Chapter 1

Introduction and Literature Review

1.1 Background

With the rapid proliferation of cellular data services in recent times, the wireless cellular network has become a significant front-runner in accessing the Internet [1, 2]. Data traffic generated by a vast number of applications of smartphones is increasing rapidly [3]. According to the Ericsson mobility report on data and forecast, the global total mobile data consumption is expected to reach 226 exabytes (EB) per month by 2026 [4]. India alone is expected to consume 35 EB per month by 2026 [4].

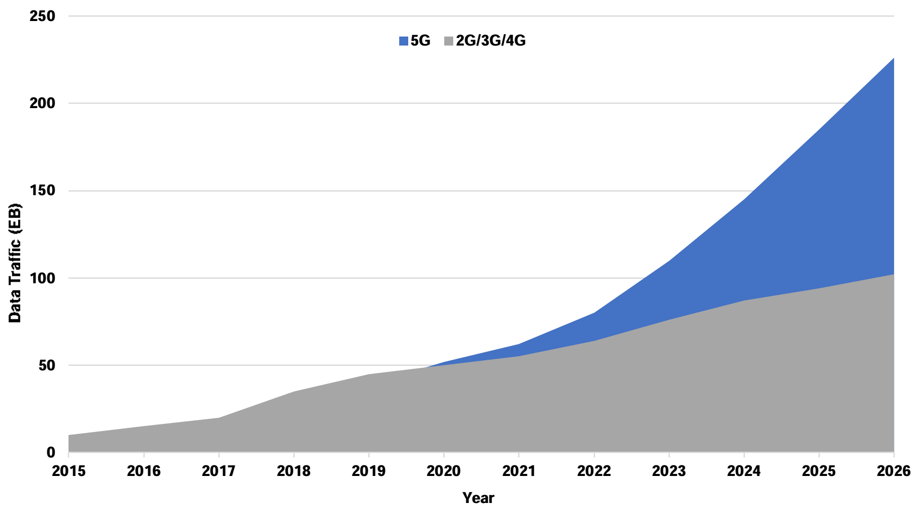


Figure 1.1: Mobile Data Traffic Globally (EB per month) [4].

To meet the huge demand for data traffic, wireless cellular networks required continuous growth from the time they were initially operational [5]. The initial evolution started with the second generation (2G) wireless cellular standards in 1991 [6]. Presently, long term evolution (LTE) and LTE-advanced proposed by the third generation partnership project (3GPP) has been vastly deployed to cater to the current need of data services [7]. However, with the massive rise in the demand for data services, a swift progression is needed in the fourth generation (4G) cellular standards [8]. Hence, we are now on the verge of adopting the fifth generation (5G) wireless cellular standards [9].

The rationale behind the transition to the 5G wireless standard is to achieve a large capacity with high data rates compared to the current standards [10]. With a larger capacity and high data rate, 5G cellular standards also target to achieve ultra-low latency and ultra-high reliability [11]. Hence to achieve the aforementioned goals, new methodologies must be adopted for the envisioned 5G network. Few such contenders expected to be adopted in the 5G architecture are device-to-device (D2D) communications, massive multi-input and multi-output (mMIMO), visible light communication (VLC), cognitive-radio networks (CRN), two-tier architecture, technologies working on millimeter wave (mmWave) to name a few [8]. Further, among the above mentioned methodologies, D2D communication is a prominent and potential candidate to get adopted in 5G architecture [12].

1.2 Device-to-Device Communication

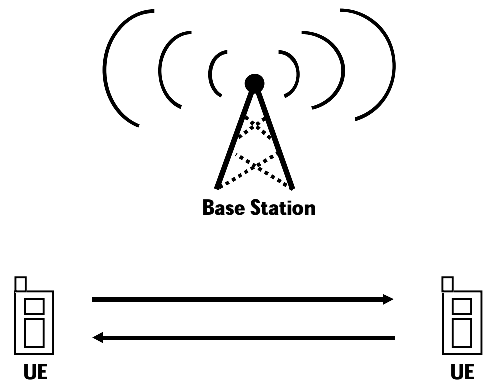


Figure 1.2: D2D communication system.

D2D communication is a promising methodology in which close proximity user equipment (UE) are allowed to establish direct communication with each other [13]. The core advantage of this methodology is that the signal transmission happens without the involvement of the base station [14]. A single hop D2D communication system is shown in Figure 1.2. Benefits of such methodology are traffic offloading, reduced delay, improved spectrum reuse, and reduced energy consumption [15]. Further, the implementation of D2D communication can typically be categorized by three operating modes [16]. These modes are i.) underlay mode, ii.) overlay mode and iii.) cellular mode. In underlay mode, the D2D UE uses the same spectral resources as used by the cellular UE of the network [17]. Overlay mode, on the contrary, provides dedicated spectral resources to D2D UE for communication [18]. Lastly, in cellular mode, the UE communicates with the help of the base station [16]. Comparing the above D2D communication modes, underlay mode is considered to be much more beneficial if higher spectrum efficiency is the network requirement [19].

Along with various benefits of the underlay D2D communication methodology, there exists a certain downside also. The downside is that the fundamental essence of underlay D2D communication can cease to exist if the channel quality between the UE is not good or if the separation between the UE is too large [2, 20]. In both cases, the destination UE may either receive a corrupt signal or may not receive any signal. To counter such adversities, implementing a relay-assisted cooperative communication technique in an underlay D2D systems is a promising solution [20].

1.3 Cooperative D2D Communication

Relay-assisted cooperative D2D communication offers diversity to combat fading. It acts as a virtual multi-input multi-output (MIMO) diversity technique [21]. In this, the relay nodes offer themselves to cooperate for the signal transmission between the source UE and the destination UE [22]. Incorporating relay nodes between source UE and destination UE helps attain multiple independent faded signals at the destination UE without using the MIMO antenna array [22]. Importantly, cooperative communication provides benefits in terms of low latency, high data rate, enhanced coverage area, reduced energy consumption, and reliable communication [23, 24].

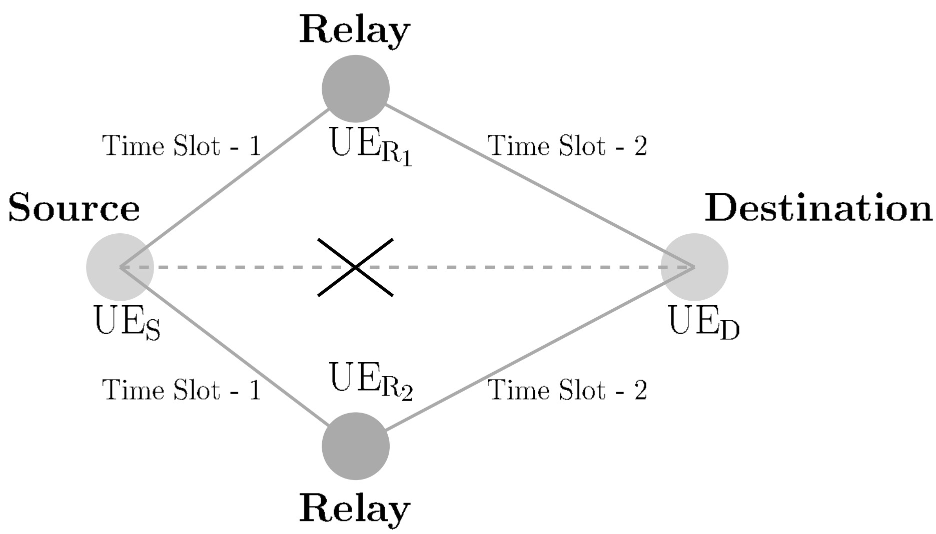


Figure 1.3: A two-hop relay-assisted cooperative D2D communication system model.

Figure 1.3 illustrates a relay-assisted cooperative D2D communication system model with two relays assisting the D2D UE. In this system model, source UE (UE_S) aspires to transmit the information signal to the destination UE (UE_D). However, the reliable transmission range of UE_S is less than the distance between the UE_S and UE_D. Hence UE_S cannot directly transmit the signal to UE_D. Therefore, relays assist the UE_S for signal transmission. The transmission of the information signal occurs in two-time slots, described below [25,26].

Time Slot 1: In the first time slot, the UE_S broadcasts the information signal to both the relays UE (that is, UE_{R_1} and UE_{R_2}).

Time Slot 2: In the second time slot, the relays process the received information signal based on the relaying policy adopted. After processing, the information signal is transmitted to UE_D. At the end of time slot 2, the coherent receiver could perform maximal ratio combining and maximum likelihood (ML) detection. Here, it is assumed that the ML receiver has the knowledge of channel state information (CSI).

1.3.1 Motivation

To reveal the true potential of the relay-assisted D2D communication system for practical implementation, it is important to further enhance the system's spectral efficiency and energy efficiency. Conventionally, spectral efficiency and energy efficiency are the two most crucial physical (PHY) layer performance measures [27,28]. To improve these performance measures for the relay-assisted D2D communication system, the research community considers two vital aspects. These aspects are i.) the relaying policy [29], and ii.) the relay selection policy for the system [30]. These two aspects have garnered a great deal of research interest and are the key theme of this thesis. In the upcoming sections, we will briefly discuss the various possibilities in the above two aspects with the key benefits and the policies proposed in the literature.

1.3.2 Relaying Policies

As discussed, the relay processes the information signal before transmitting the signal to the destination UE. This processing of the signal by the relay node depends on the relaying policy adopted. There are multiple relaying policies extensively discussed in the literature [31,32]. Based on the literature, we can categorize the relaying policies into two major classifications, that is, 1.) conventional relaying policies and 2.) hybrid relaying policies. Below, we briefly describe both the classifications.

1. *Conventional relaying policies:* Typically, the relaying policies under the conventional category are amplify-and-forward (AAF) relaying policy [33] and decode-and-forward (DAF) relaying policy [34]. Both these relaying policies have their unique processing abilities. AAF relaying policy is a simple policy that just amplifies the signal before re-transmitting it to the destination [35,36]. On the

other hand, DAF relaying policy is more advanced since it decodes the received signal and transmits the re-encoded signal to the destination [37].

2. *Hybrid relaying policies:* Relays that take up hybrid relaying policy have the capability to perform both the functionality of AAF relays and DAF relays [38]. Relays opting hybrid relaying policy can perform in two ways, that is, i.) relay either act as DAF relay or AAF relay based on specific criteria or ii.) relay performs both the DAF and AAF functions simultaneously. Choosing a hybrid relay to assist in the cooperative D2D communication system model helps in enhancing the systems' performance. However, the implementation complexity is also high for hybrid relays. Both the conventional relaying policies and the hybrid relaying policies are summarized briefly in Table 1.1.

Table 1.1: Comparison of conventional and hybrid relaying policies.

View point	Conventional relaying		Hybrid Relaying
	AAF relaying	DAF relaying	
Function	Amplification → transmission.	Decode → re-encode → transmission.	Perform both AAF and DAF functions.
Regeneration capabilities	Non regenerative repeater.	Regenerative repeater.	Have both regenerative and non-regenerative capabilities.
Implementation complexity	Low.	High.	Very high.
Downside	Amplify noise along with received signal.	High processing delay.	Implementation complexity and processing delay both are high.
Cost	Low.	High.	High.

Further, the various hybrid relaying policies proposed in the literature are discuss in the following sub-section.

1.3.3 Literature Study on Relaying Policies

The research community has been showing a significant interest in exploring and analyzing various relaying policies for cooperative communication systems. The proposed policies in the literature are designed to enhance performance measures like outage, symbol error rate, and spectral efficiency. For example, authors in [39] propose a static hybrid relaying policy, where the relay having large separation from source acts as DAF relay and relay with less separation from source acts as AAF relay. For such a policy, bit error rate and block error rate probabilities are analyzed. However, in this thesis, no location information is required by the proposed relaying policies. Furthermore, the proposed policies in this thesis performs both the functions of AAF and DAF simultaneously.

In [40], the authors propose a selective combining-based hybrid relaying policy. In this policy, the output signal power to noise power ratio (SNR) of the received signal is calculated by the relay based on both AAF and DAF relaying policy. If the DAF relay's output SNR value is greater than the AAF relay's output SNR value, it acts as a DAF relay. Otherwise, it acts as an AAF relay. The policy proposed in this thesis is different since both the AAF and DAF relaying tasks are performed simultaneously. Moreover, the relay's amplification is adaptive and based on the link quality between the relay and destination links. Furthermore, a hybrid decode forward and amplify forward relaying policy is proposed in [41]. In this policy, relays that cannot successfully decode the received signal act as AAF relay, and the rest of the relays act as DAF relays.

Authors in [42] propose a hybrid decode-amplify-forward relaying policy. According to this policy, if the received signal SNR is less than or equal to a particular threshold SNR, the relay will act as an AAF relay. Otherwise, the relay will act as a DAF relay. Furthermore, a hybrid decode-amplify-forward incremental cooperative diversity policy is proposed [43]. In this policy, the relays are allowed to assist the source if the link between the source and the destination is weak. Further, the relay's decision to act as DAF or AAF relay is based on the SNR value of the source to the relay link.

Unlike the policies proposed in the literature, a power-adaptive decode-and-forward (PA-DAF) relaying policy is proposed in this thesis. PA-DAF relay performs the task of decoding $\rightarrow$ re-encoding $\rightarrow$ amplification before transmitting the signal to the destination. Note that the relay gain is set optimally based on the relay to destination link for amplification. Three different relaying policies are developed for the PA-DAF relay-assisted cooperative D2D system to optimize the end to end performance. The three performance measures that we consider are, fading averaged symbol error rate (FASER), fading averaged spectral efficiency (FASE), and fading averaged energy efficiency (FAEE). FASER helps in analyzing the link reliability, FASE helps in analyzing the information rate for given bandwidth, and lastly FAEE helps in analyzing the energy efficiency of the proposed system model. Furthermore, to analyze the performance gain, the proposed PA-DAF relaying policy is compared with the benchmark policies.

1.3.4 Relay Selection Policies

Practically, in a cooperative D2D communication systems, there can be multiple relay nodes present in between the source UE and the destination UE. In such a scenario, multiple relay nodes or only a single relay node (relay selected via relay selection policy) can assist the source UE in forwarding the signal [44]. It is evident that the adaptation of multiple relays in cooperative D2D systems helps to achieve extended transmission coverage and more reliability. However, these benefits can also be achieved if a best single relay is selected to forward the signal to the destination UE [45]. Along with that, the selection of the best relay also provides benefits like reduced hardware complexity [30, 46], reduced problem of synchronization [47], reduced CSI requirement, reduced power consumption, and increased spectral efficiency [30, 48]. Furthermore, several relay selection policies are studied in the literature on the cooperative communication system. These are discussed in the following subsection.

1.3.5 Literature Study on Relay Selection Policies

The simplest solution for selecting a relay to forward the signal to the destination is choosing a relay randomly. However, random relay selection (RRS) can lead to the worst system performance [49, 50]. Hence various optimal or sub-optimal relay selection policies have been proposed in the literature to enhance the system performance. For example, a location-based relay selection approach is proposed in [51,52]. In [51], the relay node closest to the destination node is selected to forward the signal. However, the policy proposed in [52] is more complex since the separation between source node to relay node and relay node to destination node is considered for relay selection. Furthermore, the best relay node selection based on the distance criteria is not optimal since shadowing, interference, and multi-path fading have a far more significant impact on the received signal SNR at the destination [31]. In this thesis, the proposed relay selection scheme considers channel characteristics for the selection of the best relay.

In [53], the authors proposed a switched examine relay selection scheme. In [53], each relay is examined one at a time based on the channel gain of the source to relay link and relay to the destination link. If the channel gain of both the links of a particular relay is greater than a specific threshold value, that relay is selected as the best relay to forward the signal. Note that each relay is examined in a round-robin fashion to investigate whether the relay can be the best relay or not. Further, a power aware relay selection policy is proposed in [54]. In [54], the authors initially proposed the method to obtain the optimal power required to transmit the signal to the destination via source and the relays. Based on the optimal power and the residual power of the relays $(P_{r,i}, P_i)$ and the source $(P_{r,s}, P_s)$, the best relay node is selected. The selection criteria proposed is $\max_i \min\{P_{r,s} - P_s, P_{r,i} - P_i\}$, where $i \in \{1, 2, ..n\}$ denotes the i^{th} relay. However, the policy proposed in this thesis selects the DAF relay based on weights, which are the functions of the first hop's average SNRs. Thus, the proposed policy is a partial relay selection policy that depends on the average CSI between source to relay link only. Therefore, there is no need for global CSI (that is, CSI of source to relay and relay to destination link) for the relay selection. Since no global CSI information is required by the relay nodes for relay selection, CSI burden is reduced.

The SNR based relay selection policy is proposed in [55]. In this policy, initially, all the relay nodes having the source to relay SNR values greater than a certain threshold forms a group. The relay having the maximum SNR value of the relay to the destination link from the group is selected to forward the signal to the destination. Furthermore, an opportunistic relay selection scheme is proposed in [56], in which the relay has global CSI and the selection criteria is $\max_i \min\{\gamma_{sr_i}, \gamma_{r_id}\}$, where γ_{sr_i} and γ_{r_id} are the channel power gain of the source to relay link and relay to the destination link respectively and $i \in \{1, 2, ..n\}$ denotes the i^{th} relay. Further, a similar approach is shown in [57], where SNR of the source to relay link and relay to the destination link is considered in place of channel power gain. In [57], the authors derived the outage probability of the optimal DAF relay selection policy. In their system model, authors assume that the relay has full CSI, which shows the selection policy's complexity. The system model analyzed in [57] considers a direct link between source to destination for signal transmission. However, in our proposed model, we assume that the direct link is absent. This assumption is valid when the destination is not within the transmission range of the source. The relay has to play a critical role in forwarding its receiving signal to the destination. The regenerative relay is selected by PRSP, which requires partial CSI for relay selection; however, policy in [57] requires global CSI. Furthermore, in [57], only symbol error probability is analyzed. However, this thesis analyzes various PHY performance measures, namely, FASER, FASE, and FAEE.

As mentioned above, relay selection policies that require global CSI need CSI of the source to relay link and relay to destination link [58]. The processing capabilities of relays should also be high so that the best decision on relay selection can be taken [59]. However, the increase in processing capabilities and enhanced information exchange leads to increased complexity and resource utilization of the relay nodes [59]. This makes the system less feasible and less friendly for practical implementation. This thesis proposes a simple and intuitive probabilistic relay selection policy requiring partial CSI at the relay for relay selection. Sub-section 1.6.1 briefly describes the novelty of the work followed by the contributions.

Till now, the appropriate selection of relay selection policy and relaying policy in cooperative D2D systems have been discussed. However, to take the discussion further, the energy-efficient design is also a necessity of time for the 5G communication systems [60]. Furthermore, the deployment of ultra-dense communication nodes to meet the demand of cellular traffic in the 5G communication system poses a risk of high CO_2 emissions [61]. Therefore to contribute to one of the sustainable development goals (SDG), the recent interest in energy-efficient system designs has enhanced manifold. Moreover, the over-utilization of energy resources of the relay nodes is also a point of concern. Therefore, in the next section, we will briefly discuss the issue of over-utilization of the relay node's energy resources and search for the appropriate solution to enhance energy efficiency. We also present an attractive application of cooperative communication in spectrum sharing systems or cognitive radio systems in section 1.5.

1.4 Green Cooperative D2D Communication

As discussed, the relay-assisted cooperative D2D communication systems offers enhanced network capacity and increased coverage area. However, frequent transferring of data signal through the battery-equipped relay node can decrease its battery life. Furthermore, replacing or frequent charging of the relay node's battery is not a feasible and convenient solution for relays in a cooperative D2D systems.

To overcome the problem of limited battery capacity in the relay node of the cooperative D2D systems, the researchers have shown a great deal of interest. One famous approach predominantly accepted by the researchers is energy harvesting (EH) by the relay node. In this approach, the relay node charges its battery through ambient resources like solar, wind, or radio-frequency (RF) signals [62]. However, solar and wind resource's environmental dependence makes them inefficient and unpredictable for relay node adaptation [63]. Hence, radio-frequency energy harvesting (RF-EH) is the most attractive solution, since RF resource is more controllable and reliable [64].

1.4.1 Simultaneous Wireless Information and Power Transfer

Simultaneous wireless information and power transfer (SWIPT) is the most accepted technique for RF signal-based EH in green cooperative D2D communication systems [65]. There are two main implementation protocols for SWIPT technology: i.) power-splitting protocol (PSP) and ii.) time-switching protocol (TSP) [66]. In TSP, the relay node selects the EH and information decoding tasks over time by a single antenna with a simple switch [67]. This thesis considers TSP, given its ease of implementation and simplicity.

SWIPT and its associated ideas have earned researcher's attention due to its unique concept of concurrent transmission of power and information. Further, in the literature, both multiple EH relay nodes and single EH relay node (selecting the best relay based on relay selection policy) models are discussed. Below we present the literature on the relay selection policies for EH cooperative communication scenario.

1.4.2 Literature Study on Relay Selection for EH Relay Assisted Cooperative System

As discussed for the non EH relay-assisted cooperative D2D communication systems, the relay selection in EH relay-assisted cooperative D2D communication also has lots of benefits. Relay selection in such systems increase overall systems's energy efficiency [68], reduce hardware complexity and synchronization problem at the receiver [69] and increase spectral efficiency. Various relay selection policies have been investigated in the literature on the EH relay-assisted cooperative systems. In [70], the authors proposed a distance-based relay selection policy and analyzed the outage probability. Further, a selective max-max relay selection policy is proposed in [71]. In this policy, global CSI is required at the relay to participate in the relay selection process. For the proposed policy in [71], the outage is analyzed, and the performance is compared with the max-max relay selection policy. Note that the policy proposed in this thesis is simple since partial CSI is required at the relay for relay selection.

A non energy aware relay selection policy is proposed in [72]. In this, the relay with the best instantaneous channel power gain of the relay to destination link is selected to assist the source. For this policy, the outage is analyzed. Note that the policy proposed in this thesis does not require the relay to the destination channel power gain. Further, in [73], the authors proposed a partial relay selection policy, where the relay with the highest SNR of the source to the relay link is selected as the best relay. Note that the policy proposed in this thesis also selects the same EH relay as selected by [73]. However, the novelty lies in the second hop transmission. Specifically, the selected EH relay transmission is constrained by the link outage. This constrained transmission helps in conserving the power of the cooperative EH system in outage conditions, leading to a greener system. However, no such outage-constrained transmission policy is proposed in [73]. In the above aspect the proposed policy in this thesis is different from the policy proposed in [73].

A battery aware relay selection policy is proposed in [74]. In this policy, the relay which harvests energy more than a specific threshold forms a group. Further, the relay which delivers maximum SNR at the destination is selected to forward the signal from the group formed. A similar policy is proposed in [75] also. However, all the relays in the group participate in data transmission.

Furthermore, a two EH relay-assisted cooperative communication system is considered in [76]. In [76], if the probability of SNR of source to relay 1 is higher than the probability of source to relay 2, then relay 1 is selected. Otherwise, relay 2 is selected. Further in [77], the authors propose a max-min policy that selects the relay based on $\max\{\min\{\Gamma_{sr_i}, \Gamma_{r_id}\}\}$ (where $i \in 1, 2, .., L$) criteria. Note that Γ_{sr_i} and Γ_{r_id} denotes the instantaneous SNR of the source node to the i^{th} relay node link and the i^{th} relay node to the destination node link, respectively. For such an algorithm, the outage probability is analyzed.

The authors [78] employed a relay selection policy that selects the EH relay, which harvests maximum energy. In it, the authors investigated end-to-end link outage analysis in the high SNR regime. However, communication policy, objectives, and analysis are different and exhaustive in this thesis. The critical difference lies in the selected EH relay strategy to forward the information. Precisely, the selected maximum EH relay decides to transmit or does not transmit based on the channel conditions between itself and the destination. This fundamental change in relaying strategy based on the outage brings more novelty, usefulness, and significance to the policy and its fading-averaged spectral efficiency and fading-averaged energy efficiency analysis. Furthermore, the authors in [79] also propose a similar policy as proposed by [78]. In [79], if the SNR of the source to destination link (direct link) is greater than the selected relay to the destination link, in that case, the relay is turned off and a direct transmission will take place between source to destination. However, in the system model proposed in this thesis, no direct link exists between source and destination.

The authors in [80] proposed a relay selection policy for the buffer-aided relays. In [80], all the relays initially decide whether to participate in the relay selection based on comparing the source to relay SNR with some threshold. Further, based on the buffer state of the relays, the relay selection is performed. It is important to note that the system model and the policy proposed in this thesis are different. The system model considered does not assume relays to have buffer capabilities. Furthermore, the relay which harvests maximum energy is selected to forward the signal to the destination.

Unlike the policies in literature, a novel outage-constrained energy harvesting-based relay selection (OC-EHRS) policy is proposed in this thesis. In OC-EHRS policy, the best relay selection is based on maximum energy harvested, and the novelty lies in the fact that the selected relay's transmission is outage constrained. This means that the best-selected relay does not forward the signal to the destination if there is an outage in the link between relay to destination. This conserves energy and enhances energy efficiency. Further, in next section, we discuss an interesting application of the relay-assisted cooperative communication technique in the cognitive radio system.

1.5 Spectrum Sharing System

This section discusses the exciting application of cooperative communication in cognitive radio systems or spectrum sharing systems (SSS). As discussed, 5G wireless communication technology is a new era technology, developed to cater to high data speed and large capacity compared to LTE [81]. However, to achieve these goals, the most significant challenges are spectrum scarcity and efficient spectrum utilization [82]. To overcome these challenges and enhance the system's spectral efficiency, SSS is a promising solution [83].

SSS is the system where the unlicensed/secondary user (SU) avails the under-utilized licensed frequency band. However, SSS has a constraint that SU should not cause harmful interference to the licensed/primary user (PU) [84]. Thus delivering enhanced spectral efficiency along with high throughput, coverage area, and several users [85]. Further, spectrum access is one of the important aspects of SSS. This can be classified into three categories, that is, i) interweave (SU access the channel if PU is inactive), ii) underlay (SU transmit in the presence of PU; however, the transmit power of SU is below tolerance level), and iii) overlay (SU perform interference pre-cancellation based on the message received by PU) [86]. However, underlay is considered to be simpler, efficient, and easily implementable among the aforementioned spectrum access categories.

As discussed, to avoid interference at PU, SU restricts its transmit power in the underlay mode. However, this constrained SU's transmit power poses a limitation to the system's performance in terms of reduced coverage area by SU transmitter [87]. A promising solution to counter this drawback is a cooperative communication technique [88]. When employed in underlay SSS, the benefits of cooperative communication techniques are extended system coverage and improved system performance [89].

As discussed for the D2D communication systems, further improvement of the aforementioned system model can be achieved by appropriately choosing two crucial aspects. The first aspect is based on considering multiple relays or selection of single relay based on relay selection policy. The selection of a single relay in underlay cooperative-SSS (C-SSS) has more benefits in terms of less hardware complexity, enhanced bandwidth efficiency, reduced CSI, and reduced synchronization challenges [47,48,90]. Furthermore, the second aspect of improving the performance is the selection of the best relaying policy. In the following sub-section, we discuss the relevant literature on to relay selection and relaying policy in C-SSS.

1.5.1 Literature Study on Relay Selection and Relaying Policy in C-SSS

Authors in [91] proposed a system model with two secondary relays in underlay C-SSS and analyze outage probability. In [91], the first relay act as DAF, and the second relay act as AAF with both relays having interference-constrained transmit power. For relay selection, if the DAF relay successfully decodes the signal, then the DAF relay is selected else the AAF relay is selected. In comparison to the system model considered in [91], each relay of the system model proposed in this thesis can perform both AAF and DAF tasks simultaneously. In [92], the author proposes a DAF relay-assisted C-SSS, in which the transmit power of the relay is set as min{interference threshold power, relay transmit power}. Further, for relay selection, the relay with the best source to relay channel power gain is selected for signal transmission. For such a system model, outage probability is analyzed. A similar relaying policy has been proposed in [93] with an opportunistic relay selection policy, and outage analysis is done for the system model. It is important to note that authors in [92,93] does not consider power adaptation of relay with interference-constraint, which is proposed in this thesis.

In [94, 95], authors considered hybrid decode-amplify-forward (HDAF) relaying policy. In this, the relay either acts as DAF or AAF relay based on the successful decoding or unsuccessful decoding, respectively. However, the relay selection policies considered in [94] and [95] are different. In [94], authors consider minimum outage criteria for relay selection, whereas in [95], authors consider the best SU source to relay channel gain for relay selection. In comparison to [94, 95], our thesis also consider partial relay selection policy. However, the relaying policy proposed in this thesis is unique since each relay performs both DAF and AAF relaying operations. Furthermore, the amplification of the relay is adaptive and based on the channel characteristics of various channel links. Further, authors in [45] analyzed the outage probability of the system model with DAF relaying policy, having transmit power controlled based on the relay to PS's destination link average channel power gain and interference threshold power. Along with that, the relay which provide maximum SNR at the destination is selected to forward the signal. However, the relay selection policy and the relaying policy proposed in this thesis are different.

Unlike the above-mentioned research works, we propose an interference-constrained power-adaptive decode-and-forward (IC-PA-DAF) relaying policy. The IC-PA-DAF relaying policy initially performs the DAF function. After DAF operation, the relay adaptively amplifies the re-encoded signal based on the channel power gain of various links. These various links are SU's source to relay link, relay to SU's destination links, and relay to PU's destination links. Furthermore, to avoid interference at PU's destination, the relay transmit power is average interference-constrained. Specifically, we develop two different optimal relaying policies to optimize the end-to-end performance of the two-hop cooperative SSS. The two performance measures that we consider are FASE, and FAEE. Furthermore, we analyze the performance of IC-PA-DAF relaying policy in both EH scenario and non-EH (N-EH) scenario. For the analysis, the performance of the IC-PA-DAF relay is compared with the conventional relaying policies. In the following sub-section, we briefly describe the specific contribution presented in this thesis.

1.6 Thesis Contributions

Looking at the literature for the relay selection, we can observe that most of the relay selection policies are complex since global CSI is needed for the selection of the relay. This requirement poses a burden on the relay nodes in terms of complexity and energy consumption. Hence in this thesis, we propose a partial relay selection policy for both EH relays and N-EH relays. For N-EH relays, we propose a simple and intuitive relay selection policy named "probabilistic relay selection policy" (PRSP). Furthermore, for EH relays we propose an outage-constrained energy harvesting-based relay selection (OC-EHRS) policy.

To further optimize the performance, we propose a PA-DAF relaying policy for cooperative D2D systems. Furthermore, we propose IC-PA-DAF relaying policy for cooperative spectrum sharing system (C-SSS). The IC-PA-DAF policy is proposed for both the EH relay-assisted C-SSS model and the N-EH relay-assisted C-SSS model. It is observed in the analysis that implementing the proposed relaying policies with proposed relay selection policies greatly improves the performance of the system in terms of FASER, FASE, and FAEE. Below we discuss in detail about the key contributions in each objective.

1.6.1 Probabilistic Relay Selection Policy

As discussed, relay selection poses a burden on the relay nodes since they require global CSI for it. Furthermore, relay selection is an essential factor in enhancing the

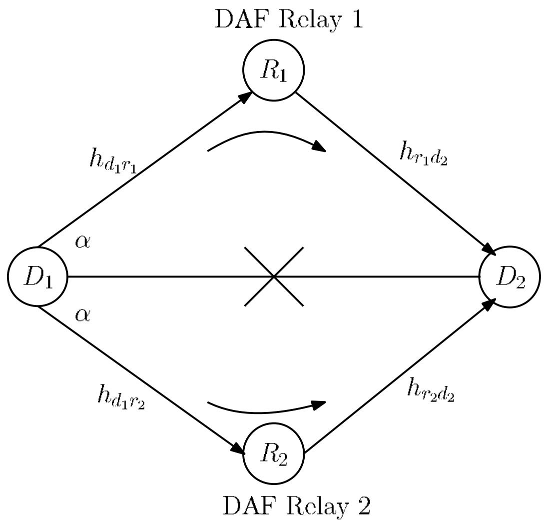


Figure 1.4: DAF relay-assisted, two hop cooperative D2D system.

performance of the cooperative D2D communication system model. Therefore, we propose a simple but insightful PRSP in this thesis. The system model considered to analyze the performance of the proposed policy is shown in Figure 1.4. The novelty of the proposed relay selection policy lies in the fact that the policy gives the least burden to the relay in the sense that it requires partial CSI, which makes implementation easier. Specifically, it is a partial relay selection policy that depends on the first-hop SNRs. Moreover, it also considers the path loss model for the selection of the relay. Further, to analyze the performance of the proposed policy, FASER, FASE, and FAEE are analyzed. The specific contributions are as follows.

- A PRSP is proposed for two-hop, DAF relay-assisted cooperative D2D wireless system over different fading scenarios in the first hop.
- Closed-form expression of FASER and its upper bound are derived for the proposed policy considering both M-ary phase-shift keying (MPSK) and M-ary quadrature amplitude modulation (MQAM) schemes.
- To further extend the analysis, we investigated and analyzed the FASE and FAEE of the proposed system model.
- An insightful diversity order analysis in the scaling regime for the MPSK scheme is also analyzed for the proposed policy.
- Extensive numerical results are presented for the proposed policy. These results will serve as a useful theoretical benchmark for DAF relay-assisted cooperative D2D communication systems.

1.6.2 Power-adaptive Decode-and-Forward Relaying Policy

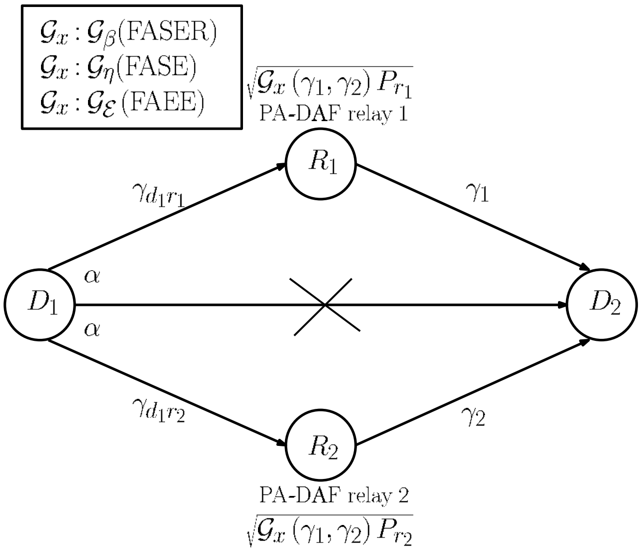


Figure 1.5: PA-DAF relay-assisted, D2D cooperative wireless communication system.

Relay selection policy with optimized relaying policy can significantly enhance the performance of the cooperative D2D communication system model. Therefore, we propose a PA-DAF relaying policy in this thesis. The relays adopting the proposed policy on receiving the signal performs decoding → re-encoding → amplification. The amplification of the signal is based on the relay gain, which is adaptive and dependent on channel conditions between the relay and the destination. The system model considered to analyze the proposed policy is shown in Figure 1.5. For the system model, the PRSP is adopted. We develop three different optimal relaying policies for the PA-DAF relay-assisted cooperative D2D communication model to optimize end to end performance. The performance measure considered to analyze the proposed system model are FASER, FASE, and FAEE. Below we present specific contributions.

- A PA-DAF relaying policy is proposed, which, apart from working as a DAF relay, also sets its gain and transmit power to optimise various performance measures. Specifically, we derive three different optimum relay gain adaptation policies to optimize three important performance measures, namely, FASER, FASE and FAEE.

- A comprehensive analysis is done for the following optimal relaying policies.

  - FASER optimal relaying policy: In this policy, the relay gain and its transit power are optimally set to enhance the average symbol error rate performance of the system. The analysis is done for both MPSK and MQAM schemes.

  - FASE optimal relaying policy: In this policy, the relay gain and its transit power are optimally set to enhance the average spectral efficiency performance of the system.

  - FAEE optimal relaying policy: In this policy, the relay gain and its transit power are optimally set to enhance the average energy efficiency performance of the system.

- To further analyze the system model, we present the diversity order analysis in an insightful scaling regime.

- Extensive numerical results are presented to show that FASER optimal, FASE optimal, and FAEE optimal relay gain policies deliver superior performance in comparison to the benchmark policies.

1.6.3 Outage-Constrained EH based Relay Selection Policy

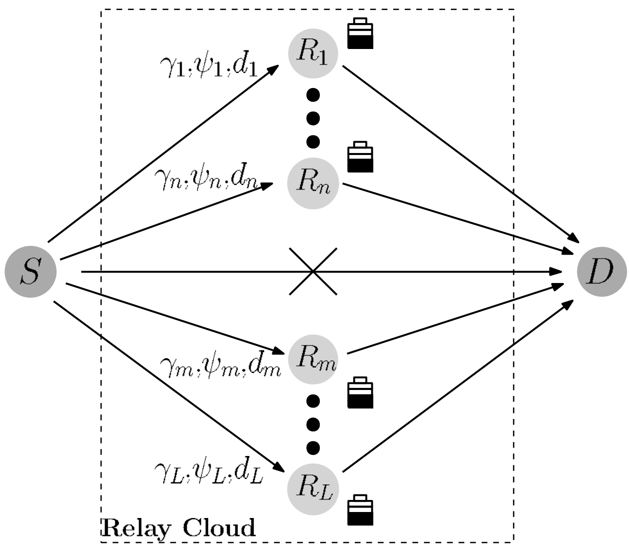


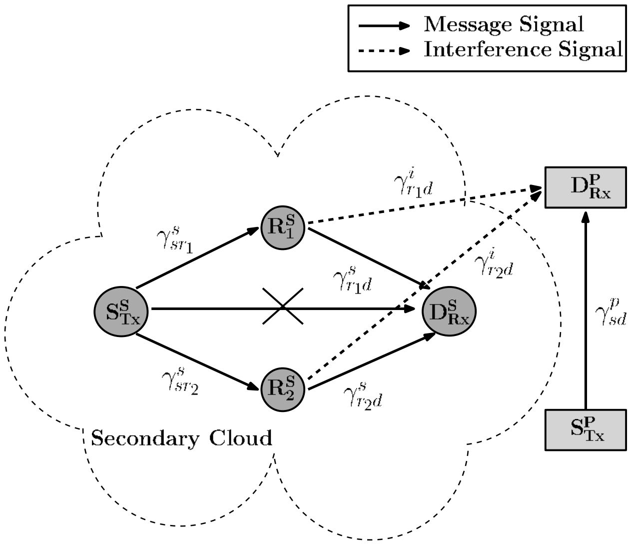
Figure 1.6: EH relay-assisted, two hop cooperative D2D system.

Since the 5G architecture envisions deploying an ultra-dense, heterogeneous network, it poses a significant threat to high carbon dioxide emissions. Noting that climate action is one of the SDG proposed by the united nations, energy efficiency becomes a crucial parameter for next-generation wireless systems. Therefore, this thesis considers relays to have RF-EH capabilities. The system model is shown in Figure 1.6. For such a system model, we propose an outage-contained energy harvesting based relay selection (OC-EHRS) policy. The proposed OC-EHRS policy selects the relay based on the maximum energy harvested by the nodes. Furthermore, the novelty of the proposed policy lies in the fact that the outage constrains the selected EH relay transmissions. The system model considered EH non-regenerative relays. Moreover, TSP is adopted for simultaneous power and information transfer between the source and EH relay nodes. For the proposed system model, outage probability, FASE, and FAEE are analyzed, which are insightful for the performance analysis. Following are the specific contributions related to the system model considered in Figure 1.6.

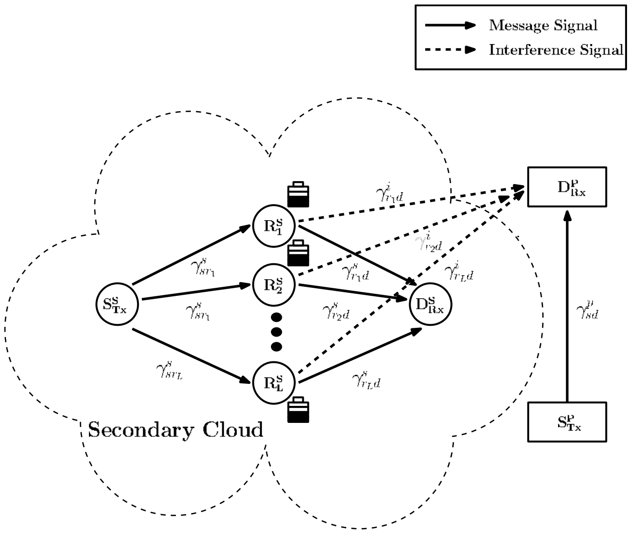
- An OC-EHRS policy is proposed for the multi-EH relay-assisted cooperative D2D communication system model. The proposed policy selects the relay which harvests maximum RF energy. Furthermore, the selected relay's transmission is constrained by the outage probability of the relay to the destination link.
- Since the relay nodes harvest random energy, an order statistic problem is formulated for deriving the average maximum energy harvested by the relay node. For the analysis, we consider small-scale fading with shadowing and path loss.
- To analyze the performance of the proposed policy, link outage probability is analyzed for the relay to the destination link. We also develop an asymptotic analysis for outage probability for better performance analysis.
- Further, we also analyze the performance measures like FASE and FAEE for the proposed system model. We derive single integral expression for exact FASE, and FAEE and closed-form upper bound of both FASE and FAEE. To gain more insight, we also present asymptotic FASE, and FAEE analysis in the scaling regime.
- Lastly, we numerically evaluate outage probability, average spectral efficiency, average energy efficiency and compare them with two benchmark policies.

1.6.4 Interference-Constrained PA-DAF Relaying Policy

To further extend the cooperative communication analysis, we consider cooperative communication technique in a spectrum sharing environment. We propose an IC-PA-DAF relaying policy for N-EH and EH relay-assisted C-SSS. The system models for N-EH and EH relay-assisted C-SSS are shown in Figure 1.7. The proposed relaying policy optimally sets the relay gain based on the link between the relays and the destination (both primary and secondary). Specifically, we develop two different optimal relaying policies to optimize the end-to-end performance of the two-hop C-SSS wireless system. The two performance measures that we consider are FASE and FAEE. For the analysis,



(a) N-EH relays



(b) EH relays

Figure 1.7: Relay-assisted C-SSS systems.

the performance of the IC-PA-DAF relay is compared with the conventional relaying policies. Following are the specific contributions of this study.

- Firstly, the authors propose a novel IC-PA-DAF relay-assisted underlay C-SSS model and formulate optimization problems for it. The IC-PA-DAF relay adapts its transmit power to meet the average interference constraint and optimizes the system performance. Note that the IC-PA-DAF relaying policy is analyzed independently for both EH and N-EH relay scenarios.

- We derive IC-PA-DAF relaying policy for C-SSS that optimizes FASE or FAEE. Note that the optimal relaying happens after the probabilistic relay selection (for N-EH relays) or EH based relay selection (for EH relays), which are less complicated in terms of CSI acquisition.

- For the proposed optimal (IC-PA-DAF) relaying policy, we derive optimal fading averaged spectral efficiency (OFASE) and optimal fading averaged energy efficiency (OFAEE). We also derive the upper bound for these exact performance measures.

- To validate the analytical results and gain quantitative insights, we conduct Monte-Carlo simulations. Further, we compare and show that the proposed IC-PA-DAF policy outperforms benchmark policies.

1.7 Thesis Organization

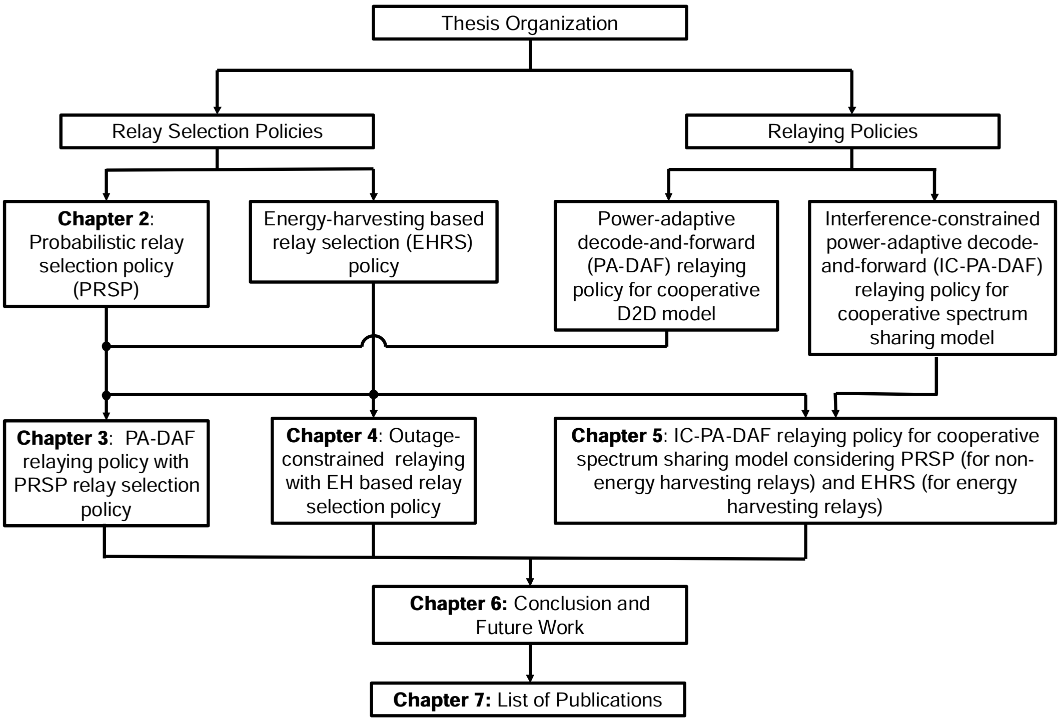


Figure 1.8: Thesis Organization.

The content of the thesis is organized in the following manner. Chapter 2 presents the PRSP and its analysis. The optimal PA-DAF relaying policy is proposed and analyzed in Chapter 3. Further, for EH relays, an OC-EHRS policy is proposed and analyzed in Chapter 4. An IC-PA-DAF relaying policy for N-EH and EH scenarios is proposed in Chapter 5. Lastly, the conclusion and future work for the work presented in this thesis is shown in Chapter 6 and the list of publications is shown in Chapter 7. In Figure 1.8, we show the thesis organization in the form of a flow diagram.