with 10 D2D pairs is used in the figures. As the number of D2D pairs increases the decision to stay in

VLC for longer interval become more efficient. In our simulation, the MVHO performs better with regard to average bit-rate for nine and ten pairs. In Fig. 5.6a we can see that MVHO and DVHO changed the position compared to the scenario with four to eight pairs, while UVHO with dynamically set dwell still performs better than all other VHO approaches. The average bit-rate is higher for UVHO while it is able to reduce the average interruption compared to MVHO, see Fig 5.6b. From these results, we can conclude that in order to achieve the high level of average bit-rate for the high number of D2D pairs in the system, the best strategy is to set long dwell timer. The overall capacity of the system can be improved by allowing the UE to stay in VLC mode for longer. However, if the dwell timer is without any limit the performance is not optimal as UE which perform VHO to VLC will suffer long interruptions of communication.



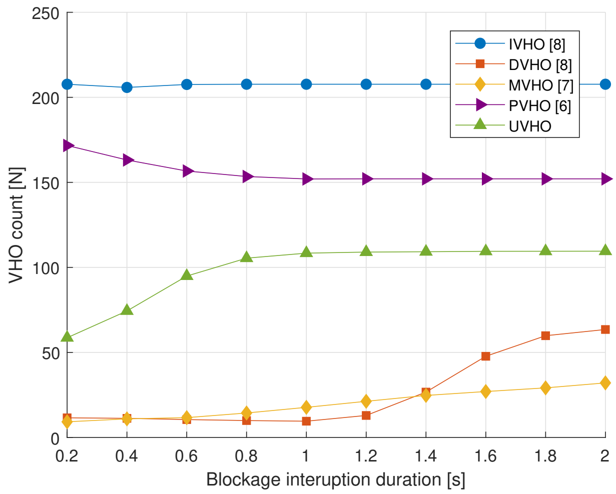
(a)



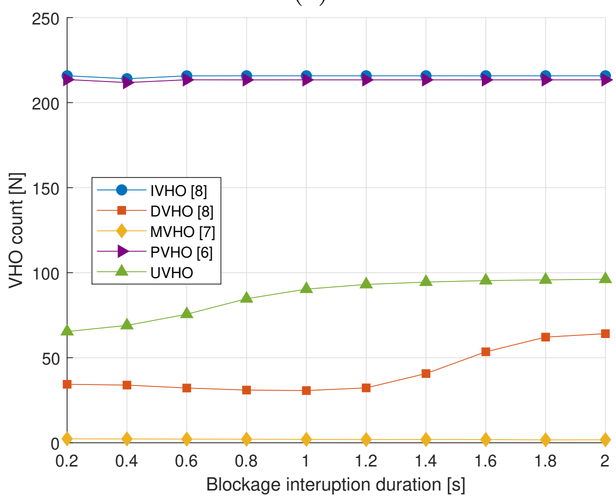
(b)

Figure 5.6: Impact of blockage interruption duration on (a) average bit-rate and (b) average interruption for 10 pairs

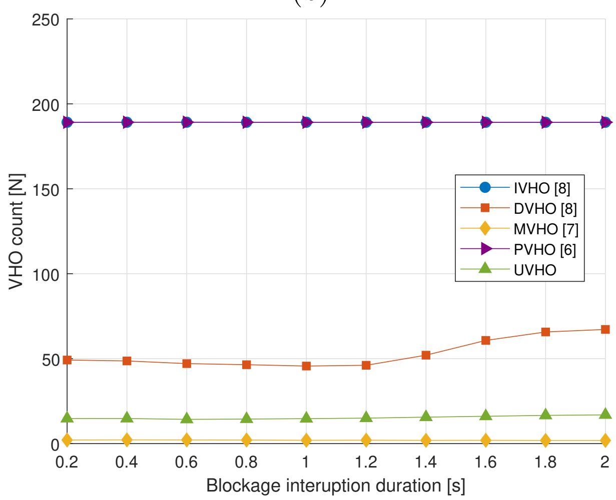
Fig. 5.7 shows the number of performed VHOs for three scenarios which correspond to previously presented groups. In 5.7a The lowest number of VHO is performed by MVHO. However, as shown in Fig. 5.4a the average bit-rate of this approach is the worst of all studied alternatives. As previously described for the small number of D2D pairs in the system the best performing solution are those that perform VHO fast. While the average bit-rate of IVHO and PVHO is best for this scenario the increase of VHO count is also significant. This indicates that the approaches which tend to switch very fast are not suitable for use cases that are sensitive to frequent switching of communication mode. In Fig. 5.7b we can see that the gap between DVHO and UVHO is smaller compared to 5.7a. The count of VHO of UVHO increases until 1.2 second long interruptions, indicating that any longer interruptions do not affect the performance of this approach, as the dwell timer will always expire. For the scenario with ten D2D pairs, we can see that the VHO count is constant. This means that the VHO is performed only in cases of interruptions longer than two seconds. see Fig. 5.7c. In all presented scenarios it is possible to see the see the effect of dwell timer set to 1.5 seconds in case of DVHO. Once the blockage interruption duration reaches the value of dwell timer the count of VHO starts to increase.



(a)



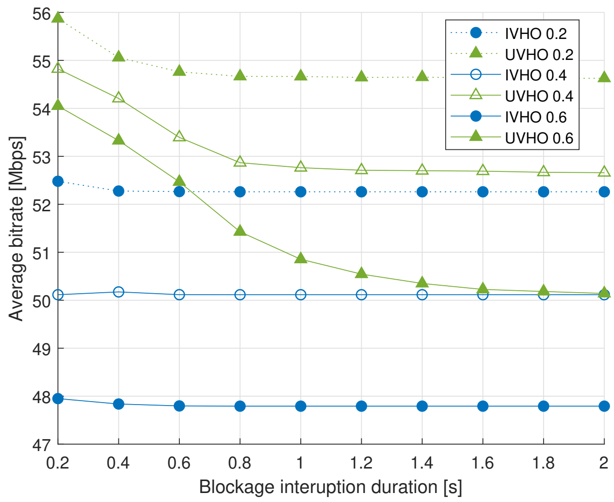
(b)



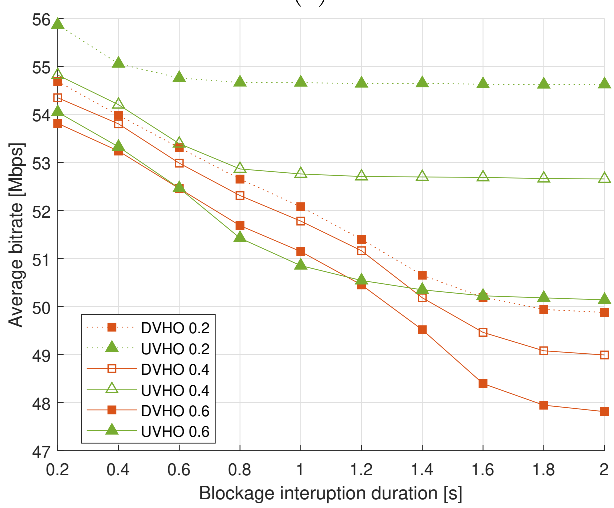
(c)

Figure 5.7: Impact of blockage interruption duration on VHO count. (a) 2 pairs (b) 5 pairs (c) 10 pairs

Fig. 5.8 illustrates the influence of RF access value on average bit-rate. For clarity, the performance of UVHO is compared to IVHO in Fig. 5.8a and to DVHO in Fig. 5.8b. The PVHO and MVHO are not shown as they perform comparably or worse. The number of pairs is set to five in this comparison. It can be observed in both figures that with RF access set to 0.2 seconds the average bit-rate is higher than for RF access set to 0.6 seconds. This confirms that a higher value of RF access delay negatively affects the performance of the system. Even if UE decides to switch from VLC to RF, it is not able to communicate for a longer period of time in case of longer RF access, hence the reduction in average bit-rate. Fig. 5.8a shows that proposed UVHO always performs better than IVHO if the same value of RF access is considered. In the case of DVHO, we can see in Fig. 5.8b that while for short RF access the performance of UVHO is overall superior. In case of longer RF access, the DVHO performs similarly with UVHO for short blockage durations. However, in case the blockage interruption increases over the values of fixed dwell time, the UVHO performs better.



(a)



(b)

Figure 5.8: Impact of RF access delay and blockage interruption duration on average bit-rate. (a) UVHO vs IVHO [8] (b) UVHO vs DVHO [8]

To summarize, the proposed UVHO performs best in scenarios with four and more D2D pairs. While the IVHO and PVHO perform better in scenarios with the lower number of D2D pairs, it is weighted by the cost of the increase in VHO count. Further, the IVHO and PVHO do have shortest average interruption durations. However, for more than 3 D2D pairs this shorter interruption leads to a significant decrease of average bit-rate. UVHO manages to maximize the performance metric of average bit-rate while maintaining lower average interruption duration than MVHO and DHVO.

Chapter 6

Conclusion and Future Work

In this work, the concept of RF-VLC D2D communication is explored. The solution for the decision on selection of communication mode between VLC and RF is proposed. The dwell timer is calculated in relation to the number of D2D pairs in the system. The AHP, CG, and RD are used to make a decision about VHO. By means of simulations, the performance and efficiency of the proposed method of handover are assessed, in an indoor scenario with mobile UEs. The proposed UVHO is demonstrated to be more efficient in the majority of tested scenarios. With significant improvement over the solution of using VLC and RF simultaneously by all pairs. The high level of channel quality variation in the case of VLC is concluded to be a significant challenge.

Due to this unpredictability of VLC channel, many other challenges have to be addressed in future research. The choice of centralized or distributed control of VHO, scheduling, and signalization is not the main focus of this work. However, for the fruition of the VLC-RF D2D system, all of these challenges must be addressed. The option to perform handover from D2D to cellular communication and evaluate which type of D2D link should be utilized could also be studied, in order to minimize the outage of communication. Moreover, it is necessary to focus on different traffic type scenarios to evaluate the capability of the algorithms in the future works. With persistent progress in research of artificial intelligence, the application of machine learning algorithms should be further researched as well.

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