Terminal Cooperation in Next Generation Wireless Networks: Aerial and Regional Access Networks

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Sathyanarayanan Chandrasekharan
November 2017
A humble contribution for a better future...

and...

To my beloved father, mother & sister.....
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Abstract

Throughout the years, progress of humankind has depended on the power of communication and over the decades, the ways of communication has witnessed mammoth changes. Specifically wireless communication in the last decade has completely revolutionized the way we communicate with each other. Smartphones have become an ubiquitous part of our life. With most operators throughout the world deploying fourth generation wireless communication systems, peculiar use cases and scenarios are being envisioned such as public safety networks, aerial networks, etc. to be addressed by the next generation wireless systems. Moreover, as urban areas are becoming saturated commercial network operators are looking for business cases to move towards the untapped regional areas. However, to deploy networks in regional areas economically, novel technologies and architectures need to be developed and investigated.

In this thesis, we study the novel concept of terminal cooperation in the context of next generation wireless communication systems especially looking into aerial and regional access networks. In the first part of the thesis, we investigate the physical radio channel for device-to-device (D2D) communication which would help in enabling terminal cooperation in wireless networks. Specifically, we propose propagation model for D2D in rural areas using 922 MHz and 2466 MHz, a channel model for vehicular communications using 5.8 GHz and a propagation model for D2D using millimetre wave frequencies. In the second part of the thesis, we evaluate the coverage performance of aerial access networks using different technologies and develop algorithms to enhance the coverage using terminal cooperation in regional access networks. Specifically, we evaluate the performance of two different technologies, LTE and WiFi, in aerial access networks. We propose game-theoretic algorithms to enable terminal cooperation to enhance coverage in regional access networks and perform system level simulation to evaluate the proposed algorithms. In the last part of this thesis, we analyse and develop techniques to enhance energy efficiency in aerial access networks using terminal cooperation. Specifically, we propose a clustering algorithm called EECAN which improves the energy efficiency of the terrestrial nodes accessing the aerial base-station, a clustering algorithm based on Matern Hardcore Point Process which allows
us to optimize cluster head spacing analytically and we further enhance this algorithm by including impairments introduced by the wireless channel.

Throughout this thesis, we verify and validate our analytic results, algorithms and techniques with Monte-Carlo simulations of the considered scenarios. Most of the work presented in this thesis was published in-part or as a whole in conferences, journals, book-chapters, project reports or otherwise undergoing a review process. These publications and reports are highlighted in the course of the thesis. Lastly, we invite the reader to enjoy exploring this thesis and we hope that it will add more understanding to this promising new technology of terminal cooperation in aerial and regional access networks.
Chapter 1

Introduction

In the last couple of decades, wireless communication technologies have exhibited mammoth advancements and have greatly influenced our lives. On one hand, cellular mobile technology and its industry including the network operators and equipment manufacturers have grown exponentially in the past decade. On the other hand, short range communication technologies such as WiFi, Zigbee, Bluetooth, etc. have been pervasive into our everyday lives. With the Internet-of-Things (IoT) revolution on the brink, low power wide area network technologies such as LoRaWAN and Narrowband IoT (NBIoT) are gaining increased interest from researchers and industry.

With regards to cellular mobile technology, as the fourth-generation long-term evolution (LTE) is being deployed by network operators worldwide, some peculiar use-cases and future research paradigms are being identified. It is expected that the next-generation mobile communication technology will address some of these unique use-cases such as public-safety networks, regional area networks, etc. in addition to providing a quantum leap in terms of coverage, capacity and energy efficiency compared to the current generation [2]. Many novel technologies are being investigated in the context of next-generation wireless communications [3] such as massive multiple-input-multiple-output (MIMO), dynamic spectrum access, millimetre-wave communications, mobile femtocells, etc. Massive MIMO is an innovative technology in which multiple antennas, typically tens, at both the transmitter and receiver is used in communications to achieve high spectral efficiency and energy efficiency [4–6]. The antennas at the transmitter and the receiver may be co-located or distributed in space. Dynamic spectrum access using cognitive radio technology is a technique that aims to use under-utilized spectrum called spectrum holes autonomously by learning the radio environment in which the terminals operate and with no coordination with the primary incumbent user of the spectrum [7, 8]. As the spectrum under 6 GHz band
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is getting congested, millimetre wave spectrum is being investigated for various use cases exploiting the fact that the millimetre wave spectrum is vastly vacant due to technical challenges [9, 10]. Mobile femtocell is a new technology that combines the mobile relay concept with femtocells which is promising to increase spectral efficiency and reducing signalling overhead during handovers [11].

Among the different technologies mentioned above, one technology that stands out is terminal cooperation. The idea of cooperative communications have been investigated previously in literature mainly with regards to theoretically maximizing or minimizing for attaining a specific objective [12]. In this thesis, we investigate the concept of terminal cooperation and the way it addresses challenges posed by novel wireless architectures such as aerial and regional access networks. This chapter introduces the concept of terminal cooperation in the context of aerial and regional access networks. It defines the research questions and contributions made in this thesis alongwith a publication list. The rest of the chapter is structured as follows: Section 1.1 details the concept of terminal cooperation and describes briefly its benefits. Section 1.2 introduces aerial access networks and its challenges while section 1.3 explains regional access networks and its challenges. In section 1.4 we outline the research questions defined and the contributions made as part of this thesis and in section 1.5 we present the list of publications. In section 1.6 we present the structure of the rest of this thesis.

1.1 Terminal Cooperation

The idea of cooperation is very appealing and the gains of cooperation are well known in the field of sociology. Terminal cooperation borrows this idea in which terminals cooperate with each other to achieve specific gains [13, 14]. The concept of cooperative communications traces back to Cover and El Gamal where they investigated the information theoretic characteristics of the relay channel [15]. Cooperative communications is mainly explored to mitigate the channel impairments such as fading and receiver noise by using the phenomenon of spatial diversity. It exploited the broadcast nature of the wireless channel where the relay node overhears the message being transmitted by the source to the destination and then forwards it to the destination realizing diversity gains [16]. Figure 1.1 (a) shows cooperative communication where the source node sends a message to the destination which is overheard by the relay node due to the broadcast nature of the wireless channel. The relay node then relays the message across to the destination. Many different relaying schemes such as decode-and-forward, amplify-and-forward, coded-cooperation, etc. and
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Fig. 1.1 (a) Cooperative Communication; (b) Device-to-device (D2D) Communication; (c) Coverage extension using terminal cooperation; and (d) Capacity or energy-efficiency improvement with terminal cooperation.

their corresponding performances were investigated [13, 17].

On the other hand, D2D communication has been gaining increased interest by the 3GPP standards community [14]. D2D allows direct communication between two mobile terminals without accessing the base-station and promises to enhance reliability, throughput and energy efficiency for proximity-based communications [18–21]. Figure 1.1 (b) shows D2D communication among two mobile terminals.

Unlike cooperative communications in which the destination is accessible by the source node and device-to-device communications where the two devices do not need to access the base-station, terminal cooperation allows the source node to access the base-station through the relay node. In other words, instead of terminals communicating with the base station directly as it would in a traditional cellular network, terminal cooperation enables terminals to communicate with each other to reach the base-station. This could lead to multiple benefits [22]:

- **Coverage Extension:** Terminal cooperation allows us to extend coverage of the base-station. Figure 1.1 (c) shows the scenario where the relay node which is under the coverage area served by the base-station cooperates with the source node which is out
of coverage area to access the base-station.

- **Capacity Improvement:** The cell-edge terminals usually suffer from signal attenuation and interference from co-channel cells. Terminal cooperation allows to improve the capacity of the terminals in shadowed regions.

- **Energy-efficiency Improvement:** Terminal cooperation allows the terminals with high residual battery charge to help out the terminals with low residual battery charge and extend their life time. Figure 1.1 (d) shows capacity or energy-efficiency improvement using terminal cooperation where source could be energy or rate deprived and relay node by means of cooperation enhances energy efficiency or capacity.

However, multiple challenges need to be addressed before we can implement terminal cooperation in wireless networks to reap the benefits of it. The numerous challenges are [23–27]:

- **Channel modeling for D2D communications**
- **MAC-level techniques and protocols to enable terminal cooperation**
- **Coverage and energy efficiency estimation in networks enabled with terminal cooperation**
- **Efficient Resource Allocation**
  - Interference management among cooperating terminals
  - Mobility management
  - Backward compatibility

In this research, we focus on the first four challenges mentioned above and summarize the gaps in literature. We believe addressing these challenges would allow us to bring a step closer in reality to implement terminal cooperation in wireless networks.

### 1.2 Aerial Access Networks

Recent advances in microelectronics have allowed to reduce the size and weight of the wireless communication equipment. This has significantly boosted the prospects of implementing aerial access networks in which an aerial platform, constrained by its payload
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Both, researchers and industry, have envisioned compelling use cases for such aerial access networks in several projects and initiatives. EU-funded FP7 ABSOLUTE [28] project investigated and demonstrated rapidly deployable aerial communication network to provision wireless coverage to emergency personnel in the aftermath of a large-scale disaster and for temporary large events such as sporting events. The Public Safety and Homeland Security Bureau of USA has studied and recognized the benefit of the role of deployable aerial communications architecture [29]. Industry giants such as Google and Facebook have initiated investigation in aerial communication networks to provide Internet access in emerging countries. Google Loon is an ambitious project intended to provide affordable network coverage in remote and rural areas using a fleet of high-altitude balloons operating at an altitude of about 20 km in the low stratosphere. Facebook endeavors to provide economical Internet access to people from the sky using high-altitude drones [30]. It is expected that 5G will enhance the usability of aerial platforms and are being considered for Beyond 5G networks.

Various types of aerial platforms exist such as drones, aircrafts, airships and platforms tethered to the ground [31]. Each of them possess their own advantages and disadvantages along with payload constraints. Several open issues have been investigated recently in lit-
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The authors in [32, 34, 45] have proposed novel channel models for air-to-ground communication and [39] comprehensively surveys air-to-ground channel models found in literature. Figure 1.2 (a) shows one such elevation angle based channel model. In [28, 35, 36] the authors propose aerial communication networks as an alternative for emergency or public-safety networks. In [37], the authors present a technique to efficiently place the aerial platform in next generation cellular networks in order to maximize the revenue generated. In [33], the authors have presented a technique to optimize the altitude of a low-altitude platform to maximize coverage area. Figure 1.2 (b) depicts the relationship between the altitude of an aerial platform and its coverage area. In [43, 44] the authors present relaying and clustering techniques to improve the energy efficiency at the terrestrial terminals served by an aerial base-station. Figure 1.2 (c) depicts clustering of terrestrial nodes to access the aerial base-station. Even though there has been significant interest and research done in aerial access networks, there are still important challenges that need to be addressed. The challenges are:

- **Coverage estimation of aerial access networks**
- **Energy efficiency of terrestrial terminals**
  - Interference management with terrestrial base-stations
  - Backhauling techniques
  - Inter-aerial platform communications

In this research, we focus our attention towards the first two challenges mentioned above and summarize the literature gaps. Even though there has been some work presented in literature regarding coverage estimation with an aerial platform, there has not been any work comparing the coverage provided by different technologies such as LTE and WiFi. As the distance between the aerial platform and the terrestrial nodes is large, techniques to improve the energy efficiency of the terrestrial terminals is an imperative and the research in this area is still at a nascent stage. Figure 1.2 (d) shows the challenges relating to backhauling and inter-aerial platforms link.

1.3 Regional Access Networks

As urban areas are becoming saturated, commercial network operators are investigating business cases to move towards untapped regional area markets. Moreover, many governments around the world are looking towards connecting every single citizen of the country
in every region including regional areas to the internet. Therefore, in the recent years, regional area communications and connectivity is identified as one of the crucial aspects in communications technology development. Regional areas are peculiar with the characteristics of low population density spread across large areas. It is noteworthy to state that current existing cellular technologies prove prohibitively expensive for commercial network operator to deploy and maintain in regional areas. Therefore, enhancements to current cellular technology is necessary to entice commercial network operators to deploy regional access networks. Regional access networks are not considered as a priority in 5G standards and are considered separately in IEEE 802.22 standard which proposes to utilize the white spaces in the broadcast television frequencies in lowly populated regional areas using cognitive radio techniques such as dynamic spectrum access [46]. With regards to the IEEE 802.22 standards, literature can be found with respect to performance estimation and enhancement of wireless regional area network using cognitive radio [47–51].

With this context, we investigate terminal cooperation technology to enhance coverage in regional access networks which would in turn reduce the capital and operational expenditure for a network operator in deploying infrastructure in regional areas. Figure 1.3 depicts a typical regional access network where some of the terminals are not covered by the base-stations due to difficulty in reaching those areas or it is not viable for a network operator to deploy another base-station for a very few number of subscribers. There is very few literature available where terminal cooperation is included in regional area networks. In [52], the
authors propose using D2D in wireless regional area networks to increase spectrum utilization and energy efficiency. However, many challenges, given below, remain unaddressed:

- Physical channel modeling of D2D in regional areas
- MAC-level techniques to enable terminal cooperation in regional access networks
- Business models for network operators and subscribers to enable terminal cooperation
- Spectrum and interference management between D2D and macro-cell

In this thesis, we focus on the first two challenges mentioned above.

1.4 Research Questions and Contributions

In this section, we formulate the research questions based on the challenges mentioned in the above sections and we present the contributions made with respect each research question briefly.

1.4.1 Research Question 1 and Contributions

What are the physical channel characteristics of D2D links to enable terminal cooperation?

Under this research question, we investigate the physical channel characteristics of D2D links that enable terminal cooperation under three different scenarios:

1. In the first scenario, we investigate the D2D channel characteristics in regional areas, especially in the ISM bands of 922 MHz and 2466 MHz, where the population density and the man-made structure density are low. The channel characteristics would include statistical characterization of path-loss exponents, standard deviation of shadowing phenomena and the correlation distance of shadowing.

2. In the second scenario, we investigate the channel characteristics for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications in the 5.8 GHz band for CEN-DSRC in urban areas.
3. In the third scenario, we investigate the millimetre wave channel characteristics in urban areas, especially in the ISM bands of 24 GHz and 61 GHz. We characterize the path-loss exponent and shadowing variance for D2D communication in urban areas using ray-tracing. Moreover, we study the utilization of techniques and schemes such as beam steering that can overcome propagation impairments in the millimetre wave band.

**Contributions under Research Question 1**

   In this contribution, we performed D2D channel propagation measurements in a rural area in 922 MHz and 2466 MHz. We characterized the D2D channel in terms of path-loss exponent, standard deviation of shadowing and the correlation distance of shadowing.

   In this contribution, we performed channel propagation measurements to characterize the V2I channel in 5.8 GHz for CEN-DSRC. We characterized the channel in terms of path-loss exponent and standard deviation of shadowing.

   In this contribution, we study the path loss performance of millimeter wave in urban environment using ray-tracing simulations. Using the channel loss from the simulations, we show that millimetre wave communication can be used to enable D2D using beam steering techniques.
1.4.2 Research Question 2 and Contributions

What is the expected coverage performance of aerial access networks without terminal cooperation and how to improve the coverage performance in regional access networks using terminal cooperation?

Under this research question, we investigate the coverage performance using existing technologies in aerial and regional access networks without terminal cooperation and propose novel techniques to improve coverage performance using terminal cooperation. The two studies performed under this research question are:

1. The first study evaluates the performance of existing technologies such as LTE and WiFi in aerial access networks. We characterise the performance of capacity and coverage by reporting the outage probability to achieve a certain throughput at a certain distance from the base-station.

2. The second study evaluates the coverage performance of LTE in regional access networks and proposes novel game-theoretic techniques to improve the coverage performance using terminal cooperation.

Contributions under Research Question 2


   In this contribution, we evaluate the coverage, capacity and delay performance of two vastly different technologies; LTE and WiFi in Aerial Networks. We characterize the coverage and capacity performance by reporting the outage probability to achieve a certain throughput.


   In this contribution, we first evaluate the coverage performance of LTE in regional area. We then propose game-theoretic algorithms to improve the coverage performance in regional areas using terminal cooperation. To verify the efficacy of the proposed algorithm, we show system level simulation results as proof-of-concept.
1. Introduction

1.4.3 Research Question 3 and Contributions

What is the expected energy efficiency of aerial access networks with terminal cooperation and how to optimize it?

Under this research question, we evaluate the expected energy efficiency of terrestrial nodes in an aerial access network. We then propose techniques using terminal cooperation to improve the energy efficiency at these battery-constrained terrestrial terminals. Three studies were performed under this research question:

1. The first study proposes a novel clustering technique to reduce the energy consumption of terrestrial nodes covered by an aerial base-station. The proposed algorithm is validated using system-level simulations.
2. The second study proposes a novel clustering technique using stochastic geometry which allows us to optimize the cluster-head spacing to improve energy efficiency at terrestrial terminals covered by an aerial base-station.
3. The third study proposes a clustering technique using Matern Point Processes using realistic channel conditions to improve energy efficiency of terrestrial nodes in an aerial access network.

Contributions under Research Question 3

   In this contribution, we proposed a novel clustering algorithm to improve the energy efficiency of terrestrial terminals covered by an aerial base-station. System-level simulation results show that the proposed clustering algorithm outperforms the existing algorithms found in literature.

   In this contribution, we proposed a novel clustering algorithm using stochastic geometry to improve energy efficiency of terrestrial nodes in an aerial access network. The proposed clustering technique can be expressed in analytical form and allows to optimize the cluster head spacing to improve energy efficiency.

In this contribution, we propose a clustering technique using Matern Point Processes using realistic channel conditions to reduce energy consumption at terrestrial nodes in an aerial access network. The proposed technique allows for optimization of cluster-head spacing to minimize energy consumption at terrestrial nodes.

### 1.5 Publications List

#### 1.5.1 Book Chapter


#### 1.5.2 Journal Articles


#### 1.5.3 Conference Papers


1.5.4 Technical Reports

1. S. Chandrasekharan, A. Al-Hourani, S. Kandeepan, and et. al., "D3.2.2 Evaluation of Opportunistic Relaying for Disaster Relief and Temporary Events", Accepted by European Commission, FP7 ABSOLUTE Project, 2015.


1.6 Thesis Structure

This thesis is mainly structured around the three research questions identified in section 1.4 where chapter 1 introduces the concepts of terminal cooperation, aerial access networks and
regional access networks in addition to identifying the research questions explored in this thesis. The rest of the thesis is structured as follows: Chapter 2 identifies the related works found in literature and provides a brief background on mathematical tools such as game theory and stochastic geometry which are used in the research work presented in this thesis. Chapter 3 addresses research question 1 wherein we provide our contribution in identifying the physical characteristics of the D2D link to enable terminal cooperation. In chapter 4, we address research question 2 and provide our contribution with respect to evaluation and improvement of coverage performance in aerial and regional access networks. In chapter 5, we address research question 3 and provide our contribution with respect to evaluation and improvement of energy efficiency in aerial access networks. Chapter 6 provides concluding remarks and future research directions.
Chapter 2

Related Works & Background

In this chapter, we identify the related works found in literature and provide a brief background on mathematical tools such as game theory and stochastic geometry which are used in the research work presented in this thesis.

2.1 Related Works

In this section, we present the related works with respect to the research questions formulated in the previous chapter and summarize the research gaps in literature. Specifically, we present a review of works found in literature with respect to channel modeling for terminal cooperation, coverage evaluation and enhancement using terminal cooperation and energy efficiency improvement using terminal cooperation.

2.1.1 Channel Modeling for Terminal Cooperation

Traditionally, there are many channel models available for the link between the mobile terminal and the base-station. However, to enable terminal cooperation, one of the key links is the link between two mobile terminals. There has been some work performed and documented to understand the characteristics of the D2D channel. Prior research on empirical measurements based characterization of propagation channels ranging from cellular, D2D, V2V and millimetre-wave communications, can be found in literature [53–57]. The measurement campaigns were conducted in different propagation conditions to characterize different propagation phenomena (path-loss, small/large-scale fading, time-delay spread), in different propagation environments (urban, suburban, rural, indoor/outdoor) and in different carrier frequencies. The characteristics of the signal propagation in a 3.5 GHz band...
2. Related Works & Background

A summary of other measurement campaigns according to carrier frequencies, environments and channel statistics/characteristics is shown in Table 2.1. It can be seen from the table that some measurement campaigns have received values of path-loss exponent \( \alpha \) below 2 and this is due to the gains received from reflected signals.

Table 2.1 D2D Channel Propagation Measurements

<table>
<thead>
<tr>
<th>Carrier Frequency</th>
<th>Environment</th>
<th>( \alpha )</th>
<th>( \sigma ) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>950 MHz[59]</td>
<td>Outdoor-Indoor</td>
<td>1.34-2.85</td>
<td>5.01-6.91</td>
</tr>
<tr>
<td>2.4 GHz[59]</td>
<td></td>
<td>1.89-3.63</td>
<td>2.11-4.21</td>
</tr>
<tr>
<td>5.2 GHz[53]</td>
<td>Highway</td>
<td>1.77</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>1.68</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Suburban</td>
<td>1.59</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>-</td>
<td>2.6</td>
</tr>
<tr>
<td>2.3 GHz[60]</td>
<td>Urban, low traffic</td>
<td>1.95</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Urban, high traffic</td>
<td>2.18</td>
<td>4</td>
</tr>
<tr>
<td>5.25 GHz[60]</td>
<td>Urban, low traffic</td>
<td>2.02</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Urban, high traffic</td>
<td>2.13</td>
<td>4</td>
</tr>
<tr>
<td>5.8 GHz[61]</td>
<td>Urban</td>
<td>1.9-4.02</td>
<td>2.79-3.50</td>
</tr>
<tr>
<td>5.8 GHz[62]</td>
<td>Highway</td>
<td>1.77</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>1.68</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Suburban</td>
<td>1.53</td>
<td>3.5</td>
</tr>
<tr>
<td>3.5 GHz[58]</td>
<td>Rural, flat terrain</td>
<td>2.5</td>
<td>8.9-9.4</td>
</tr>
<tr>
<td>5.9 GHz[63]</td>
<td>Suburban, route 1</td>
<td>2.32</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Suburban, route 2</td>
<td>2.75</td>
<td>5.5</td>
</tr>
<tr>
<td>28 GHz[10]</td>
<td>Urban, microcellular</td>
<td>3.73-4.51</td>
<td>8.36-8.52</td>
</tr>
<tr>
<td>38 GHz[10]</td>
<td>Urban, microcellular</td>
<td>0.12-1.28</td>
<td>6-8</td>
</tr>
</tbody>
</table>

The channel statistics \( \alpha \) and \( \sigma \) are the path-loss exponent and standard deviation of the shadow fading, respectively.

D2D channel is an emerging type of radio channel of which it’s characterization is still at an infancy stage. Characterization of shadowing in D2D channels presented in [64] is an imperative step towards full understanding of the characteristics of this channel. Substantial work has been proposed in literature characterizing the D2D channel for different environments and carrier frequencies [64], [65], [66]. In most of the prior literature on the D2D channel, authors have mainly focused on urban and suburban environments. In [66] human body shadowing in cellular D2D communications is investigated. Specifically, a novel statistical model is proposed and validated through field measurements. The work in [64] characterized shadowing in D2D communications in an indoor environment utilizing...
2. Related Works & Background

the shadowed fading model proposed in [66]. Likewise, the D2D channel measurements for outdoor urban environment were investigated for different everyday usage scenarios in [65] using the proposed statistical model in [66]. A particular feature of interest in this study is to analyze the effect that the human body shadowing has on the D2D communications channel. A comprehensive survey on D2D communication in cellular networks is presented in [14].

The authors in [53] have presented parameterized path-loss models for V2V communications based on channel measurements in four different signal propagation environments of highway, rural, urban and suburban. In [54], the authors have reported the results of wideband radio channel measurements at 5.9 GHz for car-to-car channel in rural, highway and urban environments. The authors in [55] have performed channel measurements using an on-road vehicular testbed in highway and rural propagation environments at frequency of 5.9 GHz. In [56], path-loss measurements for V2V channel are reported for typical urban, suburban and rural-motorway environments and compared with existing mobile wireless channel models. In [57], the authors provide a comprehensive survey for V2V propagation models found in literature.

Results for channel measurements performed at millimetre-wave frequencies for 28 GHz and 38 GHz is given in [10]. The authors have proposed a new channel model which includes a floating intercept compared to close-in free space reference path-loss. Novel large-scale path loss models are presented in [67] where the authors have conducted propagation measurements for an ultra-dense indoor office environment at 28 GHz and 73 GHz. The authors in [68] have provided an excellent overview of millimetre-wave based communications and channel models in addition to proposing novel channel models based on extensive measurements at 28, 38, 60 and 73 GHz. In [69], the authors have investigated and characterized the persistence of multipath components in D2D scenarios at 30 GHz.

Even though there has been some work performed as mentioned above, we believe that the characterization of the D2D channel is still in nascent stage especially with respect to regional areas to enable and utilize terminal cooperation.

2.1.2 Coverage evaluation and enhancement using Terminal Cooperation

With more commercial operators looking to reduce their capital expenditure, coverage extension and enhancement with the current infrastructure has become an important topic of interest to researchers and industry. Laneman et. al. [70] investigated cooperative diversity
in wireless networks and developed efficient low complexity cooperative protocols to mitigate effects of the multipath environment. In this thesis, we study systems where cooperative diversity is not possible since the terminal requesting cooperation is not in the coverage of the base-station. More precisely, we investigate relaying and clustering schemes to cater different objectives such as coverage and energy efficiency improvements.

In [71], the authors have investigated the problem of optimal relay placement for coverage extension in LTE-A networks jointly considering uplink and downlink scenarios. In [72], the authors have suggested multi-hop relays for extended coverage in wireless networks. In [73], the authors have studied the performance of multi-hop relay networks with respect to coverage and capacity enhancement. The authors in [74] have presented the idea of coverage and capacity enhancement in a cellular network using D2D mobile relays. In [75], the authors have considered a cooperative game in which the terminals are willing to achieve an optimal channel capacity through cooperation. They prove that the game is a two-person bargaining problem and utilize the Nash bargaining solution to obtain the unique solution of the game. In [76], the authors have proposed Stackelberg game to help source nodes find optimal relay nodes in terms channel gains and maximize the system performance. Moreover, the proposed scheme also allows the relay nodes to maximize their revenue. In [77], the authors have provided analytical models using coalitional game theory for outband D2D-clustering in 5G cellular networks to increase coverage and capacity using LTE-A and WiFi Direct technologies. The authors in [78] have presented a quantitative study of the benefits of mobile relays in providing coverage and throughput enhancement of the base-station’s performance. The authors in [79] show the uplink capacity enhancement in two-hop cellular networks with limited mobile relays operating in the network. In [80], the authors have addressed the problem of optimal relay selection to expand coverage in cooperative wireless networks. Firstly, they propose distributed nearest neighbor relay assignment in which other users in the network act as relays and secondly, they propose infrastructure-based relay assignment in which fixed relay nodes are deployed to help the users forward their information. In [81] the authors have proposed an energy efficient and optimal relay node placement algorithm to maximize the network coverage under energy constraint while maintaining SIR in LTE-A networks. The authors in [82] have studied multi-hop coverage extension in relay-union networks. In [? ], the authors have studied coverage extension using multi-hop relaying in disaster recovery scenarios. The authors propose multi-hop relaying as a technique to provide coverage to emergency personnel in disaster-struck areas with no or low coverage.

Even though there has been some study and investigation performed by researchers in
extending coverage using terminal cooperation, to the best knowledge of the author, none exists which actually focuses on aerial and regional access networks.

2.1.3 Energy efficiency improvement using Terminal Cooperation

One of the key requirements for the next generation wireless communication networks is energy efficiency. Especially with respect to public safety networks, energy efficiency of terminals used by emergency personnel is paramount for the extended operation of the communication network. Even with commercial networks, energy efficiency of devices which extends the single-charge battery lifetime of terminals is becoming increasingly an advantage in the competitive environment. Energy efficiency has been explored and investigated extensively with respect to wireless sensor networks. Various techniques such as multi-hopping, relaying [43, 44, 83–92] and clustering [1, 93–98] have been studied in literature. In one of the seminal works in the field of node clustering, the authors in [93] have proposed low-energy adaptive clustering hierarchy (LEACH) and low-energy adaptive clustering hierarchy-centralized (LEACH-C) clustering protocol to improve the energy efficiency of the wireless sensor nodes. In [94], the authors have presented a distributed clustering protocol called hybrid energy-efficient distributed clustering (HEED) to reduce the energy consumption at the sensors in an ad-hoc sensor network scenario. In [95], the authors have proposed a centralized clustering scheme called base-station controlled dynamic clustering protocol (BCDCP) which distributed the energy consumption evenly among all sensor nodes to maximize the network lifetime. In [1], we proposed a centralized clustering algorithm to improve the energy efficiency of terrestrial terminals served by an aerial base-station. The authors in [96] have proposed a spectral efficient and energy aware clustering scheme in cellular networks to reduce the capital and operational expenditure for mobile network operators in dense networks. The scheme is aware of the extra energy consumption at the cluster heads and handles it. The authors in [97] have proposed a dynamic clustering scheme for cooperative wireless sensor networks which evenly distributes the energy demand at the cluster heads and optimizes the number of sensor nodes involved in event reporting. In [98], the authors have proposed an energy efficient ring clustering routing protocol for wireless sensor networks.

The authors in [43] and [44] have proposed cooperative strategies for terminals served by an aerial base-station to improve energy efficiency. In [83] the authors have proposed an auction framework to enable power trading among terminals to improve energy efficiency at the device level. In [84], the authors have proposed a Stackelberg game framework for
distributed relay selection and power control in multiuser cooperative communication network to reduce the energy consumption at the terminals. The authors in [85] propose a novel selective single-relay cooperative scheme with power control to minimize the energy consumption per data packet and to maximize the network lifetime. The authors utilize the RTS/CTS signaling mechanism to minimize the signaling overhead. In [86], the authors have addressed the dynamic cooperative partner selection problem with incomplete information in relay-assisted cellular networks using evolutionary game approach. Optimal relay selection and power control under QoS constraints for wireless body area networks is presented in [87] using game theory. The existence of Nash equilibrium is proved and the Nash power control solution is calculated analytically in addition to providing a distributed algorithm to reach the solution. The authors in [88] propose a cooperative control scheme using correlated equilibrium addressing the joint issue of relay node selection and power control. Moreover, they derive the conditions under which the correlated equilibrium is Pareto optimal. The authors in [89] have used axiomatic bargaining techniques to develop Pareto-efficient cooperative energy allocations in relay-assisted wireless networks. Moreover, the derivation of necessary and sufficient conditions under which natural cooperation without extrinsic incentives is provided. In [90], the authors have examined the energy-efficient relay selection problem as a non-cooperative automata game proving that it is an ordinal game. Moreover, they provide a stochastic learning-based distributed relay selection algorithm which is shown to converge to a Nash equilibrium state using numerical analysis. The authors in [91] have used double auction framework to model the optimal relay selection problem. They propose an energy-efficient maximum weighted matching algorithm to solve the energy efficiency optimization problem in a double auction. In [92], the authors propose auction-based relay power allocation scheme to obtain the unique and Pareto optimal Nash equilibrium.

We can observe that most of the clustering work found in literature with regards to energy efficiency has been performed for wireless sensor networks. Aerial and regional access networks are fundamentally different to wireless sensor networks, which allows to propose custom-made clustering algorithms to optimize for the objective of improved energy efficiency. We would also like to note that most of the game-theoretic schemes to improve energy efficiency can be augmented to improve coverage and capacity by using fixed maximum transmit power instead of using transmit power control.
2.2 Background

In this section, we provide a brief background on tools such as game theory and stochastic geometry which have been used in the research work presented in this thesis.

2.2.1 Game Theory

Due to the shared nature of the wireless channel, behavior of one terminal would significantly affect other terminals in the vicinity. Game theory is a mathematical discipline that allows us to model situations in which decision makers have to make specific actions that have mutual consequences. Modern game theory began with a seminal book co-authored by Neumann and Morgenstern [99] followed by the famous Nash equilibrium. Game theory has been utilized by economists for decades to study the effects of national economic decisions and monetary policy. However, now we see a trend of utilizing game theory to model behaviors of wireless devices to study the dynamics involved in the system and to incentivize cooperation among wireless devices to enhance a specific objective such as coverage, capacity or energy efficiency [100–102].

Usually, game theory is categorized into cooperative games and non-cooperative games. Cooperative game theory provides mathematical tools to analyze and study the behavior of rational players when they cooperate with each other. Concepts of cooperative game theory, namely coalitional games, and its application to wireless networks is comprehensively covered in [103]. The authors classify coalitional games into three categories: Canonical coalitional games, coalition formation games and coalitional graph games.

On the other hand, non-cooperative game theory investigates the strategic choices resulting from the dynamics of competing players. Non-cooperative games are usually classified as static games with complete information, static games with incomplete information, dynamic games with complete information and dynamic games with incomplete information [104]. Static games with complete information are the games in which all the players in the game are fully aware of each other’s utility functions and action sets and every player has to take an action in the game simultaneously without knowing other’s actions. Solution concepts for such games include, but not limited to, pure strategy Nash equilibria and mixed strategy Nash equilibria. Static games with incomplete information are the games in which the players are not aware of each other’s utility functions but have a fair idea of the distribution from which it is derived from. Bayesian games and auctions are examples of static games with incomplete information. Dynamic games with complete information are the games in which every player is aware of each other’s utility functions and action
sets, however they do not play simultaneously [105]. In other words, some players in the
game play first and other players can see the first-moving player’s action before taking their
action. Solution concepts for such games include subgame perfect equilibria. Finally, dy-
namic games with incomplete information are the games in which players are not aware of
each other’s utility functions even though they have a fair idea of the distribution and there
exists a hierarchy of game play. Signaling games are an example of such a game.

Auction theory is comprehensively covered in [106]. Modern day auction theory origi-
nated with the work of William Vickrey in 1961 [107]. In literature we can find a number
of works which utilizes the concepts introduced by auction theory in wireless networks,
especially with regards to wireless spectrum and resource allocation [108, 109].

2.2.2 Stochastic Geometry

Stochastic geometry is a field in mathematics which studies random spatial patterns. In
wireless networks, the location of the nodes could be considered to be random and they yield
themselves to be modelled with the help of stochastic geometry as point processes [110].
Haenggi introduces point process theory, random geometric graphs and coverage processes
in his book that enables the reader to estimate the performance of wireless networks [111].

Point Process: The most fundamental aspect of stochastic geometry is point processes
which are a random collection of points in space. A point process is defined as a measurable
mapping $\Phi$ from some probability space to the space of point measures on some space $E$
[112]. Each such measure can be represented as a discrete sum of Dirac measures on $E$
given by,

$$\Phi = \sum_{i} \delta_{X_i} \tag{2.1}$$

where $X_i$’s are random variables which take their values in $E$ are the points of $\Phi$.

Poisson Point Process: Poisson point processes (PPP) are defined as follows; let $\Gamma$
be a locally finite measure on some metric space $E$. A point process $\Phi$ is Poisson on $E$ if:

- For all disjoint subsets $U_1,...,U_n$ of $E$, the random variables $\Phi(U_i)$ are independent
- For all sets $U$ of $E$, the random variables $\Phi(U)$ are Poisson.

Usually, PPP is used to model nodes in wireless networks due to its simplicity and conve-
nient mathematical properties which lends itself to tractable solutions.

Matern Hardcore Process Type-II: Hardcore processes are point processes where points
are forbidden to be closer than a certain minimum distance called hardcore distance [111].
To form a Matern Hardcore Process of type-II, let’s consider a uniform PPP $\Phi_b$ with intensity $\lambda_b$. To each point in $\Phi_b$ assign an independent random variable called mark $m(x)$ which is uniformly distributed on $[0,1]$. Flag all points that have a neighbor within the distance $r$ that has a smaller mark. Remove all the flagged points to get a Matern Hardcore Process of type-II. The process of removing points from a point process is called *thinning*. Formally it is defined as,

$$
\Phi = \{ x \in \Phi_b : m(x) < m(y) \forall y \in \Phi_b \cap b(x,r) \setminus \{x\} \}
$$

(2.2)

In literature, stochastic geometry is mainly utilized to model interference in wireless networks to estimate the network performance [113]. In [114], the authors study the performance of D2D communication underlaying a cellular wireless network using stochastic geometry. In [115], the authors have studied the intra-cell interference caused by D2D users underlaying a finite cellular network region. In [116], the authors have derived the exact nearest-neighbor and contact distributions for Matern Cluster Process and in [117] have derived the same for Thomas Cluster Process. In [118], the authors have performed analysis of downlink coverage of a network served by an UAV. One of the main benefits of using PPP and stochastic geometry is the tractability of the solution it provides.
Chapter 3

Terminal Cooperation Channel Modelling

A communication channel is the medium through which an information signal is sent from the transmitter to the receiver. It possesses the capability to alter the transmitted signal while it carries it to the receiver. Especially, in a wireless channel, the signal undergoes reflection, diffraction and penetration when it interacts with the surrounding environment such as walls, buildings, glass windows, etc. However, one of the most important effects is that of the reduction in signal power with distance. Channel models are utilized to capture these interactions of the wireless signal with the surrounding environment. Many channel models can be found in literature for different environments with different frequencies of wireless signal deployed in different scenarios. Wireless system designers utilize these channel models to evaluate and propose novel wireless communication protocols and systems.

To enable terminal cooperation, we need to investigate and study D2D technology which is the ability of nodes to communicate with each other with or without the assistance of network infrastructure. This technology has recently gained a special focus with the continuing development of LTE-Advanced and cellular networks towards 5G networks [2]. The demand to accommodate D2D technology can be mainly ascribed to public safety agencies [119, 120] as well as to commercial cellular operators, since the anticipated gains will significantly enhance the network availability and the spectral efficiency.

When D2D devices are in close proximity, the required transmit power is much lower than normally needed to communicate with a cellular base station, thus leading to lower interference in the cellular network, and a higher energy saving. Moreover, a D2D-enabled device is expected to have cognitive radio features [121] and can act as a mobile-relay assisting other devices to access the cellular network, a scenario that can reduce network
Fig. 3.1 Main scenarios of D2D communication as defined by 3GPP.

deployment costs, as well as, provide an essential backup in case of major network failure due to a natural disaster [? ]. Fig. 3.1 depicts the four major scenarios for using D2D technology identified by 3GPP [122], the first scenario I-A shows a D2D pair out of the reach of the main cellular network, a situation that is frequently faced by public safety personnel (for example during a fire fighting operation in remote bush fire). In scenario I-B one device acts as a mobile relay aiming to extend cell-edge coverage. While scenarios I-C and I-D represent the case when D2D communication takes place underlaying a cellular coverage where a local source-sink type traffic is occurring between the two nearby devices (such as local voice/video calls, file transfer, etc...).

A radio channel model is required to model the expected path-loss between a communicating D2D pair and how much interference it might cause to other D2D devices.

This chapter addresses research question 1 through three key contributions: (i) Propagation model for D2D in rural areas in section 3.1, (ii) Vehicular Channel Modelling in section 3.2, and (iii) Propagation Model for D2D using Millimeter Wave Frequencies in section 3.3. This chapter is based on the following publications contributing towards sections 3.1, 3.2 and 3.3 respectively:

3. Terminal Cooperation Channel Modelling

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3.1 Propagation Model for D2D in Rural Areas

Rural areas are distinctive by their low building density and vast open areas. Moreover, due to the low population density in rural areas, deployment of network infrastructure becomes economically unviable. However, due to increased competition in already saturated urban areas, network operators are turning their attention towards rural areas to increase their revenue and subscriber base. Terminal cooperation is considered one of the promising technologies in reducing the capital expenditure involved in network deployment.

In this work, we investigate the radio propagation behaviour of D2D channel in rural areas by conducting field measurements. We characterize the D2D channel by estimating the path-loss exponent and the standard deviation of the shadowing phenomena and by presenting the shadowing correlation analysis in various propagation environments using ISM band frequencies of 922 MHz and 2,466 MHz.

3.1.1 Environments

Three different environments in a rural area were selected which can be classified as: (i) Structures on both sides (ii) Structures on one side and (iii) Forest. Two test areas were selected for each environment and measurements were conducted in these test areas. The selection of the different environments were performed in such a way that we are able to characterize and understand reflected signal propagation from structures on either side of the road.

Structures on both sides: Figure 3.2 depicts the test areas, Hewson and Grundy, selected in the first environment (Structures on both sides), their transmitter locations and the path taken during the measurements in each of the test areas respectively. It can be observed from the figure that man-made structures are present on both sides of the road. The selected
path was around 450 metres for Hewson and 400 metres for Grundy from their respective transmitter locations. The width of the street was around 5 metres in both the test areas and had very limited pedestrians and road traffic. Test area Hewson had a downward slope after 160 metres away from the transmitter such that the signal conditions turned non-line of sight whereas test area Grundy had no inclination in the street level.

**Structures on one side:** Figure 3.3 shows the test areas, Follet and Watts, selected in the second environment (Structures on one side) and their transmitter locations and the path taken during the measurements in each of the test areas respectively. It can be observed from the figure that man-made structures are present on one side of the road and vegetation to the other side. The selected path was around 450 metres in the case of Follet and 550 metres in the case of Watts from their respective transmitter locations. In both the test areas, the width of the street was around 4 metres with no inclination in the street level, and the pedestrian and road traffic was very limited.

**Forest:** Figure 3.4 shows the two test cases, Reserve$_{S01}$ and Reserve$_{S02}$, in a forest. This
Fig. 3.3 Measurement environment (ii): Structures on one side with Follet test area on top and Watts test area below (Map data: Google, CNES/Astrium).

Fig. 3.4 Measurement environment (iii): Forest showing the path taken during measurements in test areas Reserve$_{S01}$ in green and Reserve$_{S02}$ in pink respectively (Map data: Google).

category is particularly important for public safety and emergency networks in the case of firefighting during a bushfire scenario. The forest consisted of tall trees and half-to-one
metre bushes. The green line and the pink line in the same figure shows the path taken during measurements in Reserve$S_{01}$ and Reserve$S_{02}$ respectively. Test area Reserve$S_{01}$ had partial line-of-sight conditions whereas Reserve$S_{02}$ had non line-of-sight conditions with trees and bushes blocking the line of sight of the signal. The selected path was around 160 metres in the case of Reserve$S_{01}$ and 130 metres in the case of Reserve$S_{02}$ from their respective transmitter locations.

### 3.1.2 Measurement Setup

Figure 3.5 shows the measurement setup used to conduct the measurements. The transmitter used is a wide band continuous wave transmitter capable of producing a maximum output power of approximately 10 dBm which was connected to a transmit antenna with -10.2 dBi gain at 922 MHz and 2.75 dBi gain at 2,466 MHz. As shown in the figure, the transmitter was mounted on a telescopic mast at a height of 1.5 metres, thus emulating a human carrying a device capable of D2D, and was powered using a laptop. The receiver used is a handheld spectrum analyzer (Agilent FieldFox) connected to a receive antenna with similar parameters as that of the transmit antenna. A laptop is connected to the spectrum analyzer to record the measurements. At the same time, the laptop also records the location of the receiver using a GPS device connected to it. The receiver equipments were condensed into
a portable form and was carried by a person during the time of measurements. Considerable effort was made to keep the receive antenna at the height of 1.5 metres at all times during the measurement. Internal pre-amplifier of the spectrum analyzer was used to boost the received signal power. Table 3.1 lists all the measurement parameters.

Table 3.1 Measurement Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>922 MHz &amp; 2,466 MHz</td>
</tr>
<tr>
<td>Integration Bandwidth</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Cable Loss</td>
<td>2.33 dB at 922 MHz</td>
</tr>
<tr>
<td></td>
<td>4.44 dB at 2,466 MHz</td>
</tr>
<tr>
<td>Transmitter Antenna Gain</td>
<td>-10.2 dBi at 922 MHz</td>
</tr>
<tr>
<td></td>
<td>2.75 dBi at 2,466 MHz</td>
</tr>
<tr>
<td>Receiver Antenna Gain</td>
<td>Same as Transmitter Antenna</td>
</tr>
<tr>
<td>Transmitter Antenna Height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Receiver Antenna Height</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

In every test area, the location of the transmitter was recorded using the same GPS device. Each sample point recorded during the measurement includes (i) the received power in the channel being measured and (ii) the GPS coordinates of the location of the receiver.

3.1.3 Measurement Results

The measurements were conducted in all the test areas described in the section 3.1.1. The sample points recorded during the measurements were post-processed using MATLAB®. The distance between the transmitter and the receiver was calculated using their GPS coordinates recorded in the sample points. The received channel power in the sample points was compensated for the gains/losses of all the equipment such as cables, antennas, internal pre-amp, etc. used in the measurement setup to calculate the actual path-loss. Furthermore, they were binned and averaged over a bin width of 1 metre. This was performed to remove any small scale variations present in the sample points and to give equal weights to the points at each metre during linear fitting.
Path-loss Exponents

To characterize the D2D channel, we adopt the widely accepted log-normal shadowing model [123] which is given by,

\[ PL(d) = PL(d_0) + 10\alpha \log_{10} \left( \frac{d}{d_0} \right) + X\sigma, \]  

(3.1)

where \( PL(d) \) is the path-loss in dB at a distance of \( d \) metres from the transmitter, \( PL(d_0) \) is the reference path-loss in dB at a distance of \( d_0 \) metres from the transmitter, \( \alpha \) is the path-loss exponent and \( X\sigma \) is a zero-mean Gaussian distributed random variable with a standard deviation of \( \sigma \) dB. \( X\sigma \) incorporates the shadowing component of the received signal in the model.

To find the path-loss exponent and the standard deviation of shadowing, according to the log-normal shadowing model given in equation (3.1), linear fitting was performed on the measurement samples of all test areas such that the difference between the measured and estimated path loss is minimized in a mean square error sense. Figures 3.6 and 3.7 shows the measured path-loss and the calculated path-loss exponents \( \alpha \) for different test areas at frequencies 922 MHz and 2,466 MHz respectively. It can be readily observed from the figures that 2,466 MHz frequency encounters much higher path-loss than 922 MHz frequency.

It can be observed from the figures that except Watts test case, all other test cases have higher path-loss exponents for 2,466 MHz compared to 922 MHz. The path-loss of a signal highly depends on the specific environment being measured, the types of structures around the vicinity and the amount of vegetation present in the environment. In our case, we can see from figure 3.2, figure 3.3 and figure 3.4 that large amount of vegetation was present around the vicinity of measurements. The effect from vegetation can be clearly seen from the higher path-loss exponents observed for the environment (iii) forest ReserveS01 and ReserveS02 cases. Also, the structures present around the environment causes interference due to scattering which can be clearly observed from figure 3.6 and figure 3.7 in which environment (i) Structures on both sides of the road shows higher path-loss exponents for both the frequencies compared to environment (ii) Structures on one side of the road. Due to these reasons, the path-loss exponents presented in this paper is higher than the ones found in literature and presented in table 2.1. Moreover, the path-loss in D2D vastly varies from the path-loss in traditional terrestrial network due to (i) the height of the transmitter being lower and (ii) both the transmitter and the receiver could be mobile.
Fig. 3.6 Measured path-loss in dB and curve fitting for all test areas at 922 MHz.

**Standard deviation of shadowing**

The standard deviation of shadowing $\sigma$ was found by calculating the standard deviation of the measured path-loss with respect to the linearly fitted line. Mathematically, it can be
3. Terminal Cooperation Channel Modelling

Fig. 3.7 Measured path-loss in dB and curve fitting for all test areas at 2,466 MHz.

expressed as [123]:

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [PL(d_i) - \overline{PL(d_i)}]^2},
\]

(3.2)

where \( N \) is the number of measured samples, \( PL(d_i) \) is a path-loss sample measured at a certain distance \( d_i \) in dB and \( \overline{PL(d_i)} \) is the corresponding mean path-loss in dB obtained
from the curve-fitting process. The standard deviation of shadowing obtained for different test areas along with their corresponding path loss exponents for both the frequencies, 922 MHz and 2.466 MHz, are presented in table 3.2. From the table we can observe that the highest standard deviation of shadowing is in Follet test case for 922 MHz and Grundy test case for 2.466 MHz. The shadowing effect highly depends on the surroundings of the individual test cases and the frequencies of the signal being measured. We can observe that the standard deviation of shadowing is higher for all test cases when 2.466 MHz is used compared to 922 MHz.

<table>
<thead>
<tr>
<th>Environments</th>
<th>922 MHz</th>
<th>2.466 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PL(d₀)</td>
<td>α</td>
</tr>
<tr>
<td>Hewson</td>
<td>46.81</td>
<td>3.55</td>
</tr>
<tr>
<td>Grundy</td>
<td>41.99</td>
<td>4.09</td>
</tr>
<tr>
<td>Reserve₀₁</td>
<td>44.49</td>
<td>3.67</td>
</tr>
<tr>
<td>Reserve₀₂</td>
<td>48.43</td>
<td>5.29</td>
</tr>
<tr>
<td>Follet</td>
<td>52.96</td>
<td>2.97</td>
</tr>
<tr>
<td>Watts</td>
<td>48.40</td>
<td>3.31</td>
</tr>
</tbody>
</table>

Moreover, table 3.2 also presents the path-loss at reference distance d₀ metres for all test areas at both the frequencies. The reference distance d₀ was chosen to be 20 metres for all test cases. As expected, it can be observed that the path-loss at reference distance d₀ is higher for 2.466 MHz compared to 922 MHz.

**Shadow Correlation Analysis**

The auto-correlation function of the random shadowing component Xσ is of great interest to us to understand the correlation of the shadowing process with respect to the distance d. This knowledge then helps us to recreate similar conditions when simulating such channels for the performance analysis of communication systems. After computing the path-loss exponent from the measured data the shadowing component was estimated as follows;

\[ \hat{X}_\sigma = PL(d) - \overline{PL(d)} \]  

(3.3)

where, \( PL(d) \) is the measured path-loss at distance d and \( \overline{PL(d)} \) is the computed path-loss at distance d by using the computed value for \( \alpha \). In other words \( \overline{PL(d)} \) is the same as the fitting curve as depicted in figure 3.6 and figure 3.7. Assuming \( \hat{X}_\sigma \) is a wide sense stationary process the autocorrelation function of the estimated shadowing component then
is computed by,

\[ \hat{R}_X = |E[\hat{X}_\sigma(d + \Delta d)][\hat{X}_\sigma(d)]| \]  

(3.4)

The corresponding autocorrelation analysis was done for all the test areas for both the frequencies with a displacement distance of \( \Delta d = 1m \), and the results are depicted in figure 3.8. The correlation rapidly reduces (exponentially) over 10’s of meters in all the cases as we observe from the figures, for Reserve\(_{301} \), Reserve\(_{302} \) and Watts it reduces to zero around 20m and for the remaining environments it reduces to zero around 70m. The "sinc" like observation in the correlation function is also observed in other experiments reported in the literature [124],[125] and is specific to the type of environment as we observe from the figures.

### 3.2 Vehicular Channel Modelling

Dedicated Short-Range Communications (DSRC) technology in the 5.8 GHz band is a key enabler to support a safer and more efficient vehicular transportation in the future. The chosen 5.8 GHz frequency band is therefore of great interest for us to study the propagation of signals under various environments. In this work we investigate and record the propagation effects of 5.8 GHz radio signals in an urban and sub-urban like environments with experiments conducted in the city of Melbourne for an infrastructure-to-vehicle (I2V) use case. The experiments were conducted for a transmitter-receiver separation from 20 m to 150 m with line-of-sight conditions for the three chosen environments with and without the vehicle for comparisons. Based on the measurements we estimate the pathloss exponent and the shadowing standard deviation for the chosen scenarios.

#### 3.2.1 CEN DSRC Standard

DSRC is a term used to identify short to medium range communication standards described for automotive use. The same acronym DSRC is used for incompatible technologies that operate in different frequency bands according to different standards around the world. In this work, we will focus on the DSRC communication technology deployed in Europe, which is also called CEN DSRC, because it is based on the standards developed by the European CEN (Comité Européen de Normalisation) standardization CEN 278 body. The definition of the physical layer standards of DSRC is described in CEN 12253:2004 [126]. CEN DSRC operates in the 5.8 GHz range, more precisely in 5.795 GHz to 5.815 GHz bands in Europe. CEN DSRC provides a downlink bit rate of 500 kbit/s and an uplink rate
of 250 kbit/s, which is amply sufficient for various applications. The primary application is electronic road usage fee collection and CEN DSRC systems are widely deployed in Europe for this purpose. For such applications, the V2I and V2V pointing accuracy is very good. Typical communication footprints on the road surface are about one lane wide and 8-10 meters long. This DSRC standard has been optimised for high volume application in

Fig. 3.8 Estimated autocorrelation of shadowing for the respective test areas.
vehicles focusing on low costs of the on-board equipment. Low costs are achieved because CEN DSRC on-board equipment does not contain an active radio transmitter. The on-board equipment does not generate radio signals independently. The energy for the answering radio signal is obtained from the received road-side signal. CEN DSRC on-board equipment acts like a mirror that reflects back the road-side signal, and adds information by modulating the reflected signal.

The carrier frequencies and channels specified for CEN-DSRC in CEN 12253:2004 [126] are defined in table 3.3.

3.2.2 Vehicular Channel

Unlike conventional cellular channel models, vehicular channel has an inherited nonstationary nature due to the high mobility of scatterers (mostly vehicles). This nonstationary nature can be spotted in both V2V and Vehicle to Infrastructure (V2I) scenarios [127]. In addition to that, V2V communication usually takes place between peers that are below 2 metres in height, whereas outdoor cellular communication takes place between a user equipment (UE) with a height of 1-2 metres and a much higher Base Station (BS) at 10-60 metres. Thus, cellular channel models largely deviate from V2X ones leading to the need for the investigation of the particular nature of the vehicular channel. The main factors that affect the propagation of radio signals in V2X, are the following [128]:

**Dynamic Multi-Path Environment**

 Scatter rich environment causes multiple copies (echoes) of the transmitted signal to arrive at a receiver at different times, carrying different amounts of power. In the case of high bit rate communication, these extended copies might overlap with one another, creating Inter Symbol Interference (ISI). An effective way of tackling this issue is to utilize Orthogonal Frequency-Division Multiplexing (OFDM) which concurrently transmits the data on narrow adjacent sub-carriers. OFDMA is used in DSRC to effectively mitigate the ISI is-
sue by properly setting guard intervals. Also, the nature of the V2X channel is dynamic (time-varying) caused by the rapidly changing scattering environment due to the mobility of the scatterers (vehicles). This results in the loss of orthogonality between the subcarriers resulting in Interchannel Interference (ICI) [129]. Multi-path environment contributes to the fast-fading component of the received signal that can be characterised by its statistical distribution such as Rayleigh, Rician or m-Nakagami [130].

**Dynamic Shadowing:**

The slow-fading component of the received signal results from the changes in the attenuation. However, unlike static environment (such as cellular), the dynamic shadowing in V2X caused by the relative movement of vehicles and objects, introduces higher rate slow-fading than conventional cellular channels. This type of environment continuously fluctuates the average received power, and causes gray-zone phenomenon as it is called in [128], indicating that good packet reception is not always guaranteed over V2X channel.

**Doppler Shift:**

The high mobility nature of the transmitter, receiver, and scatterers causes doppler frequency shift of the received signal coming from different directions. The amount of frequency shift varies between the multi-path components, thus when combined at the receiver side causes what is called doppler spread or frequency dispersion [131]. This spread leads to additional ICI [132] between the subcarriers. In order to compensate such spread a guard gap is provided in the CEN-DSRC.

The impairments of the radio signal resulting from the above listed factors can be quantified using the following metrics [127]: (i) Pathloss, representing the average attenuation in the signal, (ii) Fast-fading, representing the rapid changes in the signal level, (iii) Doppler spread, as explained previously, and (iv) Delay spread, caused by multi-path component arriving at different times. In our experimental setup we focus on the pathloss characteristic of V2X, and adopt the widely accepted log distance model [133], according to the following equation:

$$P_r(d) = P_r(d_o) - 10\alpha \log \frac{d}{d_o} \quad (3.5)$$

where $P_r(d_o)$ is the reference received power at a distance $d_o$ and $\alpha$ is the path loss exponent. The selection of the reference distance $d_o$ is dependent on the specific propagation environment [123], typically $d_o$ is chosen to be 1 m for indoor scenarios, 100 m for outdoor micro-cellular scenarios and 1600 m for outdoor macro cellular scenarios. In our applica-
tion, the scenario is different where the communication usually takes place within a street over a range up to 100 to 200 metres. Therefore, we propose to use a reference distance around 10 m to 20 m. Furthermore, the log-distance model can be extended to adopt the random shadowing component by incorporating a Gaussian distributed random variable in equation (3.5) in the dB scale with a standard deviation $\sigma$ dB. Therefore the log-normal shadowing model, as used in section 3.1.3, is given by [123]:

$$P_r(d) = P_r(d_o) - 10\alpha \log\frac{d}{d_o} + X_{dB} \tag{3.6}$$

where, $X_{dB} \sim N(0,1)$ is a zero mean Gaussian distributed random variable in dB with a standard deviation of $\sigma$ dB.

### 3.2.3 Environments

We have selected three different local road environments for this experiment shown in figure 3.9: (A) Urban type-A (B) Urban type-B and (C) Suburban Type-C.

**Urban Type-A Environment:** As shown in figure 3.9 the environment consists of 6 m wide lane, 1-3 m wide walk surrounded by high-rise buildings from both sides. The selected test path is around 120 m line, no inclination in the street level. This road is usually busy with pedestrians, and has limited vehicular traffic. The transmitter is placed at one end of the test path, as shown in figure 3.9.

**Urban Type-B Environment:** This environment consists of two parallel 6 m wide lanes with a 5.5 m wide island in the middle for car parking, also two side-walks about 3 m wide for pedestrians. This road is surrounded by high-rise buildings on both sides and is busy with many cars in both directions with some cars parked on the sides as well as in the middle island. The transmitter is placed on the middle of the road at one end of the test path as indicated in figure 3.9. The road is flat with no inclination and sparse vegetation is present around the road.

**Suburban Type-C Environment:** Although this environment is located in a suburban district, however it can be seen as a transition between urban environment towards suburban. It consists of two parallel 6 m wide lanes with a 5 m wide island in the middle for parking and 3 m side-walks for pedestrians. This road is surrounded by one and two-storey buildings on both sides. Sparse vegetation can be observed on the sides of the road. The transmitter is placed on the middle of the road at one end of the test path as shown in figure 3.9. The terrain of the environment is flat with no inclination.
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3.2.4 Scenarios

In order to spot the effect of the car body on the pathloss exponent, we have performed the measurements for two scenarios:

**Scenario-1 No Vehicle**: A transmitter is placed on top of a telescopic mast, while the receiving antenna is placed on another mast, as indicated in figure 3.10.
Scenario-2 With Vehicle: It is similar to scenario-1, however, the receiving antenna is placed on the middle of the roof of the car near to the back side window, as indicated in figure 3.11. The same antenna is used for both scenario-1 and scenario-2.

3.2.5 Experimental Setup

All measurements are conducted for two different antenna heights of the transmitter (H1 = 1.5 m and H2 = 3 m), while the receiving antenna is always kept at 1.5 m. The aim of this is to mimic the V2V and V2I situations when using H1 and H2 respectively. The used transmitter is a commercial analog video extender having 14 dBm EIRP power, with selectable carrier frequency, our experiment is conducted at (f = 5.82 GHz), while at the receiver side we use an omni directional antenna mounted on a 1.5 m mast connected to a handheld spectrum analyzer (Agilent FieldFox) capable of performing accurate channel power measurement. The spectrum analyzer was connected to a laptop to record the readings along with the location of the receiver which was measured using a GPS device connected to the same laptop. For each reading, we have averaged 15 samples of the measured channel power. The internal pre-amplifier of the spectrum analyzer is utilized for increasing the Signal to Noise Ratio (SNR), thus enhancing the power accuracy. Experiment parameters are listed in table 3.4.
In each environment, the location of the transmitter was recorded using the same GPS device. Field measurements raw data include two key pieces of information. For each measurement point we collect: (i) The average received power of the channel, (ii) The GPS coordinates of the receiver. The distance between the transmitter and the receiver is calculated using the GPS coordinates recorded. Raw data along with the distances calculated are then fitted using Levenberg–Marquardt algorithm to a linear equation of the following form:

\[ y = P_1 x + P_o \]  

(3.7)

where in our case \( y \) is the averaged received power at distance \( d_i \), \( x = \log_{10}(d_i) \). Therefore, by comparing with the log-normal pathloss model described in equation (3.6) an estimate of the path-loss exponent \( \alpha \) is given by \( \hat{\alpha} = -P_1/10 \).

### 3.2.6 Measurement Results

We have obtained samples as indicated in figure 3.12, where the results of environment-A are indicated in the upper graph and results from environment-B and C follow below. Also, we have obtained the values for the path loss exponents which are mentioned in table 3.5.

It can be observed from figure 3.12 and table 3.5 that different environments have differ-
3. Terminal Cooperation Channel Modelling

Table 3.4 Experiment Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>5.82 GHz</td>
</tr>
<tr>
<td>Measurement Bandwidth</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Internal Pre-Amplifier Gain</td>
<td>25 dB</td>
</tr>
<tr>
<td>Transmitter EIRP</td>
<td>14 dBm</td>
</tr>
<tr>
<td>Receiver Antenna Gain</td>
<td>12 dBi</td>
</tr>
<tr>
<td>Distance</td>
<td>20-120 m</td>
</tr>
<tr>
<td>Transmitter Antenna Height</td>
<td>H1=1.5m/H2=3.0m</td>
</tr>
<tr>
<td>Receiver Antenna Height</td>
<td>1.5m</td>
</tr>
</tbody>
</table>

ent path loss profiles. Also, the transmitter antenna height has a significant influence on the path loss profile of a given environment. One consistent commonality that can be observed from figure 3.12 is that the samples collected with car are 2-10 dB lower than the samples collected using the stand-alone antenna. Also, the fitting curve for with car is always below the fitting curve for without car for all scenarios. As explained in [127], the finite conductive surfaces causes the horizontal omni pattern of the monopole antenna to be shifted upward by around 20° degrees, causing a degradation of the directivity of the receiving antenna in the horizontal plane. We believe the main reason for it is the drop in the receiving antenna directivity caused by the finite metallic rooftop of the vehicle.

Table 3.5 shows that the variation in path loss exponents for urban environments A and B for a given transmitter antenna height is high whereas for suburban environment C it is low. In other words, for suburban environment C the path loss exponent does not vary much for no vehicle and with vehicle scenarios for a given transmitter antenna height.

Table 3.5 Pathloss Exponents

<table>
<thead>
<tr>
<th></th>
<th>Height = 1.5m</th>
<th>Height = 3.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Car</td>
<td>With Car</td>
</tr>
<tr>
<td>Environment A</td>
<td>2.38</td>
<td>1.16</td>
</tr>
<tr>
<td>Environment B</td>
<td>2.21</td>
<td>1.32</td>
</tr>
<tr>
<td>Environment C</td>
<td>1.65</td>
<td>1.67</td>
</tr>
</tbody>
</table>

In order to get a general sense of the variation of the collected received-power samples
Fig. 3.12 Received power samples and fitting curves, from top to bottom: Environment-A Heights H1 and H2, Environment-B Heights H1 and H2, and Environment-C Heights H1 and H2.
Table 3.6 Standard Deviations

<table>
<thead>
<tr>
<th></th>
<th>Height = 1.5m</th>
<th>Height = 3.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Car</td>
<td>With Car</td>
</tr>
<tr>
<td>Environment A</td>
<td>2.52 dB</td>
<td>2.23 dB</td>
</tr>
<tr>
<td>Environment B</td>
<td>4.41 dB</td>
<td>5.94 dB</td>
</tr>
<tr>
<td>Environment C</td>
<td>2.27 dB</td>
<td>1.47 dB</td>
</tr>
</tbody>
</table>

with respect to the mean received-power fitting line, we have obtained the standard deviation \( \sigma \) of the difference between the samples values and the corresponding expected mean received-power at a certain distance. Below is the related mathematical expression:

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ y_i(d_i) - \bar{y}(d_i) \right]^2},
\]  

(3.8)

where \( N \) is the number of collected samples, \( y_i(d_i) \) is a received power sample collected at a certain distance \( d_i \) in dB, and \( \bar{y}(d_i) \) is the corresponding mean received-power in dB as obtained from the curve fitting process. The standard deviation of shadowing for each of the scenarios are listed in table 3.6. It is noticeable that environment B has the highest standard deviation compared to other environments which is an expected result that can be primarily referred to the high car traffic in this environment. This high traffic increases the dynamic shadowing as explained previously. Note that, considering the fact that we have a high time varying channel environment, the shadowing standard deviation values can be improved in accuracy by time averaging the results which will statistically provide a higher confidence in the estimates. This would be considered for future work in this area.

### 3.3 Propagation Model for D2D using Millimeter Wave Frequencies

In the recent years the millimeter wave spectrum is being explored as a prospective band for the next generation (5G) cellular communications especially for D2D communications. In this work we study the propagation of the the millimetre wave spectrum using ray tracing model for an urban environment. We consider the ISM bands in 24 GHz and 61 GHz in particular and conduct ray tracing simulations to study the path loss behaviour in terms of the path loss exponent and the shadowing variance for both Line of Sight and Non Line of Sight conditions. As a potential application we examine the device to device (D2D) com-
3. Terminal Cooperation Channel Modelling

Communication, which is currently being developed for LTE-A standard. The resulting pathloss exponents and the shadow variances are presented here based on ray tracing simulations for an ITU-R statistical urban model, moreover this work shows that intelligent beam steering can significantly improve the throughput for the considered D2D scenarios.

3.3.1 Millimetre Waves Propagation

The spectrum range between 30 GHz and 300 GHz is referred as the mmWave spectrum since the wavelengths for these frequencies are in order of millimeters (less than 10 mm) [134]. In general, the utilization of spectrum above 6 GHz has been greatly limited to highly directive Point-to-Point fixed communication systems, due to the fact that only longer wavelengths (i.e. lower frequencies) can diffract around terrestrial terrain and obstacles more smoothly, and can penetrate more easily through buildings, in contrary to the shorter wavelengths (i.e. higher frequencies including mmWaves) that are usually impaired with strong reflections, refractions and scattering. Also mmWave radios were usually bulky and unsuitable for mobile or handheld communication. However there is recently an increasing interest in exploiting the vast available bandwidth in mmWave spectrum for NLoS communication and for mobile and cellular systems by exploiting mmWaves ability of strong reflections. Applications like Point-to-Multipoint (PtMP) are already in the market today, while other wireless applications are currently being developed. An example of the promising next generation mmWave wireless communication systems is the IEEE 802.11ad standard that is currently under development, proposing mmWaves as the carrier for the future Wireless LAN Technology (WLAN), along with several other standards that are already in place [135] such as WirelessHD, ECMA-387. These advancements are mainly facilitated by the new RFIC technology allowing low cost, low power electronics and antenna solutions [136]. This section is addressing the general propagation characteristics of mmWaves focusing on the newly allocated ISM bands within mmWaves spectrum.

ISM Bands in mmWave Spectrum

In spite of the original intention to use the Industrial Scientific Medical (ISM) spectrum band for non-telecommunication purposes, such as the "operation of equipment and appliances locally generating and using radio frequency energy" [137], this band has acquired a major focus and interest due to its availability for non-licensed and free use (with some minor exceptions). In fact, Wi-Fi/WLAN is a very famous example of ISM band utilization installed in most of the houses and enterprises around the world. Additionally, many other
technologies like Zigbee and Bluetooth utilize ISM bands.

According to the ITU-R Radio Regulation Articles 5.138 and 5.150, both 24 GHz and 61 GHz bands are now defined for unlicensed use as ISM [137], if local radio regulation does not contradict. Table 3.7 is listing the most common applications of microwave ISM bands in addition to the two mmWave bands.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Available Bandwidth</th>
<th>Main Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.400-2.500 GHz</td>
<td>100 MHz</td>
<td>Wi-Fi IEEE 802.11b/g/n</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bluetooth IEEE 802.15.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zigbee IEEE 802.15</td>
</tr>
<tr>
<td>5.725-5.875 GHz</td>
<td>150 MHz</td>
<td>WLAN IEEE 802.11a/n</td>
</tr>
<tr>
<td>24.00-24.25 GHz</td>
<td>250 MHz</td>
<td>Point-to-Point Point-to-MultiPoint</td>
</tr>
<tr>
<td>61.0-61.5 GHz</td>
<td>500 MHz</td>
<td>WirelessHD (Overlapping)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Point-to-Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IEEE 802.15.3c</td>
</tr>
</tbody>
</table>

In addition to the globally defined ISM bands, local and regional regulators have endorsed the use of mmWave spectrum for unlicensed communication as listed in table 3.8 which summarizes the available 60 GHz band for unlicensed use in different countries [138].

<table>
<thead>
<tr>
<th>Country</th>
<th>Frequency Range</th>
<th>Available Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia*</td>
<td>59.4-62.9 GHz</td>
<td>3.5 GHz</td>
</tr>
<tr>
<td>USA</td>
<td>57.0-64.0 GHz</td>
<td>7.0 GHz</td>
</tr>
<tr>
<td>Japan</td>
<td>59.0-66.0 GHz</td>
<td>7.0 GHz</td>
</tr>
<tr>
<td>Canada</td>
<td>59.0-64.0 GHz</td>
<td>5.0 GHz</td>
</tr>
</tbody>
</table>

* Under discussion

In this work, we are proposing the use of the mmWave ISM bands for D2D communication that has its pros and cons; on one hand, since ISM is a license-free spectrum, commercial cellular operators could favor free-of-charge bands compared to the tremendous spectrum license fees currently in place, that will allow the rapid growth of D2D market and the alleviation of the congested cellular networks. While on the other hand, special
care and consideration needs to be taken when operating in unlicensed bands due to the major interference introduced by other unlicensed users and systems in the future, taking into consideration that the utilization of mmWaves is currently, to a far extent, very minimal.

An additional merit of the mmWave spectrum is that high antenna directivity can be achieved using small form factor printed antennas [139]. This high directivity will allow the mitigation of interference received from other users sharing the same spectrum by steering the receiving beam towards the direction of the intended signal only, compared to omnidirectional antenna that receives power from all directions (including the interfering signal). On the other side of the link, the transmitter will focus the entire power towards the intended receiver. This important mechanism will help in avoiding UEs to become neither aggressors nor victims of co-tier interference.

**Atmospheric Attenuation**

Radio Frequency (RF) propagation in earth atmosphere is usually impaired with minor energy losses due to the atmospheric absorption caused by the resonance of water vapor molecules and oxygen gas molecules [140], peaking near certain frequencies such as 24 GHz, 60 GHz and 120 GHz as depicted in figure 3.13, that was regenerated by curve approximation according to ITU guidelines in [140], showing a total atmospheric absorption of 0.23 dB/km and 13.55 dB/km for frequencies 24 GHz and 61 GHz respectively calculated at temperature 25°C , relative humidity 50% and pressure of 101.3 kPa. In general the signals using mmWave spectrum endure higher atmospheric absorption than signals using lower frequencies. Also, heavy rain can cause relatively higher attenuation in mmWave spectrum due to the comparable raindrop size with the mmWave wavelength. These impairments, for long time, limited the mmWave communication to only LoS scenario, while NLoS was avoided. However for short range communication applications, as in the cellular networks, atmospheric and rain absorption are not playing a limiting factor since at distances around 250 meters these absorptions are summing up to a less than 4 dB in case of 61 GHz links and 0.5 dB in the case of 24 GHz, which is rather considered as an advantage, since it can help limiting the signal propagation beyond its intended target UE(s) and causing a co-tier interference.

**3.3.2 Modeling Urban Environment**

When studying a wireless system performance requires an accurate definition of the study conditions and constraints; one of the most important conditions inside a city is the layout of
ITU-R in its recommendation document [141], is suggesting a standardized model for urban areas, based on three simple parameters $\alpha$, $\beta$ and $\gamma$, that describe to a fair extent the general geometrical statistics of a certain area of which the RF signal is going to propagate. These parameters are explained below:

- **Parameter $\alpha$:** Represents the ratio of built-up land area to the total land area (dimensionless).
- **Parameter $\beta$:** Represents the mean number of buildings per unit area (buildings/km$^2$).
- **Parameter $\gamma$:** A statistical variable that describes the building heights distribution according to Rayleigh probability density function:

$$P(h) = \frac{e^{-\frac{h^2}{\gamma^2} \gamma^2 h}}{2\gamma h}$$  \hspace{1cm} (3.9)

where $h$ is the building height in meters.

And for simulating Urban Environment we have selected $\alpha = 0.3$, $\beta = 500$ and $\gamma = 15$, although the latter is irrelevant for our study since the assumed user equipment’s height is limited to 1.5 m. In this work it has been selected to reproduce the virtual-city environment according to figure 3.14; an array of structures (buildings or houses) of an assumed square plot of width ($W$), and inter-building spacing of ($S$), that are linked to the ITU-R statistical
parameters as per the following formulas:

\[ W = 1000 \frac{\alpha}{\beta} \]  
\[ S = \frac{1000}{\sqrt{\beta}} - W \]

The selected transmitter location is shown in the same figure, as well as the locations of the distributed receivers (a total of 114 receivers). It is clear from the figure that some of the receivers can favor an LoS condition while others do not. The simulated patch area is 275 m × 275 m that includes 36 building blocks.

### 3.3.3 Antenna Beam Switching

Directional antennas transform the propagation impairments associated with mmWave links into a great advantage by leveraging the high reflections and refractions caused by urban structures as an alternative to the LoS communication. Current mobile systems (working in the range of 300 MHz - 3 GHz) depend largely on omni-directional antennas for the UE, while the base station usually exploits directive antennas (of half power beam width 60° to
forming the conventional three sectors cellular site. The uplink of the UE suffers a huge energy inefficiencies, since the RF power is transmitted in all directions, not only draining the battery energy, but also raising the level of interference in the neighboring cells, and accordingly reducing the cellular spectral efficiency. The reason of adopting omni antennas in the current UEs is mainly related to antenna dimensions, since the latter is inversely proportional to system’s frequency, and implementing directional antennas would occupy a huge space at the current standard cellular frequencies. On the contrary, in mmWave frequencies very small and highly directional antennas could be fabricated [139]. Beam switching (i.e. using RF switches) is selected for the simulation setup, rather than beam forming (i.e. using RF phase shifters), as the Switched Beam Array would be more feasible and easier to implement in future UEs [142]. The utilized antenna array in this work is based on the generic formula in [143] which relate the Directivity (G) of a planar antenna array to the half power beamwidth as per the following:

\[ G = \frac{32400}{\theta_E \theta_H} \]  (3.12)

where \( \theta_E \) and \( \theta_H \) are the half power beamwidth in E-Plane and H-Plane respectively. In the performed simulation we have selected the following for 24 GHz: (G = 24 dBi, \( \theta_E = 60^\circ \), \( \theta_H = 72^\circ \)) and for 61 GHz: (G=32 dBi, \( \theta_E = 22.5^\circ \), \( \theta_H = 45^\circ \)) aiming to form a set of 16 antennas, noticing that only one antenna at a time will be active.

### 3.3.4 Simulation Results

Two main simulation scenarios are presented in this section; (i) first scenario is for illustrating the path loss (PL) exponent behavior in urban environment assuming isotropic antennas on both the transmitter and the receiver, (ii) second scenario is performed using a limited number of receivers distributed according to figure 3.14. The second scenario is addressing three situations: (a) where all antennas are isotropic, (b) using directional antennas for the receivers (c) using directional antennas for both the transmitter and the receivers, so the results of these three cases will allow benchmarking the possible throughput enhancement when embracing the antenna beam switching technique. Ray tracing simulation were performed using Wireless InSite®, and the postprocessing of results were performed using MATLAB®, including the system level throughput estimation. The main simulation and the post processing parameters are listed in table 3.9.
### Table 3.9 Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Frequency</td>
<td>24 GHz, 61GHz</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Number of Simulated Reflections</td>
<td>2</td>
</tr>
<tr>
<td>Number of Simulated Diffractions</td>
<td>1</td>
</tr>
<tr>
<td>Number of Simulated Transmissions</td>
<td>Not Simulated (No penetration)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>101.3 kpa</td>
</tr>
<tr>
<td>Water Vapor Density</td>
<td>11.5 g/m$^3$</td>
</tr>
<tr>
<td>TX/RX Height from Ground</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Transmitter TX Power</td>
<td>23 dBm [144]</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>9 dB [144]</td>
</tr>
<tr>
<td>Fade Margin</td>
<td>15 dB</td>
</tr>
<tr>
<td>Noise</td>
<td>Additive White Gaussian Noise</td>
</tr>
</tbody>
</table>

### Path-loss Exponent

This simulation was performed in order to get a general sense of the D2D path loss behavior in built-up areas when utilizing mmWave ISM bands. Large number of receivers were deployed in the simulation environment (above 20,000 receivers) allowing more accurate path loss exponent estimation. The reference signal received power (RSRP) is shown figure 3.15, where the signal level clearly deteriorates for NLoS links.

The received power due to an isotropic transmitter can be calculated as:

$$P_r = \frac{P_t}{4\pi D^\alpha A_r}$$

where $P_t$ is the transmitted power, $\alpha$ is the path loss exponent (which is equal to 2 in case of free space transmission), $D$ is the distance between the transmitter and the receiver, and
$A_r$ is the aperture area of the receiver defined as:

$$A_r = G_r \frac{\lambda^2}{4\pi}$$  \hspace{1cm} (3.14)

where $\lambda = C/f$ is the wavelength and $G_r$ is the receiver gain and is equal to 1 in case of the isotropic receiver, accordingly equation (3.13) can be rewritten using the decibel form as:

$$PL = PdB_t - PdB_r = 20\log\left(\frac{4\pi f}{C}\right) + 10\alpha\log(D)$$ \hspace{1cm} (3.15)

As it can be noticed from figure 3.16 that the simulated path loss samples have a clear tendency towards two specular modes; one corresponds to LoS and another corresponds to NLoS. Accordingly the mean path loss (MPL), representing the highest path loss expectancy, was obtained using curve fitting (for LoS and NLoS samples separately) following equation (3.15). The samples with large deviation from the specular modes were ignored during the fitting process, that is because of two reasons; (i) In order to simplify the path loss model, (ii) the contribution of these samples is less than 15% of the total samples set. The resulting MPL(s) are listed in table 3.10. In [145] the authors have performed path-loss measurements in 28 GHz at different TX and RX heights and have observed the separation of specular modes (LoS and NLoS) as observed in this work. Moreover, the path-loss exponents that have been measured in [145] lies in the same range as we have observed in this work.
3. Terminal Cooperation Channel Modelling

Fig. 3.16 Device-to-Device Path Loss in Urban Environment

Table 3.10 D2D Mean Path Loss

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Condition</th>
<th>Path Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 GHz</td>
<td>LoS</td>
<td>60.05 + 1.95 * 10\log(D)</td>
</tr>
<tr>
<td></td>
<td>NLoS</td>
<td>60.05 + 4.32 * 10\log(D)</td>
</tr>
<tr>
<td>61 GHz</td>
<td>LoS</td>
<td>68.15 + 1.88 * 10\log(D)</td>
</tr>
<tr>
<td></td>
<td>NLoS</td>
<td>68.15 + 4.49 * 10\log(D)</td>
</tr>
</tbody>
</table>

Deviation from MPL

Another important path loss behavior aspect is the samples deviation from the MPL value. This deviation is usually caused by multiple effects; such as small-scale fading, doppler effect and large-scale fading. However, since the simulation is performed for static receiver locations with interspacing of 2 m (much larger than \( \lambda \)), the only relevant fading deviation that can be obtained from this simulation is the large-scale fading. For a receiver \( n \) we define the path loss deviation for each specular mode as \( D_n = PL_n - MPL \), where \( PL_n \) is receiver \( n \) incurred path-loss. Accordingly we can obtain path loss deviation distribution as plotted in figure 3.17. Multiple statistical distribution fitting has been compared with respect to their Bayesian Information Criteria (BIC) and it has been found that the best fit for this variation distribution is the General Extreme Value (GEV) as depicted in the same figure. However Gaussian Distribution showed a very close BIC score to GEV, and since it is a much easier way to represent a distribution, we have opted to use it for modeling the path loss variation.
3. Terminal Cooperation Channel Modelling

Fig. 3.17 Device-to-Device Deviation from MPL Distribution

distribution. Accordingly the best fit Gaussian standard deviation values are listed table 3.11.

**D2D Link with Beam Steering**

The second scenario simulation is mainly aiming to illustrate the enhancement in system level (MAC) throughput that can be achieved when utilizing antenna beam switching. The D2D transmitter is assumed to behave in a similar manner to an LTE eNodeB, and accordingly the link level and system level overhead were utilised inline with the bandwidth
Table 3.11 Deviation from MPL

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Condition</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 GHz</td>
<td>LoS</td>
<td>4.3 dB</td>
</tr>
<tr>
<td></td>
<td>NLoS</td>
<td>7.8 dB</td>
</tr>
<tr>
<td>61 GHz</td>
<td>LoS</td>
<td>1.2 dB</td>
</tr>
<tr>
<td></td>
<td>NLoS</td>
<td>4.0 dB</td>
</tr>
</tbody>
</table>

efficiency assumptions obtained in [146]. The maximum modulation and coding scheme is assumed to be QAM512, 4/5, in order to show the allowed additional gains of the setup. And hence the data throughput was linked to the SNR using the following formula:

$$TP = BW \cdot BW_{\text{eff}} \cdot \eta \cdot \log_2 (1 + 10^{\frac{\text{SNR} - \text{SNR}_{\text{eff}}}{10}})$$

(3.16)

where $BW = 20$ MHz is the system bandwidth, $BW_{\text{eff}}$ is the system level bandwidth efficiency, $\eta$ is a correction factor and $\text{SNR}_{\text{eff}}$ is the SNR implementation efficiency. These parameters are given in [146], and listed in table 3.12. It is also important to note that the system bandwidth is in linear relationship with the system throughput as shown in equation (3.16), therefore increasing or decreasing the system bandwidth will linearly increase or decrease the system throughput respectively.

Table 3.12 Parameters for Throughput Equation

<table>
<thead>
<tr>
<th>Correction Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BW_{\text{eff}}$</td>
<td>0.57</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\text{SNR}_{\text{eff}}$</td>
<td>1.25 dB</td>
</tr>
</tbody>
</table>

The cumulative distribution function of the D2D throughputs are depicted in figure 3.18, showing limited enhancement when adopting the one sided beam switching, while a major improvement can be witnessed when both the transmitter and the receivers utilize the beam switching technique giving a significant throughput increase in the lower (5%) percentiles and in also the median (50%) percentile, these enhancements are depicted in figure 3.19, showing that for both 24 GHz and 61 GHz bands, more than 95% of the receivers in the simulated patch were able to attain a usable OFDM link.
3. Terminal Cooperation Channel Modelling

Fig. 3.18 System Level Throughput at 24 GHz and 61 GHz

Fig. 3.19 Performance Benchmarking at 5%tile and 50%tile.
3.4 Chapter Summary

In this chapter we addressed research question 1 through three key contributions. Firstly, we characterized the physical channel for D2D in rural areas by performing channel measurements in 922 MHz and 2,466 MHz. Secondly, we characterized the vehicular channel by performing channel measurements at 5.8 GHz. Finally, we investigated the feasibility of utilizing D2D in mmwave frequencies for which we conducted ray tracing simulations at 24 GHz and 61 GHz to understand the propagation characteristics at mmwave frequencies.
Chapter 4

Coverage Evaluation and Enhancement using Terminal Cooperation

The coverage holes in urban areas and regional areas with the current generation wireless communication network is a cause of concern for the network operators. Moreover, network operators are continuously looking for novel technologies and architectures that reduce their capital expenditure in deploying network infrastructure while improving coverage. Innovative architectures such as aerial communication networks and new technologies such as terminal cooperation are promising to deliver the benefits network operators are looking for. With new technologies and architectures comes novel challenges that need to be addressed. With respect to aerial access networks, coverage with vastly different technologies such as LTE and WiFi are yet to be quantified. With regards to regional access networks, the claim of terminal cooperation to enhance coverage while reducing costs is yet to be verified.

This chapter addresses research question 2 through two key contributions: (i) evaluating the performance of LTE and WiFi technologies in aerial networks in section 4.1 and (ii) proposing game-theoretic algorithms to improve coverage using terminal cooperation in regional access networks in section 4.2.

This chapter is based on the following publications contributing towards sections 4.1 and 4.2 respectively:


2. S. Chandrasekharan, S. Kandeepan, K. Gomez and L. Reynaud, "Coverage Enhancement in Regional Access Networks using Terminal Cooperation", *Accepted by*
4.1 Performance of LTE and WiFi Technologies in Aerial Networks

The advantages of using aerial platforms to provide wireless coverage are many including larger coverage in remote areas, better line-of-sight conditions and resilience to certain natural disasters. In this context, we investigate the performance of using LTE and Wi-Fi technologies in aerial networks. More precisely, we consider a practical urban scenario from Melbourne, Victoria, Australia and perform ray-tracing simulations to characterize the path-loss of the air-to-ground channel. We then perform system-level simulations utilizing the channel-loss from ray-tracing to evaluate the performance of LTE and WiFi 802.11g technologies in aerial networks.

4.1.1 System Model

An aerial communication network is considered as shown in figure 4.1 which consists of an aerial platform carrying the Remote Radio Head (RRH) equipment connected to the Baseband Unit (BBU) equipment on the ground using optical fiber and satellite is utilized as a backhaul. Note that alternatives exist to tethering the aerial platform such as free space optical links or massive MIMO based beamforming to provide the backhaul link.

Fig. 4.2 Network scenario showing the annuli edges used in performance analysis of LTE and WiFi.

Geographic Scenario

An urban area in Melbourne, Victoria, Australia was selected for performance evaluation. Fig. 4.2 depicts the area chosen along with its building layouts. The red point in the figure shows the position of the aerial platform in the 2D plane. The height or the altitude of the aerial platform is varied to study the performance of the network at different altitudes. The total area of the selected scenario is approximately 5.45 square kilometers. The building heights in the selected area follows a Rayleigh distribution which is consistent with the statistical urban area model suggested by ITU [141].

LTE and WiFi System Model

Fig. 4.3 shows the data plane protocol architecture of LTE and WiFi used in the simulations, which is similar to a standard LTE [147] and WiFi [148] protocol stack. In both LTE and WiFi, an application is installed in the terrestrial nodes which sends packets continuously in the uplink. Similarly, an application is installed in the server in LTE and access point (AP) in WiFi to send packets continuously on the downlink. These applications send packets in such a way that the link between the terrestrial node and the eNodeB in LTE and AP in WiFi is always kept saturated in both downlink and uplink.

The path-loss model used between the $n^{th}$ terrestrial node and the eNodeB in LTE and AP in WiFi is given by [123],

$$L_n = PL_n + g(K_n)$$  \hspace{1cm} (4.1)

where, $L_n$ denotes the total channel-loss including fading, $PL_n$ is the path-loss obtained from ray-tracing described later in Section 4.1.2 and $g$ is loss due to multi-path fading which we

characterize using Rician fading based on the K-factor which is also explained in the next section.

As LTE uses a scheduler and OFDM, we do not simulate UE-to-UE interference. However, the D2D interference plays a significant role in the case of WiFi due to hidden-node problem. To reduce the effect of hidden nodes from the evaluation, we configure WiFi to permanently use the RTS/CTS mechanism\(^1\) for all packets rather than those above a certain threshold. This mechanism works well for larger packets as it reduces the size of the packets that collide. However, there still exists a probability of collision for the RTS packets which makes it important to consider D2D interference in WiFi. Therefore, we use log-normal shadowing path-loss model for D2D channels given by \[149\],

\[
L_{D2D}(d) = \xi + 10\alpha \log_{10}(d) + X_g + h_r \tag{4.2}
\]

where, \(d\) is the distance between the transmitter and receiver, \(\xi\) is an environment specific path-loss constant, \(\alpha\) is the path-loss exponent, \(X_g\) is the normally distributed shadowing component with a standard deviation of \(\sigma\) and \(h_r\) is the multi-path fading component characterized by Rayleigh fading.

---

\(^1\)RTS/CTS mechanism is a technique to reduce the hidden-node problem in which a node preliminarily transmits a special short frame called request-to-send (RTS). When the receiving station receives the RTS, responds with a clear-to-send (CTS) after which the data frame is transmitted.

4.1.2 Ray Tracing Simulations

As the aerial channel varies significantly from the traditional terrestrial channel, ray-tracing simulations were performed for the scenario described in the previous section. Three types of rays (direct, reflected and diffracted) were considered while transmitted rays (penetrating through walls) were neglected because their effect is minimal\(^2\). A direct ray is the ray that travels from the transmitter to the receiver without interactions with the man-made structures. The second type of ray considered, the reflected ray is a ray that reaches the receiver after reflecting from the walls of buildings which causes a decrease in the magnitude of the electric field and phase shift depending on the angle of incidence. A diffracted ray is the ray that gets diffracted by buildings which are considered as ideal knife-edges. Fig. 4.4 shows a snapshot of ray tracing with a single transmitter-receiver pair and the rays traveling between them.

A total of approximately 13500 receivers were uniformly distributed in the selected area to capture the rays emitted by the transmitter. The walls of the buildings were considered to be concrete and the terrain to be flat and wet-earth. Two types of output are generated as a result of the ray-tracing simulation. The first type of output is the received power at each of the receivers which is denoted by \( P_{RX_n} \) for the \( n^{th} \) receiver. The received power is calculated by summing (vector summation) of the electric field of all the captured rays. We can calculate the path-loss in dB from the aerial platform to the \( n^{th} \) receiver using,

\[
PL_n = 10\log_{10} P_{TX} - 10\log_{10} P_{RX_n}
\]

(4.3)

This output is used as a lookup table in the simulations. The second type of output is an ordered set containing the power of the \( m^{th} \) ray captured by \( n^{th} \) receiver denoted by \( R_{n,m} \).

\(^2\)Two reflections and one diffraction were considered in the ray-tracing simulations.
Using this information, we can calculate the K-factor to characterize the multi-path fading incurred by the $n^{th}$ receiver given by [149],

$$K_n = \frac{R_{n,1}}{\sum_{m=2}^{M} R_{n,m}} \quad (4.4)$$

where, $M = |R_{n,m}|$ and $|.|$ represents the cardinality of a set.

Fig. 4.5 shows the heat map of path-loss for different altitudes of the aerial platform obtained using ray-tracing simulations. It can be observed from the figure that coverage improves with increase in the altitude of the aerial platform until a certain point after which increasing the altitude reduces the coverage, thus giving us an insight that there exists an optimal altitude for the aerial platform to maximize coverage. The co-centric interference pattern seen for higher altitudes of the aerial platform is due to the reflected ground ray interference. Fig. 4.6 shows the comparison between the path-loss obtained from ray-tracing and well-known terrestrial channel models such as WINNER II C2 urban macrocell scenario [150], Okumura-Hata and COST231-Hata [149] for the base-station height and altitude of aerial platform at 25 m.

To characterize the D2D interference, we performed ray-tracing simulation with only 88 transceivers. As the computation of D2D increases exponentially with increase in the number of transceivers, we fit the results of the D2D ray-tracing to the log-normal shadowing model [149] given in equation (4.2) to obtain $\xi$, $\alpha$ and $\sigma$.

### 4.1.3 Performance Evaluation

The system-level simulations to study the performance of LTE and WiFi 802.11g in aerial networks was performed using the ns-3 simulator. Table 4.1 lists the parameters used in the simulations. In this section, we first present the system-level simulation results to validate the ray-tracing methodology by comparing it with well-known channel model WINNER II (C2 scenario). Second, we present the performance evaluation of LTE and WiFi 802.11g technologies with an average of 30 nodes in the network because WiFi seems to deteriorate heavily with further increase in the number of nodes. Third, we present the effect of different number of nodes on the performance of the network. We would like to note that the performance will largely depend upon the number of nodes in the network denoted by $N$. Therefore, we perform simulations for different number of nodes to evaluate its effect. We would also like to note that 802.11g WiFi uses a 20 MHz channel bandwidth for uplink and downlink together. The throughput thresholds were chosen corresponding to 20 kbps for

Fig. 4.5 Heatmap of path-loss for different altitudes of the aerial platform obtained using ray-tracing simulations.

telemetry applications, 100 kbps for voice and 500 kbps for video applications.

Evaluation of Ray-Tracing Methodology

We aim to validate the use of ray-tracing methodology compared to well-known channel model WINNER II C2 urban macrocell. We set the altitude of the aerial platform at 25 m. Fig. 4.7 shows the outage probability of LTE and WiFi 802.11g in downlink for different throughputs of 20 kbps, 100 kbps and 500 kbps, for different channel models with an average of 30 nodes in the network and an altitude of 25 m. We define outage probability as the ratio between the number of receivers that receive an average throughput denoted by $\gamma$ less than a certain value denoted by $T$ and the total number of receivers in the network given by:

$$P_{out} = \frac{\sum_{n=1}^{N_\text{out}} 1_{\gamma_n < T}}{N}$$  \hspace{1cm} (4.5)

Fig. 4.6 Comparison between channel-loss obtained from ray-tracing and well-known terrestrial channel models such as WINNER II C2 scenario, Okumura-Hata and COST231-Hata for altitude of aerial platform and base-station height of 25 m.

![Path-loss vs Distance Graph]

Fig. 4.7 Outage probabilities of LTE and WiFi in downlink using different channel models for different throughputs of 20 kbps, 100 kbps, and 500 kbps with an average of 30 nodes in the network and the altitude of the aerial platform at 25 m.

![Outage Probability Graph]

The difference seen in outage probabilities between ray-tracing and WINNER II is due to the fact that WINNER II is a generic statistical channel model whereas ray-tracing provides channel-loss specific to the selected geographic scenario which provides more accurate evaluation of the selected urban area.
Table 4.1 Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude of aerial platform</td>
<td>[25, 50, 100, 250, 500, 1000, 1250, 1500, 2000] m</td>
</tr>
<tr>
<td>Number of terrestrial nodes</td>
<td>[15, 30, 45] nodes</td>
</tr>
<tr>
<td>Throughput thresholds</td>
<td>[10, 100, 500] kbps</td>
</tr>
<tr>
<td>Terrestrial node height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>LTE mode</td>
<td>Frequency division duplex (FDD)</td>
</tr>
<tr>
<td>LTE system UL/DL bandwidth</td>
<td>20 MHz/20 MHz</td>
</tr>
<tr>
<td>LTE scheduler</td>
<td>Proportional fair</td>
</tr>
<tr>
<td>LTE eNodeB transmit power</td>
<td>36 dBm EIRP</td>
</tr>
<tr>
<td>LTE UE max. transmit power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>LTE eNodeB noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>LTE UE noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>Node TX and RX antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>WiFi standard</td>
<td>802.11g</td>
</tr>
<tr>
<td>WiFi manager</td>
<td>MinstrelWifiManager</td>
</tr>
<tr>
<td>WiFi D2D $\xi$</td>
<td>-0.8797 dB</td>
</tr>
<tr>
<td>WiFi D2D path-loss exponent</td>
<td>4.7</td>
</tr>
<tr>
<td>WiFi D2D shadowing $\sigma$</td>
<td>23.7 dB</td>
</tr>
<tr>
<td>WiFi AP noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>WiFi node noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>WiFi AP TX power</td>
<td>36 dBm</td>
</tr>
<tr>
<td>WiFi node TX power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>WiFi RTS/CTS threshold</td>
<td>Enabled</td>
</tr>
</tbody>
</table>

With $N = 30$ nodes

**Outage Probability**: We aim to understand the effect of the altitude of an aerial platform on outage probability to achieve at least a certain throughput in LTE and WiFi. Figures 4.8 and 4.9 show the outage probabilities of LTE and WiFi in downlink and uplink respectively.
Fig. 4.8 Outage probabilities of LTE and WiFi in downlink v/s altitude of the aerial platform for different throughputs of 20 kbps, 100 kbps, and 500 kbps with an average of 30 nodes in the network.

versus altitude of the aerial platform for different throughputs of 20, 100, and 500 kbps with an average of 30 nodes in the network. From the figures we can observe that LTE outperforms WiFi 802.11g significantly and WiFi 802.11g cannot support throughputs of 100 and 500 kbps in uplink and downlink at any altitude of the aerial platform when the network contains an average of 30 nodes. We can also observe that there is an optimal altitude of the aerial platform, in both LTE and WiFi, to minimize the outage probability to achieve at least a certain throughput. This effect is seen due to two contradicting factors...
in the air-to-ground channel. The probability of getting a LoS increases with increasing altitude. However, increasing altitude leads to higher distances between the aerial platform and the terrestrial nodes leading to higher path-losses. These factors lead to the existence of an optimal altitude in aerial networks. It is important to note that the optimal altitude for 500 kbps curve is not visible in the figures due to the fact that the maximum altitude of the aerial platform that was considered in the simulations was 2000 metres. However, if we consider higher altitudes for the aerial platform the optimality will be clearly visible. We can also observe that this optimal altitude is not very restrictive in the case of LTE as compared to WiFi 802.11g.

Fig. 4.12 Mean delay v/s annuli radius for LTE and WiFi in uplink for different altitudes of aerial platform and for 30 nodes in the network.

Mean Throughput: We intend to study the effect of altitude of the aerial platform on mean throughput of a receiver with respect to the ground-distance from the aerial platform. In this work, throughput is defined as goodput at the application layer. To perform this evaluation, we group the nodes from different annuli radius as shown in figure 4.2. Within each annuli, we average the throughput received by each receiver.

Figures 4.10 and 4.11 shows the effect on mean throughput for nodes in different annuli radius for different altitudes of the aerial platform in downlink with an average of 30 nodes connected to the network for WiFi and LTE respectively. We can observe from the figures that as the altitude of the aerial platform increases the throughput becomes more homogeneous as compared to lower altitudes in both LTE and WiFi 802.11g technologies.

Mean Delay: We aim to study the delay performance of the aerial network. We define delay as the difference between time of successful reception and the time of transmission of a given packet. Fig. 4.12 shows the mean delay performance with respect to annuli radius in uplink for different altitudes of the aerial platform using WiFi and LTE technologies. We can observe from the figure that the mean delay performance of LTE is better than WiFi 802.11g for all altitudes of the aerial platform.

With different number of nodes

Outage Probability: Fig. 4.13 shows the effect on outage probability in LTE and WiFi downlink to achieve a throughput of atleast 20 kbps for different altitudes of the aerial platform with different number of nodes connected to the network. It can be observed that

Fig. 4.13 Outage probability of LTE and WiFi downlink to achieve a throughput of at least 20 kbps v/s altitude of the aerial platform for different number of nodes connected to the network.

The outage probability improves with reduced number of nodes connected to the network.

Mean Delay: Fig. 4.14 shows the effect of different number of nodes connected to the network on mean delay performance w.r.t. different altitudes of the aerial platform in downlink. We can observe that as the number of nodes connected to the network increases, the mean delay performance worsens in both LTE and WiFi 802.11g technologies.

4.2 Coverage Enhancement in Regional Access Networks

As the subscriber numbers are reaching near-saturation in urban areas, the network operators are shifting their attention towards regional areas. However, due to low population density in regional areas, the capital expenditure in deploying network infrastructure is not economical. Therefore, the network operators are considering novel communication architectures and techniques to reduce the cost. In this work, we show that terminal cooperation provides coverage enhancement which in turn decreases the capital expenditure. We present game-theoretic algorithms to enable terminal cooperation in a regional access network setting and prove the efficacy of the algorithms and provide proof-of-concept for terminal cooperation by presenting results from system-level simulations. The simulation results show that significant coverage improvement can be achieved using terminal cooperation. Wireless design engineers can potentially utilize the presented results while designing next-generation cooperative wireless networks.

4.2.1 Use case

The use case considered is of a typical regional area in which some areas are covered by the terrestrial infrastructure and other areas are left uncovered due to difficulty in reaching such areas or for economic reasons.

Figure 4.15 shows a regional area partially covered by the network using terrestrial infrastructure. There are two terrestrial base stations covering the areas with most population density. But the area with smaller number of users behind the mountains is left uncovered.
This might be due to the difficulty in reaching those areas. We envision user terminal cooperation to extend the coverage to such areas as shown in the figure. For the terrestrial coverage, we consider LTE and for terminal cooperation, in this work, we consider WiFi. However, LTE-D2D or any other D2D technology could also be used for terminal cooperation.

### 4.2.2 Game Model

In this section, we present two auction game models for the objective of improving energy efficiency of the network. We also present a centralized algorithm and compare the two game models presented with the centralized algorithm. A brief overview of game theory is presented in section 2.2.1. We would like to note that energy efficiency can be traded off for increasing coverage in a network by using fixed transmit power at the nodes and vice-versa by using dynamic transmit power control. Therefore in this section, we validate the efficacy of the proposed game models using an energy-efficiency metric. However, in the next section, we show the coverage enhancement in regional access networks using system level simulations.

**Network Model**

Consider a network with $N$ source nodes denoted by $S_j$, $j = 1, 2, \ldots, N$, $K$ relay nodes denoted by $R_k$, $k = 1, 2, \ldots, K$ and one destination node denoted by $D$ (in our case the eNodeB). The received signal between any two nodes, $S_j \rightarrow R_k$, $R_k \rightarrow D$, and $S_j \rightarrow D$, ignoring the subscripts, can be given as,

$$r(t) = \frac{1}{\sqrt{L(d)}} h(t)s(t) + v(t)$$

(4.6)

where, $s(t)$ is the transmitted signal, $h(t)$ represents the small scale fading channel, $v(t)$ is the additive noise at the receiver with a double-sided power spectral density of $N_0/2$, and $L(d)$ is the mean path-loss due to the transmitter-receiver (T-R) separation of $d$ meters.

For the links $S_j \rightarrow D$ and $R_k \rightarrow D$, we use the path-loss model suggested by WINNER II project [150] for the rural macro-cell (Scenario D1). For line-of-sight (LoS) conditions, it is given by,

$$L(d) = 40\log_{10}(d) + 10.5 - 18.5\log_{10}(h_{BS}) - 18.5\log_{10}(h_{MS}) + 1.5\log_{10}(f_c/5)$$

(4.7)
and, for non-line-of-sight (NLoS) conditions, it is given by,

\[
L(d) = 25.1 \log_{10}(d) + 55.4 - 0.13(h_{BS} - 25) \log_{10}(d/100) - 0.9(h_{MS} - 1.5) + 21.3 \log_{10}(f_c/5)
\]

(4.8)

where, \(d\) is the distance between the transmitter and the receiver in metres, \(h_{BS}\) and \(h_{MS}\) are the effective antenna heights at the base station and mobile terminals respectively and \(f_c\) is the carrier frequency in GHz.

The shadow fading standard deviation for a rural environment in WINNER II is presented according to LoS conditions. For LoS conditions, the standard deviation is considered to be 4 dB when \(10m < d < d_{BP}\) and 6 dB when \(d_{BP} < d < 10\) km. For NLoS conditions, the standard deviation is considered to be 8 dB. The \(d_{BP}\) is the breakpoint distance which is given by (\(f_c\) is the centre frequency in Hz in this equation and \(c\) is the speed of light in m/s),

\[
d_{BP} = 4h_{BS}h_{MS}f_c/c
\]

(4.9)

For the link \(S_j \rightarrow R_k\), we use the channel model presented in section 3.1 for device-to-device communications which was modelled as a log-distance path-loss model with varying path-loss exponents given by,

\[
L(d) = L(d_0) - 10\alpha \log_{10}\left(\frac{d}{d_0}\right)
\]

(4.10)

where, \(\alpha\) is the path-loss exponent, \(d\) is the distance in meters between the \(S_j\) and \(R_k\), and \(d_0\) is the reference distance and \(L(d_0)\) is the reference distance path-loss.

In all the links, we consider slow and fast fading channel modelled as a Rayleigh process whose mean channel power gains are given by,

\[
\overline{h^2} = \frac{1}{t} \int_0^t h^2(t)dt
\]

(4.11)

We assume context awareness at the nodes such that the above mentioned parameters such as T-R separations \(d\), the channel power levels \(\overline{h^2}\), the path-loss exponents \(\alpha\) are known to the respective nodes. Moreover, we assume decode-and-forward relaying protocol in our work. Note that the proposed model can be extended to any other cooperation protocol such as amplify-and-forward, etc.

We consider binary DPSK communication system with QoS constraints such as BER and data rate to illustrate the game models for the energy efficiency/coverage objective. The bit error rate probability under Rayleigh fading with AWGN, ignoring the subscripts, is

given by [123],

\[ \Pi = \frac{0.5}{1+\Gamma} \]  

(4.12)

where, \( \Gamma = \frac{E_b(h^2)}{N_0} \) is the average SNR, \( E_b \) is the bit energy given by \( E_b = \frac{P_t}{L(d)\Delta} \), and \( \Delta \) is the data rate of the respective links. Moreover, if we consider \( \Pi \) to be the overall bit error probability for the communication on \( S_j \rightarrow R_k \rightarrow D \) link, and \( \Pi_S \) and \( \Gamma_R \) are the BER for \( S_j \rightarrow R_k \) and \( R_k \rightarrow D \) links respectively, then

\[ \Pi = \Pi_R(1 - \Pi_S) + \Pi_S(1 - \Pi_R) \]

(4.13)

Ignoring \( 2\Pi_S\Pi_R \) as it is much less than \( \Pi_S \) and \( \Pi_R \), the overall BER becomes,

\[ \Pi = \Pi_S + \Pi_R \]

Energy Trading Game Model

We present the energy trading game for multiple source terminals and multiple relay terminals in which the relay terminals trade energy with the source terminals to increase the energy efficiency of the source terminals. The source nodes requiring cooperation broadcast their cooperation requests with the QoS constraints. The QoS constraints considered in this work include data rate and bit error rate probability. The relay terminals respond with their bids to the eNodeB. The eNodeB applies the game model and sends the results to the winning relay nodes which inform the source terminals.

We present the multi-source multi-relay first price sealed bid procurement auction model to improve energy efficiency at the source terminals. We define the game as \( G = < I, A, \Omega > \) where \( I \) is the set of players in the game such that \( |I| = N + K \), \( A \) is the Cartesian product of set of actions available to each player and \( \Omega = \Omega_{S_j}, \Omega_{R_k}, j = 1,2,...,N \) and \( k = 1,2,...,K \).

**Source Nodes:** The reward function \( \Omega_{S_j} \) of the source nodes is given by,

\[ \Omega_{S_j} = \Lambda E_d - C_{k,j} \]  

(4.14)

where \( \Lambda \) is the base cost in Dollars/Joule known to every node in the network, \( E_d \) is the energy required by the source terminal to directly communicate with the eNodeB for \( T_{CP} \) seconds and \( C_{k,j} \) is the cost to the source node \( S_j \) to cooperate with the relay node \( R_k \). Equation (4.14) can be intuitively understood as the reward obtained by the source nodes by sending their data to the destination through the relay node compared to sending it directly to the destination. Equation (4.14) can be further simplified to,

\[ \Omega_{S_j} = \Lambda P^d_{0,j} T_{CP} - C_{k,j} \]  

(4.15)

where, \( P_{0,j} \) is the power required to reach the eNodeB directly from the source terminal \( S_j \) to achieve the data rate \( \Delta S_j \) with BER \( \xi_j \), \( T_{CP} \) is the cooperation period in seconds. The cost \( C_{k,j} \) in equations (4.14) and (4.15) can be given as,

\[
C_{k,j} = \Lambda P_{k,j}^S T_{CP} + \gamma_{k,j} \tag{4.16}
\]

where, \( P_{k,j}^S \) is the power that needs to be transmitted by the source node \( S_j \) to relay \( R_k \) during the cooperation and \( \gamma_{k,j} \) is the payment that the source node \( S_j \) needs to pay relay node \( R_k \) for its cooperation.

The source node could utilize different strategies based upon its local policy such as minimizing its transmit power thus saving energy or minimizing the payment made to the relays thus saving money. For coverage improvement, we can fix the transmit power of the source terminal to maximum. However, for energy efficiency purposes, we do not restrict the source terminals’ transmit power. Thus, we consider the source nodes to minimize its cost \( C_{k,j} \), thus given by,

\[
\max_k \{ \Lambda P_{0,j}^T T_{CP} - C_{k,j} \}, \text{s.t.} (C_{k,j}) < \Lambda P_{0,j}^T T_{CP} \tag{4.17}
\]

Thus, the source nodes try to maximize their reward. However, if the cost of all relay nodes are higher than \( \Lambda P_{0,j}^T T_{CP} \) then the source node declines all bids as cooperation is deemed to be infeasible (more expensive than directly communicating with eNodeB).

**Relay Nodes:** We assume that all the relay nodes are aware of the source nodes’ strategy to select the relay nodes given by equation (4.17) i.e. to minimize cost. After receiving all the cooperation requests from the source nodes, the relay nodes: (i) calculate their bids to the source nodes, and (ii) select which source nodes to send their bids corresponding to their maximum transmit power constraint \( P_{R_{k,\text{max}}} \).

We first explain how the relay nodes calculate their bids. The bid sent by the relay node to a source node consists of a tuple given by \( \langle \hat{P}_{S_j}^R, \gamma_{k,j} \rangle \). To calculate the bid for each source node, the relay node minimizes equation (4.16) with respect to \( P_{k,j}^S \) in which \( \gamma_{k,j} \) is given by [83],

\[
\gamma_{k,j}(P_{S_j}^R) = \Lambda \kappa_{k,j} P_{R_{k,j}}^R (P_{k,j}^S) T_{CP} \tag{4.18}
\]

where, \( \kappa_{k,j} \) is the pricing index decided by the relay node \( R_k \) for source node \( S_j \) and \( P_{R_{k,j}}^R \) is the transmit power allocated by \( R_k \) to cooperate with source node \( S_j \) to reach the eNodeB with data rate constraint \( \Delta S_j \) and BER constraint \( \xi_j \). If the pricing index is 1, then the relay node just covers its cost that it incurs to cooperate with the source node. We explain the
selection process of $K_{k,j}$ in later sections. We can observe from equation (4.18) that $\gamma_{k,j}$ is a function of $P_{k,j}^S$ in the $S_j \rightarrow R_k$ link due to the BER constraint. Considering the BER expression given in equation (4.12), $P_{k,j}^R$ for a given $P_{k,j}^S$ can be expressed as,

$$P_{k,j}^R = \left( \frac{1}{2(\xi_j - 0.5)} \right) \frac{L(d_2)N_0\Delta S_j}{h_2^2}$$  \hspace{1cm} (4.19)$$

where, $h_2^2$ and $d_2$ are the channel power and T-R separation in meters respectively in the $R_k \rightarrow D$ link, and

$$\Gamma_1 = \frac{h_1^2 p_{k,j}^S}{L(d_2)N_0\Delta S_j}$$  \hspace{1cm} (4.20)$$

where, $h_1^2$ and $d_1$ are the channel power and T-R separation in meters respectively in the $S_j \rightarrow R_k$ link.

The function $C_{k,j}$ given by equation (4.16) is convex in $P_{k,j}^S$. Therefore, to minimize $C_{k,j}$ and find the stationary point, we perform,

$$\frac{dC_{k,j}}{dP_{k,j}^S} = 0$$  \hspace{1cm} (4.21)$$

Isolating $P_{k,j}^S$, we get the closed-form solution as,

$$P_{k,j}^S = \left[ \sqrt{\frac{0.25h_{k,j}L(d_2)h_2^2}{L(d_1)h_1^2}} + 0.5 \right] - 1 \frac{L(d_2)N_0\Delta S_j}{h_2^2}$$  \hspace{1cm} (4.22)$$

Therefore, each relay node calculates its $P_{k,j}^R$ from equation (4.19) and substitutes in equation (4.18) to calculate the bid that needs to be sent to the source nodes $<\hat{P}_{S_j}^R, \hat{\gamma}_{k,j}>$.

Now we explain how relay nodes select the source nodes that it responds to with a bid considering its transmit power constraint of $P_{k,max}^R$. For this, we start by defining the reward function of the relay nodes,

$$\Omega_{R_k} = \sum_j \Lambda(K_{k,j} - 1) P_{k,j}^R T_{CP} x_{k,j}$$  \hspace{1cm} (4.23)$$

where, $x_{k,j}$ is the indicator function which takes the value one if the relay node $R_k$ wins cooperation for source node $S_j$ and takes the value zero otherwise. The strategy for the relay nodes would be to maximize $\Omega_{R_k}$ given it’s transmit power constraint of $P_{k,max}^R$. Therefore,
the relay nodes perform binary integer programming to maximize $\Omega_{R_k}$ given the constraint of $P_{k,\text{max}}^R$. The problem can be formulated as,

\[
\begin{align*}
\text{Maximize :} & \quad \Omega_{R_k} \\
\text{Subject to :} & \quad (1) \sum_j P_{k,j}^R \leq P_{k,\text{max}}^R \\
& \quad (2) x_{k,j} \text{ is binary}
\end{align*}
\]

The indicator $x_{k,j}$ selects the source nodes for each relay node.

Now we explain how a relay node selects the value of $\kappa_{k,j}$ using reinforcement learning (RL). As mentioned before, we assume this game to be played every $T_{CP}$ seconds. During the initial round, every relay terminal $R_k$ chooses a random number between 1 and 2 uniformly for $\kappa_{k,j}$. During the subsequent rounds, the relay nodes can revise its bids based on the information of whether it wins or loses its previous round with the source node. By means of RL, the relay nodes can use this learning to maximize its rewards by changing the value of $\kappa_{k,j}$. Therefore, if $R_k$ wins cooperation with $S_j$ in the present round, it can safely assume that its $C_{k,j}$ is lower than its competing relay nodes with respect to $S_j$. Hence, it can increase its $\kappa_{k,j}$ to increase its reward which is given by,

\[
\kappa_{k,j}(t + 1) = \kappa_{k,j}(t) + \omega_k^+; \omega_k^+ \in \mathbb{R}^+
\]

The value of $\kappa_{k,j}$ is increased in a greedy manner in the subsequent games until it loses a game at which time it reduces its $\kappa_{k,j}$, which is described below, and sets its $\kappa_{k,j}^\text{max}$ value above which the relay node does no increase $\kappa_{k,j}$. In the same way, if $R_k$ loses cooperation with $S_j$ in the present round, it knows that its $C_{k,j}$ is higher than its competing relay nodes and hence it decreases its $\kappa_{k,j}$ to try and win the game which is given by,

\[
\kappa_{k,j}(t + 1) = \kappa_{k,j}(t) - \omega_k^-; \omega_k^- \in \mathbb{R}^-
\]

Note that no relay node reduces its value of $\kappa_{k,j}$ below one and $\kappa_{k,j}$ has a strict upper bound corresponding to the condition $C_{k,j} < \Lambda P_0$. Therefore, the energy trading game either converges towards the second price auction or towards the strict upper bound set by the condition $C_{k,j} < \Lambda P_0$. 

Double Auction Game Model

In this section, we present the double auction game for multiple source terminals and multiple relay terminals for the objective to improve energy efficiency. In a double auction, the source terminals send their bids to the eNodeB and the relay terminals send their asks to the eNodeB. The auctioneer then decides which source and relay terminals are the winners of cooperation, the price that the source terminals need to pay and the payments relay terminals receive.

We call the source terminals as buyers and the relay terminals as the seller. The buyers bid for the seller’s services and the sellers ask for the cost of the resources they spend to cooperate. In this work, we consider all terminals to employ power control such as the overall bit error rate from the source terminal to the eNodeB is maintained above $\xi_j$. The bids submitted by the buyers are calculated according to,

$$B_{S_j,R_k} = \Lambda (P_{0,j}^t - P_{k,j}^S) T_{CP} (1 - \lambda_j)$$

(4.27)

where, $\Lambda$ is the base cost in Dollars/Joule known to every node in the network, $P_{0,j}^t$ is the power required to directly communicate with the eNodeB, $P_{k,j}^S$ is the power required to communicate with the relay terminal $R_k$, $T_{CP}$ is the cooperation period in seconds and $\lambda_j$ is a uniform random number between 0 and 1 which is called as the "mark-up". The asks submitted by the relay terminals are calculated according to,

$$A_{S_j,R_k} = \Lambda P_{k,j}^R T_{CP} (1 - H_k)$$

(4.28)

where, $\Lambda$ is the base cost in Dollars/Joule known to every node in the network, $P_{k,j}^R$ is the power transmitted by the relay terminal to communicate with the eNodeB and $H_k$ is a uniform random number between 0 and 1 called as "mark-up".

After receiving all the bids and asks from the source and relay terminals respectively, the eNodeB performs relay assignment algorithm which is described below. The problem of relay assignment in this case could be formulated as a linear programming problem given
as,

$$\text{Maximize :} EE$$

Subject to:

$$\sum_{j} p_{k,j}^{R} \leq p_{k,\text{max}}$$  \hspace{1cm} (4.29)$$

1) $$x_{k,j}$$ is binary

3) $$\sum_{k} x_{k,j} \leq 1$$

4) $$B_{S_j,R_k} \geq A_{S_j,R_k}$$  \hspace{1cm} (4.30)$$

where, $$x_{k,j}$$ is the indicator function and we define EE as the global energy efficiency given by,

$$EE = \sum_{j} \sum_{k} \frac{\Delta_{S_j}}{(p_{k,j}^{S} + p_{k,j}^{R})T_{CP}x_{k,j}}$$  \hspace{1cm} (4.31)$$

The unit of EE is bits/Joule. In the relay assignment, we allow a relay terminal to support multiple source terminals respecting the maximum transmit power constraint at the relay terminal which is embodied in the constraint (1) given in equation (4.29). However, we do not allow the source terminals to receive cooperation from multiple relay terminals which is embodied in the constraint (3) given in equation (4.29). Also, a relay terminal is assigned to a source terminal only if the bid submitted by the source terminal is greater than or equal to the ask submitted by the relay terminal which is embodied in the constraint (4) given in equation (4.29). After the relay assignment, the price to be traded is calculated using,

$$TP_{S_j,R_k} = \frac{B_{S_j,R_k} + A_{S_j,R_k}}{2}$$  \hspace{1cm} (4.32)$$

In this case, we do not consider optimal power allocation with respect the overall bit error rate probability between the source and the relay terminal. The bit error rate probability given by equation (4.13) is split equally between $$\Pi_1$$ and $$\Pi_2$$.

Centralized Algorithm

In this section, we present the centralized algorithm in which the source terminals and relay terminals are assumed to send their true valuations and costs associated with cooperation to the eNodeB. The eNodeB then allocates the optimal relay assignment such that the energy efficiency is improved. The optimal relay assignment problem is formulated as a linear
programming problem given by,

\[
\text{Maximize : } EE \\
\text{Subject to : }
\begin{align*}
(1) \sum_j P_{R,k,j} & \leq P_{R,k,\text{max}} \\
(2) x_{k,j} & \text{ is binary} \\
(3) \sum_k x_{k,j} & \leq 1
\end{align*}
\]

We use the same definition for EE as described in equation (4.31). The linear programming problem is same as the one given in equation (4.29) except in this case we do not have the bids and asks constraint. Moreover, in this centralized algorithm case, we consider optimal power allocation in addition to the optimal relay assignment.

**Game Model Simulation Results**

In this section, we perform simulations to compare the two game models described above with the centralized algorithm. For the simulations, we use the same definition for global energy efficiency given by equation (4.31). Furthermore, to compare the two game models with the centralized algorithm we define \( \theta \) as the normalized energy efficiency given by,

\[
\theta = 1 - \frac{\text{Energy spent with Relaying}}{\text{Energy spent without Relaying}}
\]

We performed monte-carlo simulations of 100 different scenarios with different terminal locations and different channel realizations. Table 4.2 lists all the parameters used in the simulations.

Figure 4.16 shows the cumulative distribution function which compares the performance of the energy trading game, double auction and centralized algorithms for the improvement of energy efficiency. From the figure, we can observe that centralized algorithm performs the best as expected. The energy trading game performs very close to the centralized algorithm. The double auction however does not perform as good as the energy trading game. This is due to the non-optimal power allocation between the source and the relay terminals with respect to the overall bit error rate probability which is due to the fact that the knowledge of the links between the source and the relay terminals is not present at the eNodeB in a double auction game. Therefore, if this knowledge is assumed and if we assume truthfulness in the bids and asks in a double auction, the performance of the double auction game will approach the performance of the centralized mechanism.
Table 4.2 Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$p_{k,\text{max}}^R$</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.8 GHz</td>
</tr>
<tr>
<td>$N_0$</td>
<td>-163 dBm/Hz</td>
</tr>
<tr>
<td>$h_{BS}$</td>
<td>30 m</td>
</tr>
<tr>
<td>$h_{MS}$</td>
<td>1.5 m</td>
</tr>
<tr>
<td>$\Delta S_j$</td>
<td>400 kbps</td>
</tr>
<tr>
<td>$\omega_k^+$</td>
<td>4</td>
</tr>
<tr>
<td>$\omega_k^-$</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1</td>
</tr>
<tr>
<td>$T_{CP}$</td>
<td>1 sec</td>
</tr>
<tr>
<td>$N$</td>
<td>4 terminals</td>
</tr>
<tr>
<td>$K$</td>
<td>6 terminals</td>
</tr>
</tbody>
</table>

Fig. 4.16 Performance comparison between energy trading game, double auction and centralized algorithm for energy efficiency.

4.2.3 System Level Simulations

To prove the efficacy of the proposed game model and terminal cooperation to improve coverage in regional access networks, we run system level simulations with LTE technology on the link between the relay node and the eNodeB and WiFi technology on the link between the relay node and the source node.
To facilitate the game model and terminal cooperation, we introduce a novel application layer module in LTE and WiFi technologies called TCOOP. The protocol architecture for terminal cooperation using LTE and Wi-Fi technologies is shown in figure 4.17. The TCOOP (Terminal Cooperation Application Protocol) inside the APP layer in the source terminal, relay terminals and the eNodeB enables terminal cooperation. In our work, we implement the terminal cooperation in two phases namely, (i) Game-Theoretic Relay Selection and (ii) Data Communications.

In this architecture, Wi-Fi Ad-hoc or IBSS mode is used for device-to-device communications between the source terminal and the relay terminal and LTE is used between the relay terminal and the eNodeB. Figure 4.18 shows the signalling architecture for terminal cooperation.

**Phase 1: Game-Theoretic Relay Selection** In this phase, the source terminal is paired up with relay terminals using the Wi-Fi interface and the LTE interface. The protocol design follows the same procedures as shown in figure 4.18 in which the relay terminals form an IBSS in Wi-Fi Ad-hoc mode. This phase starts with the relay terminals forming an IBSS. The relay terminal initially searches for any IBSS in the vicinity. If found, it joins the
IBSS or it creates its own IBSS by sending beacons which other relay terminals can join. The source terminal which requires cooperation joins the IBSS using standardized Wi-Fi procedures and broadcasts a cooperation request packet. It is noteworthy that if multiple IBSSs are present the source terminal will join the IBSS with the highest RSSI. The relay terminals participating in the game send their bid packet along with the source MAC ID to the eNodeB. The eNodeB decides on the winning relay terminal and sends the result packet to the relay terminals. The source terminal is notified by the winning terminal and it starts the data communication flow.

**Phase 2: Data Communications** After Phase 1, the data communications start between the source terminal and the relay terminal on the Wi-Fi interface and between the relay terminal and eNodeB on the LTE interface.

**Packet Structure**

In this section, we present the structure of the packets that are introduced to enable terminal cooperation. In this work, we keep the structure of the packets in the relay selection phase generic enough that newer game models can be accommodated and we show examples with regards to the energy trading game. The generic structure of the packet during relay selection phase sent by TCOOP is shown in figure 4.19. The packet type field identifies the type of the packet being sent which is of 4 bits accommodating 15 packet types. The data payload is of $N$ bits depending on the type of the packet. It is noteworthy that this packet size is at the application layer. Additional headers added by the lower layers will add to the overhead cost of the packet being sent.

We now provide an example packet structure and packet types that will be used for the energy trading game detailed in section 4.2.2. As explained previously, the source terminal broadcasts a cooperation request packet to the relay terminals. The relay terminals send their bid packets to the eNodeB which then replies with the result packet, therefore allowing the source terminals to send their data using app packets. Figure 4.20 shows the packet structure of all the packets mentioned above. Bid Packet Type 1 is sent by the relay terminal which started the IBSS to the eNodeB whereas all other relay terminals send Bid Packet Type 2. These packets are used in the simulations to verify the protocol design on a system.
level simulator.

**Results**

To provide proof of concept for coverage improvement using terminal cooperation, we have considered four different scenarios.

**Scenario 1 - with one fixed position relay node:** In this scenario, the simulation is first run for scenario shown in figure 4.21 using LTE. Each of the source node is then checked whether it could achieve a certain data rate threshold. If a source node could achieve it, it is left with its LTE module. However, the source nodes which are not able to achieve the required data rate are reinstalled with WiFi module and their LTE module is deleted. Additionally, one relay node is added for each such source node at a distance of \(d_{\text{relay}}\) metres from the source node where \(d_{\text{relay}}\) is fixed. Also, the relay node is placed in such a way that it is in between the eNodeB and the source node. This is shown in figure 4.22. Then the simulation is run with the game model.

Fig. 4.22 Scenario-1 with one fixed position relay node.

Fig. 4.23 Comparison of Success Probabilities in Uplink between no terminal cooperation and with terminal cooperation in the scenario with one fixed position relay node.

Figure 4.23 shows the comparison between the success probabilities achieved in the uplink with and without terminal cooperation with respect to this scenario for different radii. It can be clearly observed that terminal cooperation improves the success probability of the nodes in the uplink significantly.

Figure 4.24 shows the comparison between the success probabilities achieved in the downlink with and without terminal cooperation with respect to this scenario for different radii. It can be clearly observed that terminal cooperation improves the success probability of the nodes in the downlink significantly.

Scenario 2 - with one random position relay node: In this scenario, the simulation is first run for scenario shown in figure 4.21 using LTE. Each of the source nodes is then checked whether it could achieve a certain data rate threshold. If a source node could achieve it, it is left with its LTE module. However, the source nodes which are not able to achieve

the required data rate are reinstalled with WiFi module and their LTE module is deleted. Additionally, one relay node is added for each such source node at a distance of \(d_{\text{relay}}\) metres where \(d_{\text{relay}}\) is considered as a uniform random variable ranging \([0, d_{\text{relay max}}]\). This is shown in figure 4.22. Then the simulation is run with the game model.

Figure 4.25 and 4.26 shows the comparison of success probabilities in uplink and downlink respectively between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the scenario with one random position relay node. We can observe that there is not much difference in the success probabilities between the one fixed position relay node scenario and with one random position relay node scenario in both the cases of uplink and downlink.

**Scenario 3 - with five fixed position relay nodes and Game Theory:** Like scenario 2 presented in the previous section, the simulation is first run for scenario shown in figure 4.21 using LTE. Each of the source nodes is then checked whether it could achieve a certain data rate threshold. If a source node could achieve it, it is left with its LTE module. However, the source nodes which are not able to achieve the required data rate are reinstalled with WiFi module and their LTE module is deleted. Additionally, five relay nodes are added for each such source node at a fixed distance of \(d_{\text{relay}}\) metres as shown in figure 4.27. Then the simulation is run with the game model.

Figure 4.28 and 4.29 shows the comparison of success probabilities in uplink and downlink respectively between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the sce-

Fig. 4.25 Comparison of Success Probabilities in Uplink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the scenario with one random position relay node.

Fig. 4.26 Comparison of Success Probabilities in Downlink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the scenario with one random position relay node.

Scenario 4 - with a specific use-case from a regional blackspot in Australia: In

Fig. 4.27 Scenario-3 with five fixed position relay nodes.

Fig. 4.28 Comparison of Success Probabilities in Uplink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the scenario with five fixed position relay nodes with game theory.

In this scenario, we use the exact use-case of South-West Gippsland, Victoria, Australia in our simulations. We arbitrarily place eNodeB at different positions near to the use-case area to investigate the performance of terminal cooperation.

Figure 4.30 shows the use-case with terminals distributed across the area. In the figures, the image has been resized to scale so that it corresponds to the distance on the ground in metres. The terminal distribution has been performed randomly on the circles shown in the figure using MATLAB. The four figures show different positions of eNodeB used for the simulations.

For each eNodeB position, the source nodes are checked whether it can achieve a certain data-rate threshold. If a source node could achieve it, it is left with its LTE module. How-
Fig. 4.29 Comparison of Success Probabilities in Downlink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with one fixed position relay node and (iii) with terminal cooperation in the scenario with five fixed position relay nodes with game theory.

Fig. 4.30 Scenario-4 with South-West Gippsland use-case.

ever, the source nodes which are not able to achieve the required data rate are reinstalled with WiFi module and their LTE module is deleted. Additionally, one relay node is added for each such source node at a distance of $d_{\text{relay}}$ metres from the source node where $d_{\text{relay}}$ is

Fig. 4.31 Comparison of Success Probabilities in Uplink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with a specific use-case.

Fig. 4.32 Comparison of Success Probabilities in Downlink between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with a specific use-case.

considered as a uniform random variable ranging \([0, d_{\text{relay_{\text{max}}}}]\).

Figures 4.31 and 4.32 shows the comparison of success probabilities in uplink and downlink respectively between (i) no terminal cooperation, (ii) with terminal cooperation in the scenario with a specific use-case. We can observe from the figures that the increase in success probability depends on where the eNodeB is placed i.e. the location of the eNodeB.
4.3 Chapter Summary

In this chapter we addressed research question 2 through two key contributions. Firstly, we evaluated the performance of two vastly different technologies, LTE and WiFi, in aerial access networks by performing ray tracing simulations and system level simulations considering a practical scenario in Melbourne, Australia. Secondly, we developed and proposed game-theoretic algorithms to enhance the coverage performance in regional access networks. We verified and validated the proposed algorithms using system level simulations.
Chapter 5

Energy Efficiency Enhancement using Terminal Cooperation

Energy efficiency of the mobile terminals is one of the key requirements for the next-generation wireless communication networks. While considering public-safety networks, energy efficiency of mobile terminals carried by emergency personnel is eminent in the context of disaster relief operations. With the advancement of smart phones, commercial cellular networks also treasure energy efficiency to save battery power and extend the lifetime of a single battery charge of the mobile terminal. Newer architectures such as aerial access network bring in newer challenges with respect to energy efficiency which needs to be addressed with novel techniques such as clustering. This chapter addresses research question 3 through three key contributions: (i) proposing a novel clustering algorithm to reduce energy consumption of mobile terminals in aerial networks in section 5.1, (ii) optimizing cluster head spacing in aerial networks in section 5.2 and (iii) improving energy efficiency in aerial networks using Matern Point Processes in section 5.3. We would like to note that in all of the works presented in this chapter we consider only the transmission energy costs at the aerial platform and omit the energy costs of keeping the aerial platform in the air.

This chapter is based on the following publications contributing towards sections 5.1, 5.2 and 5.3:


2. A. Al-Hourani, S. Chandrasekharan, A. Jamalipour, L. Reynaud and S. Kandeepan, "Optimal Cluster Head Spacing for Energy-Efficient Communication in
Aerial-Backhauled Networks", *IEEE Global Communications Conference (GLOBECOM)*, San Diego, 2015.


### 5.1 EECAN: Energy Efficient Clustering for Aerial Networks

Hybrid Aerial-Terrestrial network based on Low Altitude Platforms (LAP) provides an excellent method to rapidly deploy flexible communications infrastructure during large-scale emergency and public events. In such situations, it is of utmost importance to extend the lifetime of the battery operated hand-held devices serving on the ground. In this work, we propose a novel clustering technique to improve the energy efficiency of the hybrid aerial-terrestrial network under uncertain channel conditions on the ground. The proposed technique is analysed by means of simulations and the results are compared with well-known clustering algorithms. The results show that the proposed clustering mechanism significantly improves the energy efficiency of the network under certain conditions.

#### 5.1.1 Network Model

The network consists of a set of $N$ terrestrial nodes with the same antenna gains where $|N| \in \mathbb{N}$ is the total number of terrestrial nodes. We use the index $i$ or $j$ for representing a terrestrial node, particularly $i$ for representing cluster member nodes and $j$ for cluster head node, and use the index 0 for representing the LAP base station. The terrestrial nodes are divided into a set of clusters defined by $C$, where $|C| \in \mathbb{N}$ corresponds to the total number of clusters. Each cluster includes a cluster head (CH) and a number of cluster members (CM) denoted by $N_C^j$ corresponding to the $j^{th}$ cluster in the cluster set $C$. The CH communicates with the LAP directly and the CMs communicate with the CH, in other words, the CH becomes the access terminal for the CMs to communicate with the LAP. The terrestrial communication between CMs and the CH uses non-persistent CSMA random access [151] and the aerial communication between CH and the LAP uses time division multiple access. We assume all nodes to be equipped with multiple radios for simultaneous communication between terrestrial nodes and LAP.
Figure 5.1 shows the considered network model. Moreover, we define the following communication parameters between two terrestrial nodes $i$ and $j$. The distance in meters is denoted by $d_{ij}$, $h_{ij}$ is the slow fading random wireless channel envelope, $\alpha_{ij}$ is the path loss exponent and $L_{ij}$ is the mean path loss. Note that the index $j$ is substituted by index 0 in the above parameters to denote the parameters between any terrestrial node and the LAP. We also assume that the reverse links have the same communication parameters when the node indices $i$ and $j$ are swapped over. The log distance path loss model [123] is given by

$$
\bar{L}(d) = L(\bar{d}) \left( \frac{d}{\bar{d}} \right)^\alpha 
$$

where $L(\bar{d})$ is the free space path loss at a close-in reference distance $\bar{d}$ and $\alpha$ is the path loss exponent.

The small scale fading ($h_{0i}$) for the aerial wireless links between the terrestrial nodes and the LAP is modeled by a Ricean fading channel and the terrestrial wireless links between the nodes is modeled by log normal shadowing [123]. We consider binary phase shift keying modulation for terrestrial as well as aerial links. We also assume context awareness at the LAP in which the nodes periodically report their location, the transmission energy used by the node during the previous clustering cycle and their residual battery energy $\varepsilon_i$ to the LAP. During the report transmissions all the terrestrial nodes transmit (i) with a constant known power allowing the LAP to differentiate between the channel gains/loss in the aerial links to select the CHs and (ii) their locations which allows the LAP to estimate the T-R separations ($d_{ij}, d_{i0}$) to select the CMs. Note that the path loss exponents for the terrestrial wireless links $\alpha_{ij}$ are unknown to the LAP. We also consider the channel as a slow varying channel such that the channel conditions do not change over a period of multiple reports.

The network uses the decode and forward strategy where the CHs relay the information
from CMs to the LAP. In our relaying approach, we also perform power controlling to meet a particular bit error rate target at the destination as described in [1]. Based on the power controlling method, the $i^{th}$ CM will have its own transmit power $P_{iT}^i$ to transmit to the CH, and the $j^{th}$ CH will have its own transmit power $P_{jA}^j$ to the LAP. We also define the power required to receive the signal at a receiver as $P_{rcv}$ which is assumed to be the same across all the terminals in the network.

5.1.2 Energy Consumption Analysis

In this section, we describe the transmission energy cost model of the network. The total transmission energy consumed by the network over a single cycle is given by,

$$E = E_T + E_A + E_{OH}$$

(5.2)

where $E_T$ is the total transmission energy consumed in the terrestrial network (for communications between CH and CMs), $E_A$ is the total transmission energy consumed in the aerial network (for communications between CHs and LAP) to transmit $N_i^b$ bits per terrestrial node at a data rate of $\Delta$ and $E_{OH}$ is the total overhead energy consumed in the network for the "report packet" transmissions by all the terrestrial nodes which is given by,

$$E_{OH} = \frac{1}{\Delta} N_R (P_{rep} + P_{rcv}) N$$

(5.3)

where $N_R$ is the size of "report packets" in bits, $P_{rep}$ is the constant transmit power used by all nodes for report packets and $P_{rcv}$ is the power required to receive the report packet at the LAP. To simplify our analysis, we assume $N_i^b = N_b$ that is the same number of bits are transmitted from all the terrestrial nodes. The total transmission energy $E_T$ for all the terrestrial links is given by,

$$E_T = \sum_{i \in \{N \setminus C\}} \left[ \frac{1}{\Delta} (P_{iT}^i + P_{rcv}) N_b \right]$$

$$= \frac{N_b}{\Delta} (|N| - |C|) P_{rcv} + \frac{N_b}{\Delta} \sum_{i \in \{N \setminus C\}} P_{iT}^i$$

(5.4)

where, the first term in the second line of equation (5.4) corresponds to the total energy for receiving the information from the CMs at the CHs, and the second term with the summation corresponds to the total energy required to transmit the information at the respective CM
5. Energy Efficiency Enhancement using Terminal Cooperation

node. The total transmission energy $E_A$ for all the aerial links is given by,

$$E_A = \sum_{j \in C} \left[ \frac{1}{\Delta} (P_{t,A}^j + P_{rcv}^j) N_b (1 + N_j^c) \right]$$

$$= \frac{N_b}{\Delta} \left[ \sum_{j \in C} P_{t,A}^j + \sum_{j \in C} P_{t,A}^j N_j^c + |N| P_{rcv} \right]$$  \hspace{1cm} (5.5)$$

where, the first term in the second line of equation (5.5) corresponds to the total energy for transmitting data from all the CHs, the second term corresponds to the total energy for relaying the data from all the CMs and the last term corresponds to the energy required to receive the data at the LAP from all the CHs. Using equations (5.4) and (5.5), equation (5.2) becomes,

$$E = E_{OH} + \frac{N_b}{\Delta} (2|N| - |C|) P_{rcv}$$

$$+ \frac{N_b}{\Delta} \left[ \sum_{j \in \{N \setminus C\}} P_{t,T}^j + \sum_{j \in C} P_{t,A}^j (1 + N_j^c) \right]$$  \hspace{1cm} (5.6)$$

The above equation can be used to verify the energy consumption for the no clustering scenario by letting $C = N$, $N_j^c = 0$ and $E_{OH} = 0$ and therefore, the energy consumption for the no clustering scenario from equation (5.6) is given by,

$$\bar{E} = \frac{N_b}{\Delta} \left[ (|N|) P_{rcv} + \sum_{j \in N} P_{t,A}^j \right]$$  \hspace{1cm} (5.7)$$

5.1.3 Energy Efficient Clustering

In this section, we propose an energy-efficient clustering mechanism. Optimal clustering can be performed based on the equations derived in (5.6) and (5.7). When the LAP possesses complete knowledge of the environment and is aware of all radio link parameters including the propagation channels for both terrestrial and aerial links then the optimum clustering criteria (for selecting the optimal clusters) becomes,

$$\hat{C} = \arg \min_C \{E: E < \bar{E} \}$$  \hspace{1cm} (5.8)$$

Note that when $E \geq \bar{E}$, there is no need for clustering as the direct transmission with no clustering is deemed to be more energy efficient than the clustering scenario. However, having the complete knowledge of the environment and all radio link parameters is not
feasible for the LAP. Therefore, we present the clustering mechanism with an expected value for $\alpha_{ij}$ as described further below.

In the above sections, we have assumed that nodes periodically update the context information to the LAP. The clustering mechanism starts with all the terrestrial nodes reporting their location, the transmission energy spent during the previous clustering cycle and residual energy to the LAP. The LAP groups the nodes into clusters by selecting the CHs and their corresponding CMs as described below. We keep two sets of nodes during the clustering process namely; (1) processing set which holds all the nodes that have not yet been clustered and (2) cluster set which holds the nodes that have already been clustered. Moreover, we also define the following in our work:

- $N_c^\text{max}$ is the maximum number of CMs per cluster
- $R_c^\text{max}$ is the maximum radius of a cluster

$N_c^\text{max}$ is chosen apriori such that the probability of a successful packet transmission is above a pre-defined value. The probability of a successful packet transmission without collision in a non-persistent CSMA channel is given by $e^{-aG}$[151], where $a$ is the ratio between maximum propagation delay and packet transmission time, and $G$ is the offered traffic for a given cluster. With these definitions, we provide EE-CAN.

The clustering is centralized at the LAP with two phases. In Phase I, the verification of clustering as the most energy efficient approach is performed. In Phase II, the CHs and their corresponding CMs are identified. During the first cycle of clustering in Phase-I, the terrestrial nodes will report $E_{\text{prev}}$ as zero and therefore, LAP will consider clustering as the most energy efficient approach. In Phase-II, the total energy consumption is estimated $E_{\text{est}}$ using equation (5.6) for the current round for a range of $R_c^\text{max}$, where the range of $R_c^\text{max}$ is $[0, M]$ and $M$ is the dimension in metres of the considered area $M \times M$. The $R_c^\text{max}$ that consumes the least energy in the estimation is selected to perform clustering. To perform the energy estimation using equation (5.6), the LAP uses an expected value for $\alpha_{ij}$ which can be known priori for different geographical regions [123] such as dense-urban, urban, suburban, rural, etc.

The clusters are reassigned by LAP periodically. In dynamic scenarios with mobile terrestrial nodes, the frequency of reclustering needs to be increased to accommodate the variation of channel parameters over time. It should be noted that higher frequency of reclustering will increase $E_{\text{OH}}$ but as long as Phase-I Step-3 is satisfied, EE-CAN will be feasible. In this work, we only consider a single clustering cycle and static terrestrial nodes and propose the clustering mechanism.
Energy Efficient Clustering in Aerial-Terrestrial Network

**PHASE I - Verification Phase**

**Step-1:** All terrestrial nodes report their location, transmission energy used during the previous cycle $E_{i}^{\text{prev}}$ and residual energy $\varepsilon_{i}$ to the LAP.

**Step-2:** The LAP calculates $E$ and $\overline{E}$ where $E$ is the summation of $E_{i}^{\text{prev}}$ for all terrestrial nodes.

**Step-3:** If $E < \overline{E}$, the LAP continues with Phase II, if not, the LAP skips Phase II and continues with the no clustering scenario in which the terrestrial nodes use direct links to communicate with the LAP.

**PHASE II - Clustering Phase**

For : $R_{c}^{\text{max}} = 0$ to $M$

Begin While (processing set is NOT NULL)

**Step-1:** Select the node from the processing set that has the highest received power at the LAP.

**Step-2:** Check if the residual energy $\varepsilon_{i}$ of the selected node is greater than or equal to the median residual energy of the set of nodes within the processing set.

**Step-3:** If step-2 is true, assign the node as a CH and proceed to step-4, if not then select the node with the next highest received power at the LAP from the processing set and loop to step-2.

**Step-4:** From the processing set, assign the nearest nodes from the CH as CMs to this cluster up to $N_{c}$, where $N_{c} = \min(N_{R_{c}^{\text{max}}}, N_{c}^{\text{max}})$ and $N_{R_{c}^{\text{max}}}$ is the number of nodes within the maximum cluster radius $R_{c}^{\text{max}}$ from the CH.

**Step-5:** Remove nodes selected as the CH and CMs from the processing set and assign them to the cluster set.

End While

**Step-6:** Calculate $E_{\text{est}}$ using known $\alpha_{i0}$ and the expected value for $\alpha_{ij}$ for a given geographical area, using (5.6). 

End For

**Step-7:** Use the cluster set with the least $E_{\text{est}}$.

### 5.1.4 Simulation Results

The hybrid aerial-terrestrial network was simulated in the OMNET++ network simulator. The simulation and transmission parameters have been adopted from Table I in [1] except those mentioned subsequently. The area considered is $600m \times 600m$, the total number of traffic packets is 1000 and the number of terrestrial nodes $N$ used for all simulations is 100. The target BER at the LAP considered is $10^{-6}$. The path loss exponent $\alpha$ was randomly assigned within the range specified in [1] such that closely spaced terminals will have lesser variation in $\alpha$ than distant terminals. The size of the report packets sent by each terrestrial
node is considered to be 64 bytes. Therefore using equation (5.3), $E_{OH}$ can be calculated which is far less than the energy savings obtained by clustering, as shown in the results. The simulations were performed to study the energy consumption at the terrestrial nodes by comparing no-clustering, LEACH, LEACH-C, HEED, EECS, BCDCP and Algo1 with EE-CAN. In our work, the multihop inter-cluster communication is not considered in HEED and BCDCP. In other words, we consider only one hop communication in this work (CM->CH->Destination). The CHs directly communicate with the LAP. For a fair comparison, the throughput of the network was kept above 95% for all simulations where throughput is calculated as the percentage of error-free packets received at the LAP to the total packets sent by all terrestrial nodes. $N_{max}^c$ is chosen as 20 such that the probability of successful transmission of a packet in the terrestrial random access network is 0.98 ($a=0.625, G=0.032$).

Figure 5.2 represents comparison of energy consumption at the terrestrial nodes between no clustering case which uses the power control mechanism and clustering with EE-CAN w.r.t. LAP altitude $d_0$ for various Rice factors $K$. From the figure, it can be observed that the energy consumption is lower in all cases when clustering with EE-CAN is performed and the energy savings are significant enough compared to the total overhead energy $E_{OH}$. The proposed EE-CAN was compared with LEACH, LEACH-C, HEED, EECS, BCDCP and Algo1. It should be noted that the $k_{opt}$ [93] value used to determine the number of CHs for LEACH, LEACH-C, EECS and BCDCP techniques in our case was adopted to the channel models presented in this work. The channel models adopted by [93] were free space for the intra-cluster and $d^4$ pathloss for the cluster head to sink communications. However, in
5. Energy Efficiency Enhancement using Terminal Cooperation

Fig. 5.3 Total energy consumption w.r.t the LAP altitude $d_0$, for LEACH, LEACH-C, HEED, EECS, BCDCP, Algo1 and EE-CAN with $K = 2$dB.

Fig. 5.4 Total energy consumption w.r.t the LAP altitude $d_0$, for LEACH, LEACH-C, HEED, EECS, BCDCP, Algo1 and EE-CAN, with $K = 8$dB.

In order to understand the effect of $R_{c}^{\text{max}}$ in EE-CAN, we disabled the energy estimation in EE-CAN and fixed the $R_{c}^{\text{max}}$. Figure 5.5 depicts the total energy consumption of EE-
5. Energy Efficiency Enhancement using Terminal Cooperation

Fig. 5.5 Total energy consumption w.r.t the maximum cluster radius $R_{c}^{\text{max}}$, for HEED and EE-CAN, with $K = 2\text{dB}$, and LAP altitude $d_0 = 1500\text{m}$.

CAN and HEED with respect to $R_{c}^{\text{max}}$. From the figure, we can observe that there is an optimal $R_{c}^{\text{max}}$ for highest energy efficiency in EE-CAN. However, due to the random node distribution and channel variation over a given area, it is very challenging to mathematically optimize $R_{c}^{\text{max}}$. Hence, an approach to estimate energy is used in EE-CAN for a range of $R_{c}^{\text{max}}$ and the $R_{c}^{\text{max}}$ with least energy consumption is selected.

5.2 Optimal Cluster-Head Spacing in Aerial Network

We have seen clustering to be extremely effective in improving the energy efficiency in an aerial network. In this work, we propose a novel analytic approach in clustering terrestrial wireless nodes which are provided coverage by an aerial platform. We propose a novel cluster-head selection algorithm based on Matern hard-core process [111] and we obtain an analytical formula to optimize the spacing between the cluster heads to minimize the overall energy consumption of the energy-constrained terrestrial nodes. The formulated problem utilizes stochastic geometry to capture the random nature of the locations of the deployed nodes, leading to a tractable analysis of the expected network metrics. Furthermore, we compare the performance of our approach with other well-known clustering algorithms, showing the improvement in energy efficiency. A brief overview of stochastic geometry is presented in section 2.2.2.

1LEACH, LEACH-C, EECS and BCDCP do not have the concept of maximum cluster radius according to their respective models. Hence, they have not been included in the comparison in figure 5.5.
The main contributions of this work include:

- It provides a practical realization to utilize Matern hardcore process in order to deploy CHs in a regularized manner.
- It provides a novel mathematical model for representing the energy consumption for both Matern and randomly clustered networks (such as LEACH) underlying aerial platforms.
- It provides an analytically tractable approach for optimizing the minimum spacing between CHs, in order to maximize the energy saving.
- It provides a tight approximation of the contact distance distribution in Matern hardcore process.
- It provides Monte-Carlo simulation to verify the presented analytical approach.

5.2.1 Network Model

We consider an aerial network, where an aerial base station is providing coverage in a certain geographical area. Terrestrial nodes are deployed in a random and homogeneous manner within this geographical area. We assume that all traffic should be either routed onboard or forwarded to further destination(s) via the aerial platform. This assumption is applicable when the majority of traffic is either server-client type or an off-site destination type. We also assume that the terrestrial nodes are capable of forming direct links with each other, where some nodes are selected to play the role of a decode-and-forward relay station, thus serving the remaining nodes, by receiving and aggregating their information-payload, and then uploading it towards the aerial platform. The whole scenario is depicted in figure 5.6 showing the layout of the proposed aerial-backhauled network. Each CH is responsible of serving a certain area called a cluster.

As stated previously the terrestrial nodes are assumed to be randomly and homogeneously distributed, where we study a temporal snapshot of the network assuming nodes to be stationary, thus following a stationary Poisson Point Process (PPP). The intensity of this process is denoted as $\lambda$, and accordingly the intensities of the CHs and the CMs are denoted as $\lambda_c$ and $\lambda_m$ respectively, where $\lambda = \lambda_c + \lambda_m$.

CMs will associate to the closest CH, that is because the closest CH provides the highest average signal power. This scheme inherently divides the plane into randomly shaped clusters called Voronoi tessellation, with the cluster heads acting as seed points in this tessella-
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Fig. 5.6 An aerial network with Matern clustering.

Fig. 5.7 Voronoi Tessellation Concept showing cluster heads and cluster members.

...tion. We illustrate the concept of Voronoi clustering in figure 5.7 showing the boundaries of the cluster regions and the associated cluster members. Noting that the minimum allowable spacing between the cluster heads (denoted as $\delta$), is yet to be optimized.
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5.2.2 Clustering Algorithm

Cluster-head Selection

Our motivation is to increase the geometrical regularity in the CHs selection by defining a minimum spacing $\delta$ between any two given CHs. We start by allocating a uniformly distributed random mark $t \sim \mathcal{U}(0, 1)$ to all nodes in the network. After that, every node broadcasts its mark to other neighboring nodes in the circular zone having a radius of at least $\delta$. It is important to note that the parameter $\delta$ is assigned by a supervisory mechanism (e.g. by the aerial platform), while the formula for calculating the best $\delta$, which is one of the major contributions of this work, is yet to be illustrated in the upcoming sections.

After conducting the broadcasting phase, every node compares its own mark to all other detectable nodes. If a node has the lowest mark, then it is flagged as a CH. When all nodes perform this kind of comparison, all non-CH nodes will become CMs. The set of CHs is denoted by $\Phi_c$, while the set of cluster members is denoted by $\Phi_m$. We illustrate the CH selection algorithm in Algorithm 1, detailing the actual process in a wireless network, where the operator $|x - y|$ represents the Euclidean distance between points $x$ and $y$. This method of assigning the role of CHs is equivalent to Matern Hard-Core Process of type II (MHC), and it is described as [111]:

$$\Phi_c \triangleq \{x \in \Phi : \mathcal{M}(x) < \mathcal{M}(y) \forall y \in \Phi \cap b(x, \delta) \setminus \{x\}\},$$

(5.9)

where $\mathcal{M}(x)$ represents the mark of point $x$, $b(x; \delta)$ is a ball centered at $x$ having a radius of $\delta$, and $\Phi$ is the parent PPP representing all nodes in the network. The above clustering scheme yields two point processes, the first process $\Phi_c$ includes the CHs described in equation (5.9). While the second process $\Phi_m$ includes the CMs, that can be expressed as $\Phi_m = \Phi / \Phi_c$. The density of the MHC process is defined as [111]:

$$\lambda_c = \frac{1 - \exp(-\lambda \pi \delta^2)}{\pi \delta^2}.$$  

(5.10)

Please note that we implicitly assume that the distances to the detectable nodes are known. This kind of awareness is not trivial to acquire when we aim high accuracy localization [152], however a rough estimation of the distance can be easily achieved when relying on the received power level.
Algorithm 1 Cluster Head Selection Algorithm

1: for all $X \in \Phi$ do
2: Mark the node $X$ as $M(X) = t \sim \mathcal{U}(0, 1)$
3: Broadcast the mark $M(X)$
4: end for
5: for all $X \in \Phi$ do
6: $X \in \Phi_c$ "Assign $X$ to cluster heads set"
7: Build the list of detectable nodes $\Phi$
8: for all $Y \in \Phi$ do
9: if $||X - Y|| < \delta$ and $M(X) > M(Y)$ then
10: $X \in \Phi_m$ “Assign $X$ to cluster members set”
11: break
12: end if
13: end for
14: end for

Contact Distance Distribution for Cluster Members

Each member of the CMs’ set $\Phi_m$ associates to its nearest CH, thus the serving region of a CH is represented by a Voronoi cell as illustrated previously. It is to be noted that in this work we concentrate on maximizing energy efficiency in a single clustering cycle, where the presented work here can be further utilized to develop full clustering algorithms that take into consideration the total life time of the network. To obtain the average energy consumption in the terrestrial nodes, we need to understand the contact distance distribution which is the distance distribution between the CMs and their respective CHs. We denote the contact distance as $R$. In order to obtain the Probability Density Function (PDF) of $R$ we perform Monte-Carlo simulations for around 40,000 points using varying values of $\delta$. After that, we fit the results into the best empirical surface equation $\hat{f}_R(r, \delta)$ given by:

$$\hat{f}_R(r, \delta) = a \frac{r}{\delta^2} \exp \left[-\left(\frac{r}{\delta}\right)^b\right] : \sqrt{\lambda} \delta \geq 1,$$

(5.11)

where $a$ and $b$ are fitting parameters given by $a=2.23$ and $b=3.32$, resulting a root mean square error of around 1% over the range $\sqrt{\lambda} \delta \in [1, 6]$. We illustrate the surface fitting in figure 5.8, showing the simulation samples as circular points and the corresponding best fit surface. We can notice from this figure the extent of the goodness of fit.
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Fig. 5.8 PDF of contact distance $R$ between the cluster members and their respective cluster heads fitting surface.

5.2.3 Energy Model

SINR is an important measure that determines the link quality and the achievable throughput. Thus, for a particular data payload say a video streaming application, the required minimum throughput can only be achieved if the SINR is above a certain threshold. We denote this threshold as $\text{SINR}_o$. In general the SINR is given by $\text{SINR} = \frac{P_r}{P_I + P_N}$, where $P_r$ is the received power from the serving transmitter, $P_I$ is the total interference power summing at the receiver, this interference is originated from all other transmitters that are active at the same radio resource interval, and $P_N$ is the noise power.

In order to achieve an SINR level of $\text{SINR} = \text{SINR}_o$ at the receiver, the transmitter should adjust its transmit power to counter the effects of the radio path-loss, the interference and the noise. In this case, the SINR at the receiver will be of the form

$$\text{SINR}_o = \frac{P_o}{P_I + P_N}$$

where $P_o = \frac{P_r}{L}$ is the received power, $L$ is the average path-loss incurred between the transmitter and the receiver and $P_I$ is the controlled transmit power.

The energy spent in the process of delivering a message between a communicating pair transmitted over a period $T_m$ can be modeled as [18]:

$$\epsilon = P_t T_m + E_{rx}$$

$$= \text{SINR}_o (P_I + P_N) L \times T_m + E_{rx},$$

where $E_{rx}$ is the energy required to receive and decode the signal at the destination. We call $\epsilon$ the energy cost of delivering a message between a communicating pair. Our interest is to obtain the optimum performance of the average energy, that represents the average system
behavior, accordingly, we consider the average interference power $\overline{P_I}$ in equation (5.13), assuming that the media access protocol is capable of keeping the level of the interference temperature [153] as homogeneous as possible.

In case of the terrestrial nodes i.e. cluster heads and cluster members, the exerted energy to deliver a message from a cluster member towards its serving cluster head located at a distance $R$, can be deduced starting from equation (5.13) as the following:

$$
\varepsilon_{\text{Terr}}(R) = \text{SINR}_o(\overline{P_{\text{Terr}}} + P_{\text{Nnode}})L_oR^\alpha \times T_m + E_{\text{rx node}}
$$

where step (a) follows from assuming a log-distance channel model with average path-loss $L = L_oR^\alpha$, where $\alpha$ is the pathloss exponent, and $L_o$ is the reference path-loss [154]. Step (b) follows from defining the constant $\mu_{\text{Terr}} = \text{SINR}_o(\overline{P_{\text{Terr}}} + P_{\text{Nnode}})L_oT_m$ as the amount of energy required to deliver a message with length $T_m$ to a receiver located at a unity distance, with the aim of achieving a desirable SINR$_o$ at the receiver. The symbol $\overline{P_{\text{Terr}}}$ denotes the average terrestrial interference power, and $P_{\text{Nnode}}$ is the nodes’ internal noise power. It is noteworthy that in our approach, the overhead required for CH selection is only the broadcasting of the individual nodes’ scores and therefore is minimal.

On the other hand, air-to-ground (AtG) communication channel follows a specific path-loss model which largely deviates from the log-distance approximation [32, 33], namely the path-loss is related to the angle at which the platform is seen from the terrestrial node (called the elevation angle). In our study we assume that the radius of the deployment area is much smaller than the altitude of the platform, accordingly the elevation angle is approximated to hold the same. Thus, all terrestrial nodes share the same fixed path-loss $L_{T2A}$ towards the aerial platform. In this case, the energy consumption involved in the process of delivering a message towards an aerial platform, can be derived starting from equation (5.13) as the following:

$$
\varepsilon_{T2A} = \text{SINR}_o(\overline{P_{T2A}} + P_{Na})L_{T2A}T_m
$$

where $\overline{P_{T2A}}$ is the average aerial interference power, $P_{Na}$ is the platform’s noise power, and $P_{orT2A}$ is the fixed transmit power required to deliver the message. The reason we have disregarded the aerial platform’s receiver energy consumption is that in this work we are only interested in the energy consumption of the terrestrial nodes.
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5.2.4 Energy Utilization Analysis

Our focus in this work is on minimizing the total energy consumption involved in uploading data from terrestrial terminals, the case where we assume that these terminals have limited energy storage capacity. This scenario is quite common in sensor networks, where the deployed sensors are battery powered. We also assume that the system is not constrained by the possible limitation in the aerial platform’s energy, and accordingly we do not account its energy consumption in the optimization analysis.

The total energy consumption in terrestrial-terrestrial communication can be seen as composed of two parts: (i) firstly, the total transmit energy from all CMs towards their CHs, (ii) secondly, the total reception and processing energy exerted by all cluster heads. Thus, the expected energy consumption can be expressed as the following:

\[
\varepsilon_{\text{TotalTerr}} = E\left[ \sum_{x \in \Phi_m} \left( \mu_{\text{Terr}} R_x^\alpha + E_{\text{rxnode}} \right) \right]
\]

\[= n_m E\left[ \mu_{\text{Terr}} R_x^\alpha \right] + n_mE_{\text{rxnode}} \]

\[\approx n_m \mu_{\text{Terr}} \int_0^{\infty} r^\alpha \hat{f}_R(r, \delta) + n_mE_{\text{rxnode}} \]

\[= A \left( \lambda - \lambda_c \right) \times \left( \frac{a}{b} \delta^\alpha \Gamma \left[ \frac{2 + \alpha}{b} \right] \mu_{\text{Terr}} + E_{\text{rxnode}} \right), \quad (5.16)
\]

where \(E[\cdot]\) is the expectancy operator, \(R_x\) is the distance between the cluster member \(x\) and its serving cluster head. Step (a) follows from the fact that the distances between CMs and their serving CHs are independent from each other. This independence is inherited from the properties of the parent PPP. On the other hand, \(n_m = E[\Phi_m(A)]\) is the average number of cluster members lying inside the target area. And since the deployment of the nodes is assumed to be homogenous, then \(n_m\) is simply given by \(n_m = A \lambda_m\), where \(A\) is the area of the deployed nodes. The approximation in step (b) is the result of assuming that the simulated contact distance distribution closely represents the actual distribution i.e. \(\hat{f}_R(r, \delta) \approx f_R(r, \delta)\) given in equation (5.11).

We can notice from equation (5.16) that terrestrial energy vanishes when \(\delta \to 0\), that is when all nodes are cluster heads, and terrestrial traffic is non-existent. In this case, the traffic is uploaded directly to the aerial platform.

The total messages being relayed towards the platform are originated from both the CMs as well as the CHs, since we assume that CHs still perform the function of normal nodes (e.g. sensing) in addition to their function as aggregation nodes. By extending equation
(5.15), we can express the terrestrial-to-aerial energy cost as the following:

\[
\varepsilon_{\text{Total T2A}} = (n_c + n_m)P_{\text{OT2A}} \xi T_m = \lambda A P_{\text{OT2A}} \xi T_m = \lambda A \mu_{\text{T2A}} \xi, \tag{5.17}
\]

where \(n_c\) is the average number of CHs in the deployment area, and \(\mu_{\text{T2A}} = P_{\text{OT2A}} T_m\). The factor \(\xi \in (0, 1]\) is the clustering energy-reduction factor that is achieved through two main mechanisms:

- Aggregating and compressing terrestrial data, by removing redundant information obtained from CMs.
- Overhead reduction, where the aggregated packets at the CH are stripped and re-encapsulated in a jumbo packet.

The compression gain profile depends on the application and the type of the data being relayed towards the aerial platform. For example, the compression in data acquisition sensors (temperature, pressure, acoustic, location, etc...) will depend on the correlation between the data being aggregated, and the details required by the sink (the base station). The aggregation process itself is an energy-consuming process, where this extra energy consumption can also be embedded within the energy reduction factor \(\xi\). Noticing the situation when no clustering is used then \(\xi = 1\). Our energy model provides flexibility in embedding the compression and aggregation effect, however in the next section we provide an example formula for \(\xi\) in order to get a better insight of the model dynamics.

### 5.2.5 Performance Comparison

In order to verify the performance of the clustered network against the original performance of the unclustered network, we define the normalized energy difference, or the clustering energy-efficiency, as the following:

\[
\eta = \frac{\varepsilon_{\text{unclustered}} - \varepsilon_{\text{clustered}}}{\varepsilon_{\text{unclustered}}} \tag{5.18}
\]

where the energy consumption of the unclustered network is simply given by equation (5.17) with \(\xi = 1\), accordingly \(\varepsilon_{\text{unclustered}} = \lambda A \mu_{\text{T2A}}\). While the energy consumption of the clustered network is the sum of the energy exerted in communicating terrestrially plus the energy
exerted in uploading the packets towards the aerial platform, accordingly:

$$\varepsilon_{\text{clustered}} = \varepsilon_{\text{TotalTerr}} + \varepsilon_{\text{TotalT2A}}$$

After substituting from (5.16) and (5.17), and performing some algebraic reductions, we can write:

$$\eta = 1 - (\beta + \xi), \quad \text{where}$$

$$\beta = \left( \frac{\lambda - \lambda_c}{\lambda} \right) \left( \frac{a d}{b} \delta \Gamma \left[ \frac{2 + \alpha}{b} \right] \frac{\mu_{\text{Terr}}}{\mu_{\text{T2A}}} + \frac{E_{\text{rx, node}}}{\mu_{\text{T2A}}} \right).$$

Similarly we can find the normalized energy difference for LEACH [93] analytically, that is when the locations of the CHs are uncorrelated. In this case CHs will follow a PPP process because the random thinning of the parent PPP will yield another PPP [111], and will have the well known closed form contact distance distribution given by $$f_R(r) = \frac{2\pi}{\pi} \lambda \exp(-\pi \lambda_c r^2)$$. Following the same steps in (5.16), we can obtain the related as:

$$\beta_{\text{LEACH}} = \left( \frac{\lambda - \lambda_c}{\lambda} \right) \left( \frac{\lambda_c^{-\alpha/2}}{\sqrt{\pi}} \Gamma \left[ 1 + \frac{\alpha}{2} \right] \frac{\mu_{\text{Terr}}}{\mu_{\text{T2A}}} + \frac{E_{\text{rx, node}}}{\mu_{\text{T2A}}} \right).$$

In order to have an efficient clustering the normalized energy difference should be positive, namely $$\eta \sim (0, 1]$$. The minimum energy consumption will be reached when the cluster spacing $$\delta$$ maximizes $$\eta$$. Accordingly, the optimal minimum CH spacing can be obtained as:

$$\delta_{\text{opt}} = \arg\max_{\delta} (\eta)$$

In order to get a deeper insight of the system performance dynamics, we utilize a simple linear aggregation model where the number of the output message packets of the aggregator is given by [155] $$y = \kappa x + \gamma$$ where $$\kappa$$ is the compression factor, $$\gamma$$ is the overhead and $$x$$ is the number of input packets. Accordingly:

$$\varepsilon_{\text{TotalT2A}} = n_c P_{\text{T2A}} y T_m$$

$$= n_c \mu_{\text{T2A}} \left[ \kappa + \frac{\lambda_m}{\lambda_c} \frac{1}{\lambda_m} \right] + \gamma \right]$$

$$= \lambda A \mu_{\text{T2A}} \left[ \kappa + \frac{\lambda_c}{\lambda_m} \gamma \right],$$
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Fig. 5.9 The energy-reduction factor $\xi$ for different values of the compression factor $\kappa$.

Fig. 5.10 The clustering energy-efficiency for different values of the compression factor $\kappa$, showing Matern hard-core case, LEACH, HEED and the algorithm presented in [1].

By comparing (5.24) and (5.17) we can deduce that $\xi = \kappa + \frac{\lambda}{\gamma} \lambda$, however by setting the condition of $\xi = 1$ at $\frac{\lambda}{\gamma} = 1$ (i.e. no energy-reduction when all nodes are CHs), then we get $\xi = (1 - \kappa) \frac{\lambda}{\gamma} + \kappa$. An illustration of the energy-reduction factor is shown in figure 5.9 for different values of the compression factor $\kappa$.

We illustrate the energy performance by substituting numerical values from table 5.1 into equation (5.20) and then we plot in figure 5.10 the resulting curves for different values of the compression factor $\kappa$. Also, we show the results of Monte-Carlo simulations, that exhibit a trend very close to the analytical results, indicating the validity of our proposed analysis.

We also compare the performance of the proposed approach to HEED [94] and the algorithm presented in [1] by performing simulations. The results are shown in figure 5.10. In HEED, the secondary parameter used to select the CHs is called AMRP and for both
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Table 5.1 Notation And Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Numerical Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNIR₀</td>
<td>10 dB</td>
<td>Target Service SINR</td>
</tr>
<tr>
<td>λ</td>
<td>1/1000 m⁻²</td>
<td>Terminals density</td>
</tr>
<tr>
<td>α</td>
<td>3.68</td>
<td>Terrestrial propagation exponent</td>
</tr>
<tr>
<td>L₀</td>
<td>26 dB</td>
<td>Terrestrial reference path-loss</td>
</tr>
<tr>
<td>L_{T2A}</td>
<td>120 dB</td>
<td>Terrestrial to Air path-loss</td>
</tr>
<tr>
<td>P_{I_{T}}</td>
<td>0</td>
<td>Terrestrial interference</td>
</tr>
<tr>
<td>P_{I_{T2A}}</td>
<td>0</td>
<td>Aerial interference</td>
</tr>
<tr>
<td>P_{N_{node}} = P_{N}</td>
<td>-99 dBm</td>
<td>Noise power</td>
</tr>
<tr>
<td>E_{RX_{node}}</td>
<td>100 mJ</td>
<td>Nodes receiving energy</td>
</tr>
</tbody>
</table>

the algorithms, simulations were performed for different cluster radii. In order to unify the x-axis with the proposed approach in this work, we translate the resulting $\lambda_c$ from other algorithms into $\delta$ using (5.10).

We can note from figure 5.10 that MHC clustering approach, proposed in this work, outperforms random clustering (LEACH), HEED and the algorithm presented in [1] especially for lower densities of CH (i.e. higher spacing $\delta$). We can also observe from the same figure that clustering is rendered inefficient when there is no compression i.e. $\kappa = 1$.

We note here that the scores given to the nodes in algorithm 1 could be altered to include parameters such as the node’s residual energy or channel conditions to the aerial platform which will be explored in the next section.

5.3 Energy Efficient Clustering using Matern Hardcore Point Process in Aerial Networks

We have seen that techniques from stochastic geometry lends itself to tractable analysis which allows to optimize the CH spacing analytically. A brief overview of stochastic geometry is presented in section 2.2.2. In this work, we use Matern hard-core processes to analyze clustering using realistic channel conditions as opposed to ideal channel conditions used in the previous work. Specifically, we include shadowing phenomenon on the air-to-
ground link which is used as the mark for clustering using Matern point processes. We then show that CH spacing can be optimized numerically and the proposed clustering technique can potentially realize significant energy savings in the terrestrial nodes served by the aerial base station.

5.3.1 System Model

Network Model

In this work, we consider an aerial base-station located at an altitude of $d$ meters above the surface of the earth providing coverage to randomly and homogeneously deployed terrestrial nodes. We assume that all terrestrial nodes are capable of not only communicating with the aerial base-station but also with each other using some kind of device-to-device (D2D) technology such as WiFi or LTE D2D. We also assume that the majority of the traffic is client-server type where the traffic has to be routed or forwarded to further destination via the aerial base-station.

Channel Model

The Signal to Interference and Noise Ratio (SINR) is an important measure that determines the link quality and therefore the achievable throughput and the energy expended. In our model, the average SINR is given by,

$$\text{SINR} = \frac{P_r}{P_I + P_N}$$

(5.25)

where $P_r = \frac{P_t}{L}$ is the average received power, $P_t$ is the transmit power, $L$ is the total expected path-loss incurred between the transmitter and the receiver which includes shadowing and fading losses as described later, $P_I$ is the average aggregated interference power and $P_N$ is the receiver noise power. For a given application, a desired minimum throughput can be achieved only if the average SINR is above a certain threshold $\text{SINR} = \text{SINR}_o$.

The wireless signal traveling between the transmitter and the receiver undergoes power losses due to natural effects of scattering, diffraction, reflection and absorption. These power losses are usually characterized by a mean component and two random components, namely slow fading or shadowing and fast fading. Shadowing mainly results from obstacles found in nature as well as from man-made structures fast fading results from the interaction between the multipath components at the receiver which causes rapid changes to the received power.
Various fast fading channel models have been proposed in the literature including Rician, Rayleigh, m-Nakagami, etc. [149]. Therefore, the path-loss $L$ becomes,

$$L = L_o d^\alpha g h$$  \hspace{1cm} (5.26)

where $L_o$ is the reference path-loss depending on operating frequency and antenna gains, $d$ is the distance between the transmitter and the receiver, $\alpha$ is the path-loss exponent, $g$ and $h$ are a random variables characterizing the shadowing and fast fading component respectively. Shadowing is widely accepted to follow a log-normal distribution given by [149],

$$g = \exp(\sigma N) : N \sim \mathcal{N}(0,1)$$  \hspace{1cm} (5.27)

where $N$ follows a standard normal distribution and $\sigma = 10^{\frac{\sigma \text{dB}}{10}}$ where $\sigma \text{dB}$ is the standard-deviation in dB.

We consider two links in this work: Aerial link between the CHs and the aerial base-station and Terrestrial link between the CMs and their respective CHs.

Aerial Link: In the aerial link between a terrestrial node and the aerial base-station, the path-loss denoted by $L_a$ is given by,

$$L_a = L_{oa} d_a^{\alpha_a} g h_a$$  \hspace{1cm} (5.28)

where $L_{oa}$ is the aerial reference path-loss, $\alpha_a$ is the aerial path-loss exponent, $d_a$ is the distance between the terrestrial node and the aerial base-station, and $h_a$ denotes the fast fading gain in the aerial link characterized by Rician fading.

Terrestrial Link: In the terrestrial link between one terrestrial node (CM) and another (CH), the path-loss denoted by $L_t$ is given by,

$$L_t = L_{ot} R^{\alpha_t} h_t$$  \hspace{1cm} (5.29)

where $L_{ot}$ is the terrestrial reference path-loss, $\alpha_t$ is the terrestrial path-loss exponent, $R$ denotes the distance between the two terrestrial nodes and $h_t$ denotes the fast fading gain in the terrestrial link characterized by Rayleigh fading.
Energy Consumption Model

The energy consumed in the process of delivering a message between a communicating pair over a period of $T_m$ can be modeled as,

$$e = P_t T_m + E_{rx}$$

$$= \text{SINR}_o L_o (\bar{P}_t + P_N) T_m + E_{rx}$$

(5.30)

where $E_{rx}$ is the energy required to receive and decode the signal at the destination, and $\bar{P}_t$ is the average interference power.

In the case of air-to-ground communication between a terrestrial node and the aerial base-station, the energy spent by a node to transmit towards the aerial base-station over a period of $T_m$ is given by,

$$e_a \overset{(i)}{=} \text{SINR}_o L_o a (\bar{P}_a + P_{N_a}) T_m$$

$$\overset{(ii)}{=} \text{SINR}_o L_o a d^{\alpha_a} h_a (\bar{P}_a + P_{N_a}) T_m$$

$$\overset{(iii)}{=} P_{t_a} T_m$$

(5.31)

Step (i) $\bar{P}_a$ is the average aerial interference power and $P_{N_a}$ is the aerial base-station’s noise power. Step (ii) follows from equation (5.28) and $h_a$ is the expected fast fading gain in the aerial link. Step (iii) $P_{t_a}$ is the required transmit power to achieve a certain $\text{SINR}_o$ and is a random variable that follows log-normal distribution given by $P_{t_a} = \exp(\mu + \sigma Z)$ : $Z \sim \mathcal{N}(0,1)$ and $\mu = \log_e(\text{SINR}_o L_o a d^{\alpha_a} h_a (\bar{P}_a + P_{N_a}))$. It is important to note that we are mainly interested in saving the energy at the terrestrial nodes, thereby neglecting the energy required to receive and decode the signal at the aerial base-station.

In the case of terrestrial communication between the CH and CMs, the energy spent by a CM node to transmit towards its CH who is at a distance of $R$ over a period of $T_m$ is given by,

$$e_t \overset{(i)}{=} \text{SINR}_o L_t (\bar{P}_t + P_{N_t}) T_m + E_{rx}$$

$$\overset{(ii)}{=} \text{SINR}_o L_o R^{\alpha_t} h_t (\bar{P}_t + P_{N_t}) T_m + E_{rx}$$

$$\overset{(iii)}{=} \mu_t R^{\alpha_t} T_m + E_{rx}$$

(5.32)

Step (i) $\bar{P}_t$ is the average terrestrial interference power and $P_{N_t}$ is the noise power of the terrestrial nodes. Step (ii) follows from equation (5.29) and $h_t$ is the expected fast fading
Table 5.2 Notations and Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_p$</td>
<td>Density of the base PPP process</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>Density of the MHC-II process or CHs</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>Density of the CMHC process or CMs</td>
</tr>
<tr>
<td>$\alpha_a$</td>
<td>Path-loss exponent for aerial communication</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Path-loss exponent for terrestrial communication</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Transmit power</td>
</tr>
<tr>
<td>$P_N$</td>
<td>Noise power</td>
</tr>
<tr>
<td>$L_{0a}$</td>
<td>Reference path-loss in aerial link</td>
</tr>
<tr>
<td>$L_{0t}$</td>
<td>Reference path-loss in terrestrial link</td>
</tr>
<tr>
<td>$g$</td>
<td>Shadowing gain</td>
</tr>
<tr>
<td>$h_a$</td>
<td>Fast fading gain in aerial link</td>
</tr>
<tr>
<td>$h_t$</td>
<td>Fast fading gain in terrestrial link</td>
</tr>
</tbody>
</table>

Step (iii) we declare a constant $\mu_t = \text{SINR}_0 L_{0t} (P_t + P_N)$ whose physical significance corresponds to the power required to be transmitted by a terrestrial node to communicate with another terrestrial node located at reference distance from itself to achieve a certain SINR$_0$.

5.3.2 Energy Improvement Analysis

The terrestrial nodes are assumed to be randomly distributed following a homogeneous PPP denoted as $\Phi$ with an intensity of $\lambda_p$ nodes per unit area. Clustering of these nodes is performed to select the cluster heads and cluster members.

Cluster Head Selection

We assume that the altitude $d_a$ meters at which the aerial base-station is set is sufficiently high. We consider the required transmit power $P_t$, in equation (5.31) to achieve a certain SINR$_0$, to be a random mark allocated to the terrestrial nodes in the network. Every node in the network broadcasts its mark to other neighboring nodes present in the circular zone having a radius of $\delta$ meters, called the hard-core distance, which is a parameter set by the aerial base-station apriori and is later optimized in this chapter. After the broadcast, every node compares its own mark to all other detectable nodes i.e. the nodes within a radius of $\delta$ metres from itself. If a node has the lowest mark among the received broadcasts, then is is flagged as a CH otherwise as a CM. When every node in the network follows this process, we get two sets of nodes, the set of CHs denoted by $\Phi_c$ which is equivalent to Matern Hard-
Core Point Process of type-II (MHC-II) [111] and the set of CMs denoted by $\Phi_m$ which is equivalent to Complementary Matern Hard-Core Point Process (CMHC) [156].

The motivation behind having this cluster head selection process is to select cluster heads which have better channel conditions to the aerial base-station compared to the cluster members within the circular zone of radius $\delta$ meters. We illustrate the CH selection algorithm in Algorithm 2, detailing the actual process in a wireless network, where the operator $||x - y||$ represents the Euclidean distance between points $x$ and $y$. We are now interested in finding the density of the CH process $\Phi_c$ which is given by lemma 1.

**Algorithm 2 Cluster Head Selection Algorithm**

1. for all $X \in \Phi$ do
2. Mark the node $X$ as $M(X) = P_t$
3. Broadcast the mark $M(X)$
4. end for
5. for all $X \in \Phi$ do
6. $X \in \Phi_c$ “Assign $X$ to the cluster heads set”
7. Build the list of detectable nodes $\Phi$
8. for all $Y \in \Phi$ do
9. if $||X - Y|| < \delta$ and $M(X) > M(Y)$ then
10. $X \in \Phi_m$ “Assign $X$ to the cluster members set
11. and remove it from the cluster heads set”
12. break
13. end if
14. end for
15. end for

**Lemma 1.** For any mark distribution $F$, the density of the MHC process generated from a PPP process with density $\lambda_p$ and hard-core distance $\delta$ is given by

$$\lambda_c = \frac{1 - \exp(-\lambda_p \pi \delta^2)}{\pi \delta^2} \tag{5.33}$$

**Proof.** When thinning a point process, the density of the child process is given by,

$$\lambda_c = \lambda_p \rho \tag{5.34}$$

where $\rho$ is the probability that a point will survive the thinning process. In the case of MHC-II process, it can be easily seen that the probability that a point from PPP will survive the thinning process, conditional on its own mark $t$, is given by $\exp(-F(t)\lambda_p \pi \delta^2)$. Therefore,
equation (5.34) becomes,

\[
\lambda_c \overset{(a)}{=} \lambda_p \mathbb{E}_t [\exp(-F(t)\lambda_p \pi \delta^2)] \\
= \lambda_p \int_{-\infty}^{+\infty} \exp(-F(t)\lambda_p \pi \delta^2) \frac{dF(t)}{dt} dt \\
\overset{(b)}{=} \lambda_p \int_0^1 \exp(-y\lambda_p \pi \delta^2) dy \\
= \frac{1 - \exp(-\lambda_p \pi \delta^2)}{\pi \delta^2}
\]

Step (a) follows from removing the condition of \( t \) from \( \rho \) by taking an expectation with respect to \( t \), step (b) follows from integration by substitution where \( y = F(t) \).

Figure 5.11 shows the MHC-II density \( \lambda_c \) w.r.t. hard-core distance \( \delta \). The match between the analytical and simulation can be observed from the figure. It is noteworthy to observe that the MHC-II density given by equation (5.33) is independent of the mark distribution \( F \) and that in the standard formulation of Matern Hard-core Processes II, it is common to consider the marks to be uniformly distributed. However, lemma 1 proves that any distribution can be used for the marks to formulate a Matern Hard-core Process II.

**Required Transmit Power Distribution of Cluster Heads**

We are interested in the required transmit power distribution to achieve a certain SINR of the CHs denoted by the random variable \( P_{tCH} \). In other words, we are interested in the distribution of the marks inside the MHC process \( \Phi_c \).
Lemma 2. The distribution of marks within the MHC process generated from a PPP process with density $\lambda_p$, marks distributed according to distribution function $F$ and hard-core distance $\delta$ is given by

$$G(x) = 1 - e^{-F(x)\pi\delta^2\lambda_p} + F(x)e^{-F(x)\pi\delta^2\lambda_p}$$  \hspace{1cm} (5.35)

Proof. Consider the average number of points from the PPP process in a given area $A$ to be $N = \lambda_p A$ and the marks associated to these points from the distribution $F$ to be a set of i.i.d. random variables $M_N = \{M_1, M_2, M_3, ..., M_N\}$. Note that the thinning process used to form the MHC-II process from PPP selects the lowest mark point within a radius of $\delta$. Therefore, to find the distribution of marks within the MHC-II process $\Phi_c$, we need to find the minimum of the subset $M_n \subset M_N$ where $n$ is the number of other points inside the disk of radius $\delta$. Therefore, the distribution of marks within MHC-II conditioned on $n$ is given by,

$$G(x|n) = 1 - [1 - F(x)]^{n+1}$$  \hspace{1cm} (5.36)

It comes from the fact that the distribution of the minimum of a set containing $n + 1$ random variables independently and identically distributed according to $F$ is given by $1 - [1 - F(x)]^{n+1}$. To remove the conditioning on $n$, we need to take an expectation with respect to $n$ which requires us to know the distribution of the points in the CMHC process which is unknown. However, for large number of points it could be approximated to follow a Poisson distribution.

$$G(x) = \mathbb{E}_n[1 - [1 - F(x)]^{n+1}]$$

$$\approx \sum_{n=0}^{\infty} 1 - [1 - F(x)]^{n+1} \left(\pi\delta^2\lambda_m\right)^n \exp\left(-\pi\delta^2\lambda_m\right) \frac{1}{n!}$$

$$= 1 - e^{-F(x)\pi\delta^2\lambda_m} + F(x)e^{-F(x)\pi\delta^2\lambda_m}$$  \hspace{1cm} (5.37)

CM to CH Distance Distribution

We are interested to learn the distribution of distances between a CM and a CH in the network which is denoted by $R$ in this work. The authors in [156] argue that the distance distribution between the MHC and the CMHC process cannot be expressed in closed-form. However, the authors provide proof that the distance distribution between a MHC and a PPP
process closely approximates the distance distribution between the MHC and the CMHC process. Therefore, we use this approximation which is given by,

\[
F_{\text{PPP} \rightarrow \text{MHC}}(R|\delta) = 1 - \exp\left(-\int_0^R 2\pi r \lambda_p \eta_{\text{PPP} \rightarrow \text{MHC}}(r, \delta) dr\right)
\]

\[
\eta_{\text{PPP} \rightarrow \text{MHC}}(r, \delta) = \frac{1 - \exp[-\lambda_p(\pi \delta^2 - l_2(r, \delta))] - \lambda_p(\pi \delta^2 - l_2(r, \delta))}{\lambda_p(\pi \delta^2 - l_2(r, \delta))}
\]

(5.38)

\[
l_2(r, \delta) = \begin{cases} 
\pi r^2 : 0 < r < \frac{\delta}{2} \\
r^2 \cos^{-1}\left(1 - \frac{\delta^2}{2r^2}\right) + \delta^2 \cos^{-1}\left(\frac{\delta}{2r}\right) : r \geq \delta/2
\end{cases}
\]

Energy Consumption Analysis

**Aerial Energy:** The CHs have to transmit not only their own messages to the aerial base-station but also the messages from their CMs. By extending, equation (5.31), we can present the average total energy exerted to transmit information from the CHs to the aerial base-station as the following:

\[
E_{\text{Aerial}} = \sum_{i \in \Phi_c} (1 + n_{m_i}) P_{\text{CH}_i} T_m
\]

(5.39)
5. Energy Efficiency Enhancement using Terminal Cooperation

Taking an expectation of the above equation (5.39), we get,

\[ \mathbb{E}[E_{\text{Aerial}}] = \mathbb{E}\left[ \sum_{i \in \Phi_c} (1 + n_m) P_{CH_i} T_m \right] \]

\[ \overset{(a)}{=} T_m \sum_{i \in \Phi_c} \mathbb{E}(1 + n_m) P_{CH_i} \]

\[ \overset{(b)}{=} T_m \sum_{i \in \Phi_c} \mathbb{E}(1 + n_m) \mathbb{E}[P_{CH_i}] \]

\[ \overset{(c)}{=} \mathbb{E}[P_{CH}] T_m \sum_{i \in \Phi_c} \mathbb{E}(1 + n_m) \]

\[ \overset{(d)}{=} (n_c + n_m) \mathbb{E}[P_{CH}] T_m \] (5.40)

Linearity of expectation is used in step (a) to take the expectation inside the summation. In step (b), the independence between the number of CMs in a cluster and the transmit power of the CH is exploited. In step (c), the dependency of the \(i\)th CH on the transmit power is removed by the expectation, therefore giving us \(\mathbb{E}[P_{CH_i}] = \mathbb{E}[P_{CH}]\). In step (d), \(\mathbb{E}[(1 + n_m)] = n_c + n_m\) where \(n_c = \lambda_c A\) is the number of CHs and \(n_m = \lambda_m A\) is the number of CMs in a given area \(A\), in other words, it comprises of the total number of nodes in the network.

**Terrestrial Energy:** The total terrestrial side energy consumption is comprised of two parts: the total transmit energy from all the CMs towards their respective CHs and the total energy exerted in the reception of these messages from the CMs at the CHs. Thus extending equation (5.32), the average total energy consumed in the terrestrial side can be given as:

\[ \mathbb{E}[E_{\text{Terr}}] = \mathbb{E}\left[ \sum_{x \in \Phi_m} (\mu_x R_x^\alpha + E_{rx_x}) \right] \]

\[ \overset{(a)}{=} n_m \mu \mathbb{E}[R_x^\alpha] T_m + n_m E_{rx} \] (5.41)

Since the distances between the CMs and their respective CHs are independent to each other, this independence is inherited from the properties of the parent PPP.

**Total Energy:** We are interested in the average total energy consumption of the network which is composed of two terms, energy consumed in the terrestrial side and the energy
consumed in the aerial side, given by,

$$E_{\text{clustered}} = \mathbb{E}[E_{\text{Network}}]$$

$$(a) = \mathbb{E}[E_{\text{Aerial}}] + \mathbb{E}[E_{\text{Terr}}]$$

$$= (n_c + n_m)\mathbb{E}[P_{\text{CH}}]T_m + n_m\mu_r\mathbb{E}[R^\alpha]T_m + n_mE_{rx} \quad (5.42)$$

Step (a) follows from the fact that the aerial channel and the contact distance $R$ are independent to each other. Plugging in equations (5.39) and (5.41) in (5.42), we can compute the average total energy consumption of the aerial network.

### 5.3.3 Performance Evaluation

In this section, we evaluate the performance of the clustering scheme using Matern point processes detailed in the previous sections against an unclustered network analytically and verify our analysis using simulations. In the simulations, we eliminate the boundary effects by constructing a voronoi tessellation and eliminating the voronoi cells that are adjacent to the simulated boundaries. We define clustering energy efficiency similar to the way we defined it in section 5.2.5 given by:

$$\eta = \frac{E_{\text{unclustered}} - E_{\text{clustered}}}{E_{\text{unclustered}}} \quad (5.43)$$

where, $E_{\text{unclustered}}$ is given by,

$$E_{\text{unclustered}} = n\mathbb{E}[P_{\text{at}}]T_m \quad (5.44)$$

where, $n = \lambda A$.

Accordingly, in order to have energy efficient clustering the energy efficiency should be between 0 and 1 given by $\eta \sim (0, 1]$. Minimum energy consumption will be reached when the cluster head spacing $\delta$ maximizes $\eta$. Accordingly, the optimal minimum CH spacing can be obtained as:

$$\delta_{opt} = \arg \max_\delta (\eta) \quad (5.45)$$

Figure 5.13 shows the clustering energy efficiency for different values of shadowing standard deviation $\sigma$ with respect to cluster-head spacing $\delta$. The solid line shown in the figure is analytically derived and the scatter plot is based on simulation. In the evaluation, we used the intensity of the PPP $\lambda$ to be 0.0001 and every simulation data point shown in
5. Energy Efficiency Enhancement using Terminal Cooperation

5.13 Clustering energy efficiency for different values of shadowing standard deviation $\sigma$ with respect to CH spacing $\delta$.

The figure has been averaged over 25 runs. It can be seen from the figure that higher energy efficiency can be obtained if the shadowing standard deviation is higher. In other words, more energy efficiency can be attained if there is significant variation in channel conditions between different terminals in the network. We can also observe that there exists an optimal CH spacing $\delta$ that maximizes the energy efficiency of the network. This optimal CH spacing can be found numerically by solving the optimization given in equation (5.45).

5.4 Chapter Summary

In this chapter we addressed research question 3 through three key contributions. Firstly, we proposed a novel energy efficient clustering algorithm to cluster terrestrial nodes served by an aerial base-station to improve energy efficiency in aerial access networks. Secondly, we proposed a novel analytic clustering technique using Matern hard-core process which allowed us to optimize the CH spacing analytically to maximize the energy efficiency in aerial access networks. Finally, we extended the analytic clustering technique to incorporate realistic channel conditions by including the shadowing phenomenon.
Chapter 6

Conclusion and Future Research

6.1 Conclusion

In this thesis, we explored the technology of terminal cooperation for next-generation wireless networks especially investigating it for aerial and regional access networks. We started with our first objective of characterizing the physical radio channel for device-to-device communication to enable terminal cooperation. We accomplished this objective by firstly obtaining a statistical channel model for D2D in rural areas by characterizing the path-loss exponent and shadowing standard deviation for different propagation environments using the ISM band frequencies of 922 MHz and 2,466 MHz. This gave us a better understanding of the D2D channel in rural areas. Secondly, we developed a statistical channel model for vehicular environment in 5.8 GHz band by conducting channel measurements in the city of Melbourne for path-loss exponents and shadowing standard deviation in different urban environments. This provided us with an insight into the behavior of signal propagation in vehicular environments. Thirdly, we studied the feasibility of using D2D in millimetre-wave ISM bands of 24 GHz and 61 GHz in different urban environments for which we utilized ray-tracing simulations to study the path-loss behaviour of millimetre-wave frequencies in an urban environment. The details of these studies and the contributions made towards research question 1 were provided in chapter 3 of this thesis.

Our second objective consisted of evaluating coverage in aerial access networks and enhancing coverage in regional access networks using terminal cooperation. We accomplished this objective by firstly investigating the performance of two vastly different technologies, LTE and WiFi, in aerial networks. We considered a practical urban scenario from Melbourne, Australia in which we performed ray-tracing simulations to characterize the path-loss in the air-to-ground channel and then performed system level simulations to evaluate
the performance of LTE and WiFi in aerial access networks. Secondly, we proposed game-theoretic algorithms to enable terminal cooperation in regional access networks with the objective of enhancing coverage. We proved the efficacy of these algorithms and validated them by using outage probability as a metric and providing system level simulations. Simulation results showed that significant coverage improvement can be achieved using terminal cooperation. Wireless design engineers can potentially utilize the presented results while designing next-generation cooperative wireless networks. The details of these studies and the contributions made towards research question 2 were provided in chapter 4 of this thesis.

Our third objective consisted of enhancing energy efficiency in aerial access networks. We accomplished this objective by firstly proposing a centralized energy efficient clustering algorithm which was validated by system level simulations and benchmarking against other well known clustering algorithms from literature. Simulation results showed that significant energy savings can be potentially realized by using clustering in aerial access networks. Secondly, we proposed a novel analytic clustering technique using Matern hard-core process which allowed us to optimize the cluster-head spacing analytically to maximize the energy efficiency of the network. This work utilizes the concepts of stochastic geometry to capture the random nature of the locations of the deployed nodes leading to a tractable analysis of the expected network metrics. Furthermore, the analytic clustering technique was compared with other well-known clustering algorithms found in literature showing the improvement in energy efficiency. Thirdly, we extended the analytic clustering technique from our second contribution in this area to incorporate realistic channel conditions by including the shadowing phenomenon in the air-to-ground link. We utilized tools from stochastic geometry to model the energy consumption which led to analytically computable results. The details of these studies and the contributions made towards research question 3 were provided in chapter 5 of this thesis.

Throughout this thesis, we have relied upon analytic, numerical and simulation-based methods to validate the proposed techniques and algorithms. For statistical significance, we have utilized Monte-Carlo technique. Majority of the work presented in this thesis has been published in-part or as a whole in peer-reviewed conference papers, journal articles, book chapters, publically available project deliverables or otherwise undergoing a peer review process. These publications have been highlighted and identified in section 1.5 and in each of the chapters.
6.2 Future Research Paradigms

Based on the research work performed in this thesis, we draw some future research paradigms that can potentially extend this work to enable terminal cooperation and see it work in reality. With research question 1 on the physical radio channel characterization of the D2D channel, a possible future work is to characterize the radio channel in number of different environments such as urban, suburban, high dense, etc., to characterize the multipath fading phenomenon and with mobility. With regards to the vehicular channel, it would be beneficial to characterize the multipath fading phenomenon and with vehicles moving. It would also be interesting to characterize the vehicular radio channel at different frequency bands and in different scenarios such as highway, 4-way intersection, etc. With the millimetre wave work, it would be exciting to perform channel measurements and compare it with the ray tracing simulation results.

With research question 2 which is based on evaluating coverage in aerial access networks and enhancing coverage in regional access networks, it would be exciting to evaluate the coverage by performing practical measurements with an aerial platform carrying base-station with LTE and WiFi technologies. It would also be really interesting to run trials to see the game-theoretic algorithms, presented in this thesis, working in practical scenarios.

With research question 3 which is based on enhancing energy efficiency in aerial access networks, it would be beneficial to run practical trials in aerial access networks with the clustering algorithms proposed and measure the energy consumption of the devices with and without clustering the nodes. Even though it is challenging analytically to perform clustering with realistic channel conditions, it would be worthwhile to investigate the terrestrial links with shadowing in Matern-based clustering.
References


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6. Conclusion


6. Conclusion


6. Conclusion


6. Conclusion


6. Conclusion


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