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# Cooperative Communications in Smart Grid Networks

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# Abstract

The conventional grid system is facing great challenges due to the fast growing electricity demand throughout the world. The smart grid has emerged as the next generation of grid power systems, aimed at providing secure, reliable and low cost power generation, distribution and consumption intelligently. The smart grid communication system within the smart grid network is of fundamental importance to support data transfer and information exchange within the smart grid system. The National Institute of Standards and Technology has identified wireless communications as an important networking technology to be employed in power systems. The reliability of the data transmission is essential for the smart grid system to achieve high accuracy for the power generation, distribution and consumption. In this thesis, we investigate cooperative communications to improve transmission reliability in smart grid networks.

Although many issues within cooperative communication have already been addressed, there is a lack of research efforts on cooperative communication for the wireless smart grid communication system which has its own network features and different transmission requirements. In our research, the smart grid communication networks were studied, and cooperative communications in smart grid networks were analysed. The research work mainly focuses on three problems: the application of cooperative relay communications to modern smart grid communication networks, the cooperative relay-based network development strategy, and the optimization of cooperative relay communication for smart grids.

For the first problem, the application of cooperative relay communication to a home area network (HAN) of smart grid system is presented. The wireless transmission reliability is identified as the issue of most concern in wireless smart grid networks. We model the smart grid HAN as a wireless mesh network that deploys cooperative relay communication to enhance the transmission reliability. We apply cooperative relay communication to provide a user equipment selection scheme to effectively improve the transmission quality between the electricity equipment and the smart meter.

For the second problem, we address the network design and planning problem in the smart grid HAN. The outage performance of direct transmission and cooperative transmission was analysed. Based on the reliability performance metric that we have defined, we propose a HAN deployment strategy to improve the reliability of the transmission links. The proposed HAN deployment strategy is tested in a home environment. The smart meter location optimization problem has also been identified and solved. The simulation results show that our proposed network deployment strategy can guarantee high reliability for smart grid communications in home area networks.

For the third problem, the research focuses on the optimization of the cooperative relay transmission regarding the power allocation and relay selection in the neighbourhood area network (NAN) of the smart grid system. Owing to the complexity of the joint optimization problem, reduced-complexity algorithms have been proposed to minimize the transmission power, at the same time, guarantee the link reliability of the cooperative communications. The optimization problem of power allocation and relay selection is formulated and treated as a combinatorial optimization problem. Two sub-optimal solutions that simplify the optimization process are devised. Based on the solutions, two different algorithms are proposed to solve the optimization problem with reduced complexity. The simulation results demonstrate that both two algorithms have good performance on minimizing the total transmission power while guaranteeing the transmission reliability for the wireless smart grid communication system.

In this thesis, we consider cooperative communications in a smart grid scenario. We minimize the outage probability and thus improve the reliability of the communications taking place in the smart grid by considering the optimization problem of power control, relay selection and the network deployment problem. Although similar problems might have been well investigated in conventional wireless networks, such as the cellular network, little research has been conducted in smart grid communications. We apply new optimization techniques and propose solutions for these optimization problems specifically tailored for smart grid communications. We demonstrate that, compared to naively applying the algorithms suitable for conventional communications to the smart gird scenario, our proposed algorithm significantly improves the performance of smart grid communications. Finally, we note that, in future work, it will be possible to consider more complex smart grid communications system models. For example, it is worthwhile considering hetregeneous smart communications by combining HAN and wide area networks (WAN). In addition, instead of assuming that all communications have the equal priority, as in this thesis, more comprehensive analysis of the priority of the smart grid communication can be applied to the research.

# Acknowledgements

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# Notation

**AF** Amplified-and-forwarded relay

**AMI** Advanced metering infrastructure

**DAU** Data aggregator unit

**DER** Distributed energy resources

**DF** Decoded-and-forwarded relay

**HAN** Home area network

**HEMS** Home energy management system

**MDMS** Meter data management system

**NAN** Neighbourhood area network

**PLC** Power line communications

SANET Sensor and actuator network

**WAMS** Wide area measurement system

**WAN** Wide area network

# Table of Symbols

$P_S$ Transmit power at the source

$P_R$ Transmit power at the relay node,

$h$ channel fading coefficients source to destination

$n$ Noise powers

$\gamma_{RD}{}^{AF}$ Received snr under AF

$\gamma_{RD}{}^{DF}$ Received snr under DF

$\beta$ $SNR$ threshold

$P_S^D$ Transmission power of the source node in direct transmission model

$P_S^C$ Transmission power of the source node in the cooperative transmission (CT)

$P_R^C$ Transmission power of the source node in the cooperative transmission (CT)

$p^D$ Reliability for the direct transmission mode

$P_S^C$ Transmission power of the source node in the cooperative transmission (CT) model

$P_{power}^D$ The total transmission power under the $DT$ mode

$P_{power}^C$ The total transmission power under the $CT$ mode

$p_{th}$ Reliability threshold

$p^D$ Probability at the received SNR

$PL$ Postloss

$m$ Transmitter location

$l$ Receiver Location

$r_{SD}$ Distance between source to destination

$r_{SR}$ Distance between source to relay

$r_{RD}$ Distance between relay to destination

# Chapter 1. Introduction

## 1.1 Background

In recent years, the increasing electricity demand throughout the world has led to a revolution in power grid systems. The electricity power grid system is facing rapid change from the conventional grid system to the smart grid system. At the same time, there is increasing interest in integrating renewable resources into the power system [1], which provides an environmentally friendly and cost-efficient solution to the existing electricity grid system. The new requirements on the grid system make it very necessary to modernize the grid infrastructure.

The concept of the smart grid has been brought into the power distribution industry aimed at providing an intelligent power system, from power generation through distribution to consumption. The smart grid system will undoubtedly be the future of the power grid system. The ideal future smart grid system should have the ability to integrate and manage real-time information, data transmission, power demand and electronic technologies, etc., to provide a comprehensive solution to the power grid industry. By incorporating consumers' activity into the decision-making, the smart grid will build up a user-centric distributed system to support a reliable and cost-effective energy supply. On the other hand, the use of renewable energy is another challenge for the power grid system, and so the design of a smart grid system also needs to take renewable energy into account, since renewable energy has the particular features of being uncontrollable and unpredictable [2–4], and inadequate control of the grid system will lead to waste of the energy and could sometimes be costly. For example, an unscheduled shutdown of a power grid can be a very complex operation, and inaccurate prediction of the renewable energy can be costly because the storage of the electricity is limited and expensive in the industry [3,5,6].

Smart grid communication integrates advanced technologies for sensing and controlling the power generation, distribution and consumption within the smart grid system. The smart grid is robust to load fluctuations, and the supply–demand balance can be properly maintained via intelligent real-time dispatching mechanisms [1] using close customer–grid interactions. Because of the heterogeneous generation and utilization systems, the grid distribution system is very complex. Multiple technologies are required to support the collaboration, integration and interoperability within the smart grid system [7]. Smart meters that deployed in the HANs of smart grid communication system are designed to support the information exchange between the grid company and its customer. The smart grid communication can support the intelligent control of the grid system, the customers can reduce their utility costs by adjusting their power usage strategy. The smart grid devices are equipped with 802.11-based sensor technology. Data is transferred to a data collector via intermediate nodes in the smart grid [1]. Since the data is used for decision making inside the grid network, the reliability of the transmission within the smart grid networks is very important. In contrast, modern grid distribution networks have almost negligible outage detection mechanisms, resulting in low reliability [8]. The existing communication infrastructure for smart grids is inadequate in terms of the response time, adaptation and control [9]. The roadmap technology for 2025 [10] will be able to identify fault locations and fault types using monitor-and-control centres. Creating a smart grid requires standardization of new communication protocols, and upgrades to existing communication infrastructure [7,10].

Although the smart grid system is designed to overcome the existing problems in the power grid system, the data communication infrastructure of the smart grid network is of fundamental importance; it must be highly reliable to ensure that the information exchange within the network is as accurate as possible, so that the dynamic demand-side management system can change and shift electricity consumption accordingly.

Owing to the smart grid system's high reliability requirement, a modern communications infrastructure is essential, especially when it supports the data communication for managing, controlling and optimizing the different types of smart devices in the smart grid system.

Both wired and wireless communication technologies have been considered for the smart grid system. Wireless communication is very popular and can be used widely to enable many parts of the smart grid system to achieve high-efficiency, low-cost data communications. Various wireless network architectures have been considered for the smart grid networks in the literature. Because the smart grid system is distributed in complex environments [11], a classic three-layer network architecture was proposed to support smart grid communications in different areas [6], which consists of three types of network: home area network (HAN), neighbourhood area network (NAN) and wide area network (WAN). The three types of network are characterized by their different size and location. Different wireless technology can be used to meet different network requirements for the different parts of the smart grid network. A HAN uses local-area or short-distance wireless communications (e.g. Wi-Fi) to provide real-time meter data transmission, electricity load control and dynamic pricing by connecting the electricity user devices, switches, display systems and smart meters [12]. A NAN consists of multiple HANs that are in a local area. The HAN gateway transfers the meter data to the data aggregator unit (DAU) through the NAN. A WAN is used to connect multiple DAUs to the meter data management system (MDMS). Due to the complex and multi-layered infrastructure of the smart grid communication system [13], there are many challenges when deploying wireless communication in the smart grid system [7], such as limited spectral resources [14] and high reliability requirement on the transmission. Cooperative communication is a good choice to address these issues.

Cooperative communication was introduced to improve the transmission performance (i.e. reliability and throughput) [15]. Taking advantage of the cooperative diversity and broadcast nature, data transmission between the source node and the destination node can be overheard by other nearby active nodes. The nodes that receive the data correctly can retransmit the received data to the destination in the following stage. The destination will benefit from these multiple independent copies received from the source and the relays through independent paths.

Since the wireless transmission reliability is identified as the issue of most concern in wireless communications for the smart grid system and the cooperative transmission can significantly improve the network reliability, it is worthwhile to apply the cooperative communications into the smart grid network. Although, the cooperative communications has been well analysed in the literature, most of them have considered traditional networks such as cellular networks [21 - 24], where capacity and transmission range are the most concerned fators, they have often ignored the unique system requirements of smart grid network. There is a lack of research efforts on cooperative communications for smart grid networks, taking into account the specific needs of smart grid system, where link reliability is the most important performance metric.

## 1.2 Motivation

Because the smart grid system always distributes in complex environments [11] and has a high reliability requirement, a modern communications infrastructure is essential for supporting data communication for the management, control and optimization of different types of smart devices in the smart grid. Cooperative communication emerges as a promising technology for overcoming these issues. Although many issues (e.g. scheduling [16], power allocation [17] and routing [18]) for cooperative transmissions have been addressed in the literature, most of them have considered only the traditional networks, such as cellular. Few of them considered the unique wireless conditions of the smart grid system, which has its own network features and different transmission requirements [19]. However, with the increasing demands on the power grid system, there will be huge potential for developing cooperative transmission in the smart grid system. Motivated by this, we firstly applied the cooperative communication in a smart grid system (Problem I in the thesis) to enhance the network reliability performance. Since the smart grid networks has multi-layer network structure, the network deployment for a smart grid system is essential to the communications performance. As few works have been done in network deployment, we developed a new network design strategy for the smart grid HANs. Following the deployment in conventional wireless networks, we also identified and solved the joint relay selection and power control problem in cooperative communications for smart grid system.

## 1.3 Thesis Research and Contributions

The research mainly focused on cooperative communication in the smart grid system, where the transmission reliability is identified as the key component of our research. The contribution of our work can be concluded into three parts.

We firstly applied cooperative relay transmission to the HAN and to extend the current user selection transmission scheme to a joint relay-based user selection and cooperative transmission scheme in smart grid HAN [20]. Based on our proposed scheme, the transmission reliability between the electrical equipment and the smart meter can be effectively improved. An evaluation of the outage performance for cooperative communication and non-cooperative communication is presented and analysed.

Secondly, we addressed the network development issue in HAN of smart grid system. Since traditional wireless network deployment strategies have mainly focused on cellular networks [21–24], where capacity and transmission range are the most important system metrics, they often ignore the unique design requirements of smart grid network deployment. There is a lack of research effort on HAN planning and implementation strategy, taking into account the specific needs of smart grid communications and networking, where link reliability is the key performance metric. We defined the data communication network design and planning problem of the smart grid from the perspective of HAN deployment, and we proposed a network development strategy of smart grid HANs based on the link reliability and the location of the smart meter. We simulated the real home environment to analyse of network design for the smart grid HAN. The smart meter location optimization problem was also identified and solved. The simulation results show that our proposed network development strategy is efficient for guaranteeing high reliability performance.

In the third part, we focus on the joint power allocation and relay selection optimization problem, which has a major impact on cooperative transmission performance [25]. Joint power allocation and relay selection have been analysed in other communication system such as cellular networks on the purpose of maximizing the total network capacity or system throughput. No work has been done within the smart grid system. Therefore, we conducted a joint optimization in the smart grid NANs, which combines the relay selection and power allocation. We formulated the optimization problem to minimize the total transmission power while guaranteeing the link reliability between the home smart meters and their data aggregator unit. Two reduced complexity algorithms were proposed to solve the joint optimization problem, and both of the algorithms were analysed and compared to the existing algorithm. The simulation results show that our proposed algorithms can achieve good performance and outperform the existing algorithm.

The thesis is organized as follows:

**Chapter 2 Preliminaries:** We first introduce the basic background knowledge and related works in the literature concerning the concepts of smart grid architecture, data communication structure in smart grid and cooperative relay transmission.

**Chapter 3 Cooperative Transmission in Smart Grid:** In this chapter, we consider the first and the second problems in our thesis. We apply the cooperative transmission to the HAN of a smart grid and propose a two-stage user selection and cooperative transmission scheme to improve the transmission reliability in the HAN. We also address the network planning issue from the perspective of HAN deployment in smart grid communication networks. We make a network development strategy for smart grid HANs based on the link reliability and the smart meter location. The location optimization problem has been identified and solved. The simulation results show that our proposed deployment strategy is can guarantee high reliability for smart grid HANs.

**Chapter 4 Joint Optimization of Power Allocation and Relay Selection for Smart Grid Neighbourhood Area Networks:** In this chapter, the joint power allocation and relay selection problem in smart grid NANs is identified. We propose to minimize the total transmission power while guaranteeing link reliability between smart meters and the data aggregator unit. We developed two reduced complexity algorithms to solve the joint optimization problem, both of which show good performance in the simulation.

**Chapter 5 Conclusion:** This chapter draws together the conclusions from our research works.

**Chapter 6 Future Works:** Finally, we provide ideas for ongoing and the future works of the smart grid communication.

# Chapter 2. Preliminaries

This section presents the important concepts of the smart grid system and the wireless communication networks needed to support the design in the following chapters. The fundamental concepts and background of the smart grid system, smart grid data communication networks and cooperative relay communication are reviewed in this chapter.

## 2.1 The Smart Grid System

The existing power grid system is experiencing a huge revolution [26]. There are many challenges for the traditional power system, which must be solved to satisfy the increasing demand for the future power system. The 'smart grid' concept has become very popular in the recent years, and it is promising to be the future grid system. With a decentralized infrastructure, the smart grid can provide an intelligent power supply that gives better demand control. The smart grid is designed to be a user-oriented system: by taking the information from generation, distribution and consumption into account, it can offer considerable flexibility, efficiency, accessibility and reliability, compared to the existing grid system. The smart grid system can also provide information and intelligence to the power grid control, efficient demand response and power grid automation. Data communication is an integral part of the smart grid, which integrates the information between the power grid system and its customers. By using two-way data communications technologies, an intelligent network of power generation, distribution and consumption can be achieved.

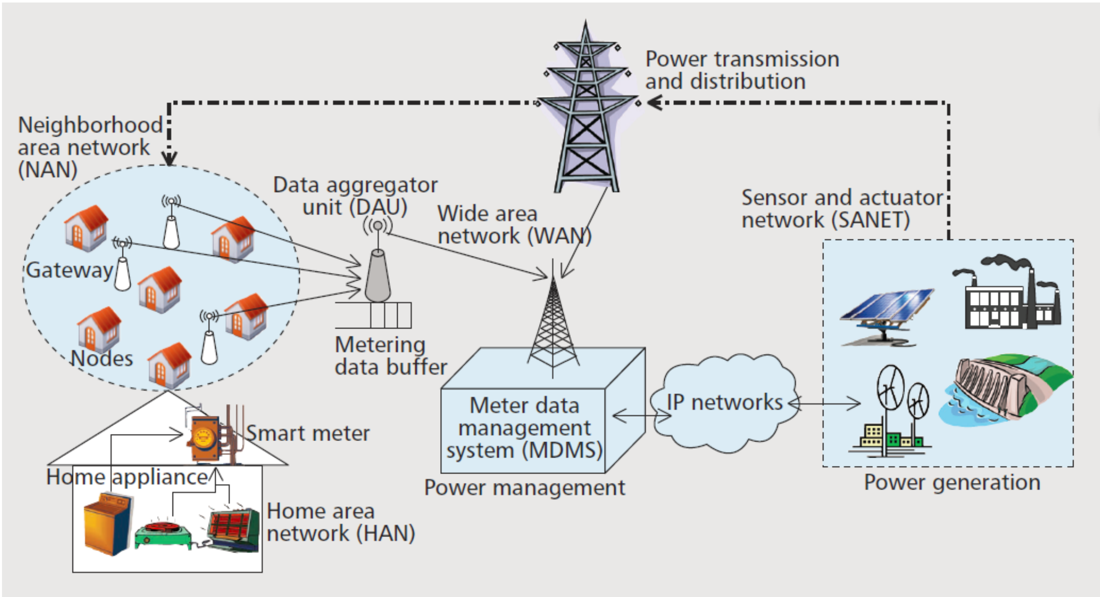


Figure 2.1 Data communications and wireless network for the smart grid

Referring to Figure 2.1 [12], for the smart grid system, the detail for each element is as follows:

### 2.1.1 Home Appliance

Home appliances refers to electricity consumption equipment located inside the smart grid home area network. Home appliances are assumed to have a sensor fitted so that the real-time power demand information of the equipment in the house can be collected and measured by the smart meter. The collected data will be transmitted to the management network for prediction.

### 2.1.2 Data Aggregator Unit (DAU)

The DAU is the core device of the smart grid neighbourhood area network (NAN). Meter data from the home area network will be collected by the DAU, which will then retransmit the data to the control centre to provide support for power consumption and for adjusting the power supply strategy.

### 2.1.3 Power Generator

The power generator is the equipment that generates electricity for the grid system. In a smart grid, it is assumed to have a smart sensor, which has the ability to update the status to the control centre. In some cases, the power generator also needs to report the cost of power to the consumers.

### 2.1.4 Power Transmission and Distribution

The power transmission and distribution system is the system for transferring electric power from the supplier to its consumers. The smart grid transmission and distribution network consists of transmission lines and distribution stations. In the smart grid, the status of the power transmission and distribution system will be updated to the control centre through the smart grid data communication system. In a free power grid market, the cost of power transmission and distribution will also be updated to the management network to make sure that the best strategy is applied.

### 2.1.5 Meter Data Management System (MDMS)

The MDMS is a meter data control centre. It is designed to provide the storage, management and meter data for other smart grid system applications. The MDMS can also collect the status and attributes information from the other parts of the smart grid system, such as power generators and the power distribution system, for control purposes. It is important that the communications system of the MDMS can support high-speed, low latency and highly reliable data transmission.

## 2.2 Data Communications and Networking Infrastructure for Smart Grid

There are different infrastructures for the data communications and networking, most of which are designed to achieve different goals for the smart grid system. There are four main networks in the smart grid, the home energy management system (HEMS), the wide-area measurement system (WAMS), the sensor and actuator network (SANET) and the advanced metering infrastructure (AMI).

### 2.2.1 Home Energy Management System (HEMS)

The main task of the smart grid system is to improve the efficiency of the power consumption in each household. The home energy management system (HEMS) is designed to achieve high efficiency of energy management at the customer side. The HEMS system is also able to monitor and control the different electrical applications by applying different communication technologies (e.g. power line communication, Wi-Fi) [27]. Therefore the smart meters, electric applications, sensor equipment and monitoring equipment such as thermostats can be monitored and controlled in real time.

The HEMS services can also support load management, real-time price-responsive and power usage analysis. The received price and load information will be analysed for the purpose of controlling energy usage of the applications, so that the consumer's requirements can be met.

### 2.2.2 Wide-Area Measurement System (WAMS)

A WAMS can monitor and control the system based on the information from different parts of the smart grid system. It can also provide sufficient security and fault tolerance for the entire power grid. With the main focus on power generation, transmission and distribution, the WAMS consists of a control centre, phasor measurement unit and phasor data aggregator unit to measure the electrical waveforms on an electrical grid so that the state and performance of the power grid can be analysed.

### 2.2.3 Advanced Metering Infrastructure (AMI)

The AMI is the core system in a smart grid, which supports data communications between the smart meter and the MDMS. The AMI is also designed to provide an interface to support other parts of the smart grid system (e.g. adaptive electrical supply and transmission, and active user interface for information access by consumers). The AMI transfers the real-time meter data information including equipment's status and outage situations to the power control centre. Multi-tier architecture with a variety of communications technologies including cellular network (e.g. LTE, GSM, CDMA), PLC and wireless access (e.g. WiMAX) can be used in the AMI.

### 2.2.4 Sensor and Actuator Network (SANET)

A SANET is composed of a number of sensors and actuators, used to monitor and control the operational characteristics and behaviour of smart grid devices so that outages and disturbances can be prevented [10]. The sensors and actuators can be used at multiple sites in the smart grid system (e.g. at a transformer, a distribution substation or a home). The sensors are used to measure different system parameters. The actuators receive and convert control signals into actions by setting the values of different parameters (e.g. displaying sensor measurements or the status of a circuit breaker). The SANET is required to provide secure and continuous information transfer between sensors and actuators using wired or wireless links.

### 2.2.5 Wireless Network Architecture

To support the data transmission and power management in the smart grid, different wireless network architectures can be used [8,9]. As shown in Figure 2.2, three main networks, different in size and location, used in the smart grid system are the home area network (HAN), the neighbourhood area network (NAN), and the wide area network (WAN).

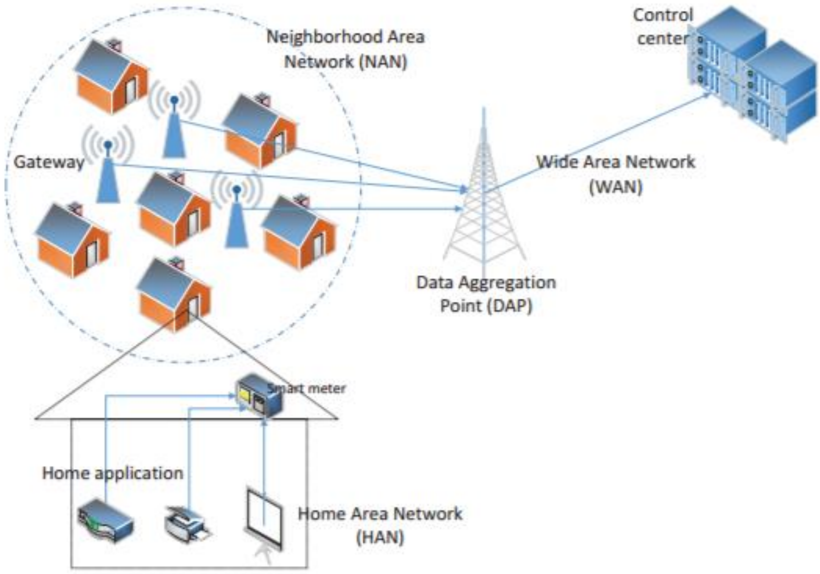


Figure 2.2 Three-layer network for smart grid communication

### 2.2.6 Home Area Network (HAN)

A HAN always adopts local area or short-distance wireless transmission (e.g. Wi-Fi ) to support pricing exchange, real-time meter data transmission and load control, by connecting the devices with sensors (e.g. SANETs), switches, smart meters and HEMS [29]. Wireless communication is very suitable for HANs due to its low installation cost, mobility and flexibility [30]. For example, Wi-Fi is a suitable technology for HANs in terms of interoperability. In a HAN, the home gateway is used to transfer data to the external entity (e.g. DAU). A HAN gateway can be integrated into the smart meter or be a stand-alone device integrated into some in-home devices, such as smart thermostats or in-home switches.

### 2.2.7 Neighbourhood Area Network

The NAN connects multiple HANs together. As shown in Figure 2.2, the HAN gateway transfers meter data to the DAU through the NAN. The DAU communicates with the HAN gateway using network technologies such as Wi-Fi. Also, the DAU can act as the NAN gateway to transfer data to the MDMS.

### 2.2.8 Wide Area Network

The WAN is used to interconnect all the smart grid control systems such as MDMS, AMI and synchronous optical network. The WAN is part of the WAMS for collecting and managing data transmission for the purposes of measurement and control. A WAN can also provide a backhaul connection ability between the customers, power generators, public utility and transmission and distribution systems. In this case, the backhaul can adopt different communication technologies (e.g. cellular network or broadband wireless access) to transfer the data from a NAN (through the DAU) to the MDMS. A WAN gateway can use the broadband connection to collect the data.

### 2.2.9 Wireless Mesh Network

A wireless mesh network always consists of various nodes linked by wireless communication; it is organized in a mesh topology and can thus enhance the coverage [31]. By taking advantage of the self-forming and self-healing network, wireless mesh networks are more reliable [32]. Wireless mesh architectures are usually implemented at the network layer or the data link layer. The wireless mesh network consists of many wireless mesh nodes, and each of the mesh nodes can share the network connection across a large area. Using wireless mesh networks to cover a large area can significantly reduce the cost and complexity compared to traditional communication. Also, the wireless mesh network has good adaptability and expandability, as wireless mesh nodes can be added or removed to adjust the coverage of a wireless mesh network. By taking advantage of cooperative diversity, the relay technologies can improve the performance of wireless links between neighbouring nodes to meet the reliability requirements of a wireless mesh network. The wireless mesh network is also a suitable choice for a wireless smart grid system, as it not only provides flexibility to network development but also supports cooperative relay transmission to enhance the reliability of the whole network [33].

## 2.3 Cooperative Relay Transmission

Cooperative relay communication has been introduced to improve transmission performance (i.e. reliability and throughput) [34], by taking advantage of the cooperative diversity and broadcast nature of wireless channels. The data transmitted from a source node to its destination node can be overheard by other idle nodes that are located close to the source node. Those nodes can act as relays to repeat the data transmission. This makes it possible for the destination to receive multiple independent copies of the transmitted data from the source and the relays respectively. The cooperative transmission has been widely considered in different communication systems, in [72] The author investigates the relay selection and power allocation issues for the cooperative underwater optical wireless communications(UOWC), the cooperative UOWC based on amplify-and-forward (AF) relaying is modeled, two optimization schemes that minimize the energy consumption and maximize the overall signal-to-noise ratio (SNR) was proposed. In [73] the authors present a noncooperative game-theoretic analysis to solve the self-interest-driven relay selection decision-making problem in Vehicular Ad-Hoc Networks. In [74] a semi-centralized cooperative control method is proposed for the cellular uplink transmissions, cooperative schemes based on device-to-device (D2D) communications are proposed to achieve transmission efficiency as well as reducing the power consumption. In [75] The authors adopt the cooperative transmission to improve wireless transmission capacity and reliability in fifth-generation (5G) small-cell networks for vehicular communications. In [76] a joint power and bandwidth allocation of an improved amplify and forward (AF) cooperative communication scheme is proposed to utilize the spectrum efficiently. More issues (e.g. scheduling [16], power allocation [17] and routing [18]) of cooperative transmission have been addressed in the literature. However, most of them only considered the traditional communciations networks, none of them considered the wireless environment for smart grid, which has different transmission requirements. The cooperative communications can help improve the overall reliability of the smart grid communications. The transmitter may encounter a bad channel state (low $SNR$) with the receiver at every available transmission channels, but even in this case, it has the possibility that both the transmitter-relay and relay-receiver channels' state are better than the direct communication channel. Thus, incorporating the cooperative communications into the smart grid communications increase the possibility for the transmitter can transmit the signal via a "good" channel ($SNR$ higher than the outage threshold), which leads to a better reliability for the communications. It is no doubt that, such mechanism may sacrifice part of the bandwidth for the cooperative communications, which will decrease the potential data rate of the communications. But considering the charateristics of the smart grid communications, in which the data for transmission is small but may contain critical information, reliability is more important than the throughput, such trade-off is worthwhile.

Cooperative relay transmission is suitable for smart grid communication since the data volume is not high, and the delay constraint of the data is not stringent.

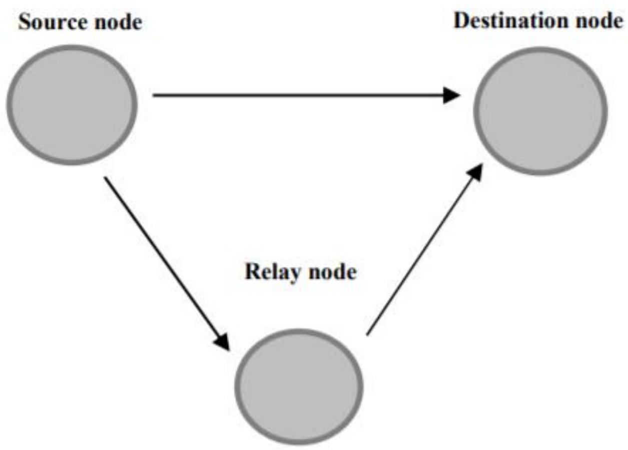


Figure 2.3 Cooperative relay transmission

A classic three-node cooperative relay model is shown in Figure 2.3, which includes a source node, a destination node and a relay node [35]. The cooperative relay transmission processes are divided into two time slots. During the first time slot, the source node broadcasts its signals and the destination node will receive a copy of data through the source-destination link. At the same time, the signals transmitted from the source to its destination can be overheard by the nearby relay nodes. The respective received signals at the destination node and the relay node can be written as:

$$\gamma_{SD} = \sqrt{P_S} h_{SD} x + n_{SR} \qquad (2.1)$$

$$\gamma_{SR} = \sqrt{P_S} h_{SR} x + n_{SR} \qquad (2.2)$$

where $P_S$ represents the transmit power at the source node, $h_{SD}$ and $h_{SR}$ are the channel fading coefficients between the source to destination and source to relay links, and $n_{SD}$ and $n_{SR}$ are the noise powers added to the source to destination and source to relay links.

In the second time slot, the relay node will retransmit the received signal to the destination, and the destination will receive another copy of the data through the independent S-R-D path. By adopting an advanced diversity combining technique, such as max ratio combining (MRC), the destination will benefit from the diversity gain provided by the two independent copies of the data [36]. On the other hand, because the alternative path has been added, the path loss effects can be minimized, and the communication link reliability between the source node and the destination node will also be improved.

In order to achieve high performance on the signal reception, the relay node will process its received signal. Amplified-and-forwarded (AF) and decoded-and-forwarded (DF) are the two most widely used relay protocols; we present the relay processes for AF and DF, respectively.

### 2.3.1 Amplified-and-Forwarded Relaying Strategy

For amplified-and-forwarded (AF), the relay will amplify the received signals from the first time slot and retransmit the signals to the destination in the second time slot. The received signal at the destination node from the relay node can be expressed as [37]:

$$\gamma_{RD}{}^{AF} = \sqrt{P_R} h_{RD} G\left(\sqrt{P_S} h_{SR} x + n_{SR}\right) + n_{RD} \qquad (2.3)$$

where $P_S$ represents the transmitted power at the relay node, $P_R$ is the transmitted power at the relay node, $h_{SR}$ $h_{RD}$ are the channel fading coefficients between the source to relay and relay to destination links, $n_{SR}$ and $n_{RD}$ are the noise powers that add to the source to relay and relay to destination links, and $G$ is the scaling gain.

Depending on whether the scaling gain $G$ is fixed or not, AF relaying can be classified into fixed-gain AF relaying and variable-gain AF relaying.

**Fixed-gain AF relaying:** In fixed-gain relaying, the relay will amplify the received signal with a fixed gain $G$, and the amplified signal will be retransmit to the destination in the next time slot. Fixed-gain relaying is simple to implement but it may not be efficient because it ignores the channel condition.

**Variable-gain AF relaying:** In variable-gain relaying, the relay will amplify the received signal with a variable gain $G$ according to its channel condition. The variable-gain AF relaying can be more efficient by taking the channel condition into account; however, in this case, the full channel state information (CSI) between the source node and the relay node is required to adjust the gain $G$. Therefore, more overheads are needed.

In our research, fixed-gain AF relaying is deployed for its simplicity; however, variable-gain AF relaying can also be applied using the same method. The maximum ratio combining is performed on the signals received during the two stages at the destination [38].

## 2.3.2 Decoded-and-Forwarded Relaying Strategy

For decoded-and-forwarded (DF) relaying, the relay node will try to decode the received signal and recover the original data, then it will re-encode and forward the data to the destination in the second time slot. The performance of DF is based on the transmission quality in the source to relay link. Normally, an $SNR$ threshold is used to identify whether a signal can be successfully decoded. For example, if the received $SNR$ at a relay node is above the $SNR$ threshold, then we assume that the data can be fully recovered; if the received SNR is below the $SNR$ threshold, we assume that the link between the source node and the relay node is in outage, and therefore the relay will not be able to participate in the transmission. In the second time slot of the DF, if the selected relay can correctly decode the message received from the source, it will then forward it to the destination node [39]. The signal received at the destination node from the relay node can be written as:

$$\gamma_{RD}{}^{DF} = \sqrt{P_R} h_{RD} x + n_{RD} \qquad (2.4)$$

where $P_R$ represents the transmit power at the relay node, $h_{RD}$ is the channel fading coefficient between the relay and the destination link, $n_{RD}$ is the noise power that was added by the relay to destination link.

## 2.4 Transmission Reliability

Transmission reliability is a key component in our research; we look at the link reliability in wireless networks first. Our analysis starts with the reliability of a point-to-point communication link. In particular, we are interested in how the reliability of a point-to-point link depends on the channel state and the distance between the two nodes. Once the reliability of a single point-to-point link is established, we extend the reliability result to a wireless relay network. The idea of cooperative diversity is introduced to improve the transmission reliability by taking advantage of wireless broadcast properties and the independence of the fading state of different links between different pairs of nodes. Therefore, the end-to-end reliability between the source and the destination node with the help of the relay node is analysed.

### 2.4.1 Point-to-Point Reliability

In this section, we look at the relationship between reliability and power in a point-to-point flat fading channel. We model the communication link between a source node and a destination node as:

$$y = h_{SD}x + n_{SD} \qquad (2.5)$$

where $x$ represents the transmitted signal, $h_{SD}$ is the signal attenuation due to propagation in the wireless point-to-point link and $n_{SD}$ is the received noise. We assume that the received noise, $n_{SD}$, is zero-mean white additive Gaussian noise with average power of $N_0$.

In general, attenuation, $h_{SD}$, depends on the distance between the communicating points and the fading state of the wireless channel. We use $d$ to represent the distance effects between the communicating nodes and $f$ to represent the fading effects of the channel. We can write $h_{s,d}$ as an explicit function that includes these two parameters:

$$y = h_{SD}(f, d)x + n_{SD} \qquad (2.6)$$

In a real system, for different propagation environments, both $f$ and $d$ change over time. However, in our research, we assume that $f$ and $d$ remain constant for a long period of time so that the effects of the distance and the fading can be captured. We decompose $h_{SD}(f, d)$ into two independent parts corresponding to the small-scale and large-scale path losses (see [40]). Given these assumptions the $SNR$ of the source to destination link is given by [41]:

$$\gamma = \frac{x^2|f|^2}{d^k N_0} \qquad (2.7)$$

where $f$ represents the small-scale path loss, $d$ is the large-scale path loss and $k$ is the propagation loss exponent, and usually varies between 2 to 4.

## 2.4.2 Reliability Formulation

In our research, we use outage probability as the metric for evaluating the reliability performance of the cooperative relay communication.

We defined that the outage event happens when the received $SNR$ is below the $SNR$ threshold [42].

### 2.4.2.1 Reliability in Direct Transmission

For a direct transmission link from source $S$ to destination $D$, we assume that the typical Rayleigh fading channel is adopted, and we characterize the transmission performance regarding reliability probability, which is defined as:

$$p^D = P_r(SNR_{sd} \geq \beta) \qquad (2.8)$$

where $SNR_{sd}$ is the received $SNR$ at the destination node, and the reliability $p^D$ is defined as the probability that the received *SNR* is higher than the *SNR* threshold $\beta$. If the received *SNR* is higher than the threshold $\beta$, then we assume that the transmission between the transmitter and the receiver is reliable. If the received *SNR* is below the threshold $\beta$, then we assume that the receiver is unable to recover the data, thus an outage happens. When an outage occurs, the data is considered lost. The $SNR$ threshold $\beta$ is determined based on the different *SNR* requirements and the receiver sensitivity. For example, the higher quality of service (QoS) will require a larger value of $\beta$.

For a direct transmission between source and destination, the received *SNR* at the destination node $D$ from the source node $S$ is given by [42]:

$$SNR_{SD} = \frac{|h_{SD}|^2 r_{SD}^{-k} P_S^D}{N_0} \tag{2.9}$$

where $P_S^D$ is the transmission power of the direct transmission model, $h_{sd}$ is the Rayleigh fading channel coefficient between the $S$ and $D$, $k$ is the path loss exponent, which varies from 2 to 4, $r_{sd}$ is the distance between $S$ and $D$, and $N_0$ is the power of the additive white Gaussian noise (AWGN). The channel fading of any link is modelled as a zero-mean circularly symmetric complex Gaussian random variable with unit variance, so that $|h_{SD}|^2$ follows an exponential distribution with unit mean. Hence, the reliability for the direct transmission mode $p^D$ can be calculated as [42]:

$$p^D = P_r(SNR_{SD} \geq \beta) = 1 - P_r(SNR_{SD} \leq \beta) \qquad (2.10)$$

$$= \exp\left(-\frac{N_0 \beta r_{SD}^k}{P_S^D}\right) \qquad (2.11)$$

### 2.4.2.2 Cooperative Relay Transmission

For a cooperative relay transmission, we assume that a relay $R$ is allocated for a pair of source $S$ and destination $D$ link. It can select DF or AF depends on the situation. The $SNR$s received at the destination $D$ and the relay $R$ from the source $S$ in the first time slot are given respectively as:

$$SNR_{SD} = \frac{|h_{SD}|^2 r_{SD}^{-k} P_S^C}{N_0} \qquad (2.12)$$

$$SNR_{SR} = \frac{|h_{SR}|^2 r_{SR}^{-k} P_S^C}{N_0} \qquad (2.13)$$

where $P_S^C$ is the transmission power of the source node in the cooperative transmission (CT) model . The $SNR$ received at the destination $D$ from the relay $R$ in the second time slot is given by:

$$SNR_{RD} = \frac{|h_{RD}|^2 r_{RD}^{-k} P_R^C}{N_0} \qquad (2.14)$$

where $P_R^C$ is the transmission power of the relay node in CT mode, and $|h_{SD}|^2$, $|h_{SR}|^2$

and $|h_{RD}|^2$ are independent exponentially distributed random variables with unit mean for link $S-D,\ S-R$ and $R-D$ respectively.

The total transmission reliability probability of the cooperative transmission $P_r^C$ can be calculated as follows [44]:

$$p^C = 1 - \Pr\left((SNR_{SD} \le \beta) \cap (SNR_{SR} \le \beta) + \right.$$
$$\left. Pr((SNR_{SD} \le \beta) \cap (SNR_{RD} \le \beta) \cap (SNR_{SR} \ge \beta)\right)$$
$$= 1 - \left(1 - f(r_{SD}, P_S^C)\right) \times \left(1 - f(r_{SR}, P_S^C) f(r_{RD}, P_R^C)\right) \quad (2.15)$$

where $f(x,y) = exp\,(-\frac{N_0 \beta x^k}{y})$, $Pr((SNR_{SD} \le \beta) \cap (SNR_{SR} \le \beta))$ denotes the probability that both the source-destination and the source-relay channels are in outage, $Pr((SNR_{SD} \le \beta) \cap (SNR_{RD} \le \beta) \cap (SNR_{SR} \ge \beta))$ gives the probability that both the source-destination and the relay-destination channels are in outage while the source-relay channel is not.

## 2.5 Power Consumption

In this section, we look at the power consumption for both direct transmission and cooperative transmission. Following the same assumption as in the transmission reliability, a relay $L$ is allocated for a pair of source $S$ and destination $D$ link.

### 2.5.1 Power Consumption for Direct Transmission

In the direct transmission (DT), the transmission is simply between the source node and the destination node. Therefore, the total transmission power $P_{power}^{D}$ under the $DT$ mode equals to the transmission power of the source node in the $DT$ mode

$$P_{power}^{D} = P_{S}^{D} \qquad (2.16)$$

## 2.5.2 Power Consumption for Cooperative Transmission

The total transmission power $P_{power}^{C}$ under the $CT$ mode can be obtained by [44]:

$$\begin{aligned} P_{power}^{C} &= P_{S}^{C} Pr(SNR_{SD} > \beta)) + P_{s}^{C} Pr(SNR_{SD} < \beta) \\ &\times Pr(SNR_{SR} < \beta) + (P_{S}^{C} + P_{R}^{C}) Pr(SNR_{SD} < \beta) \\ &\times Pr(SNR_{SR} > \beta) \end{aligned} \qquad (2.17)$$

where the $P_{s}^{C} Pr(SNR_{SD} > \beta)$ corresponds to the event that the direct link is reliable; therefore, the total transmission power equals the transmission power of the source node. The $P_{s}^{C} Pr(SNR_{SD} < \beta) Pr(SNR_{SR} < \beta)$ accounts for the event that the direct source-destination and the source-relay links are both in outage, therefore the total transmission power still equals the transmit power of the source node. The final term in the summation $(P_{S}^{C} + P_{R}^{C}) Pr(SNR_{SD} < \beta) Pr(SNR_{SR} > \beta)$ corresponds to the event that the source-destination link is in outage while the source-relay link is not, and in this case, because the source-relay link is reliable, the relay will always transmit in the second time slot, therefore the transmit power of the relay node $P_{R}^{C}$ is included.

# Chapter 3. Cooperative Transmission in a Smart Grid

## 3.1 Introduction

The cooperative communications has been proved to significantly increase the network performance with regards to coverage and reliability [25,33,45]. Recently, cooperative relay transmissions have been considered to improve the performance of wireless communications in smart grids. In [12], a cooperative transmission between the data aggregator unit and the WAN infrastructure was used to increase the reliability and throughput for smart grid communications, but the cooperative transmission was mainly designed for the backhaul communication between the DAU and the MAMS. Relay technologies were introduced to smart grid communications in [46], where the use of collaborative beamforming, unidirectional relaying and bidirectional relaying strategies were studied for the NAN of the smart grid. In [43], a smart relay node was added to the HAN for the smart grid, with increased complexity and cost. In [20], multiuser selection diversity was analysed for schedulers with affordable-rate transmission and adaptive transmission based on the absolute signal-to-noise ratio ($SNR$) and the normalized $SNR$ [47]. In [41], a multiuser selection scheme was proposed for a HAN to reduce outage probability, where all devices in the HAN transmit to the smart meter simultaneously without any mitigation of multiuser interference [48], and at each transmission time, the smart meter decodes only the data transmitted from the device that has the best link condition. Note that the communication reliability of a HAN would also be affected by the network deployment strategy, which optimizes the locations of transmitters/nodes in the network.

Conventional wireless communication network planning and deployment have focused on the cellular communication networks and have often ignored the unique design requirements for smart grid network deployment. Therefore, we address the design and the planning requirements of the smart grid communication network from the perspective of HAN deployment in the smart grid communication networks.

A HAN often deploys local-area wireless communications (e.g. Wi-Fi) to support real-time meter data transmission, load control and dynamic pricing by connecting the user devices, in-home switches, actuators and smart meters together [49]. An external data aggregator unit (DAU) collects the data from the HAN gateway through a NAN. The NAN connects multiple HANs together. A WAN is used to connect multiple DAUs to the meter data management system (MDMS).

Since HANs are where the smart-meter data is collected, the reliability is crucial to the performance of the HANs in a smart grid. The smart meter devices in homes have a low transmission power and are often deployed in complex indoor environments. The high-reliability requirement for smart grid communications needs to be achieved by using advanced wireless techniques.

In this section, we first proposed a two-stage user selection and cooperative transmission scheme to improve the communication reliability in HAN. In the first stage, the best active user device is selected to communicate with the smart meter. In the second stage, an available user device is chosen as a relay to help the communication between the user device selected in the first stage and the smart meter if the direct transmission has failed. The outage probabilities of the user-only selection and cooperative transmission with both amplified-and-forwarded and decoded-and-forwarded relaying are derived.

We then extend the outage expressions to include the effect of network node locations. Based on the extended outage probability expressions, we propose a network deployment strategy to maximize the reliability of smart-grid communications in HANs. The performance of the proposed HAN deployment strategy has been evaluated both analytically and through simulations. The outage probability results of three transmission schemes in the HAN were studied. Then we built a composite random channel model, which extends the fading-only channel model to incorporate the location-induced channel variance. Based on this composite random channel model, the outage probability results are also extended to locational outage probability, which includes the outage caused by locational variation. Thus, we apply this locational outage probability as a performance parameter in the HAN planning. As an example, we use a home environment to simulate the channel condition in the HAN. This example demonstrates that the locational outage probability is effective and the proposed planning strategy is efficient in the HAN deployment. The smart meter location optimization problem has also been identified and solved. The simulation results show that the cooperative transmission based deployment strategy is effective and can guarantee high reliability for smart grid communications in home area networks.

## 3.2 User-Selection and Cooperative Transmission Scheme

We consider a typical smart-grid HAN as shown in Figure 3.1, which is composed of $K$ user devices uniformly distributed in the HAN area and one smart meter $D$. The user devices are act as the source nodes while the smart meter is the destination node in the HAN. We consider the typical HAN wireless access technology, such as Zigbee, Wi-Fi and Narrow Band Internet of Things (NB-IoT) [50, 68]. Zigbee is a low-power, low data rate, and close proximity (i.e., personal area) wireless ad hoc network, the standardization is defined in the IEEE 802.15.4 series. The standard of NB-IoT is developed by 3GPP and its specification was frozen in 3GPP Rel. 13 in June 2016. Although NB-IoT is mainly developed for the low-power wide area network (LPWAN), it is also widely adopted for HAN IoT transmission [51]. We assume that each device has the features of the wireless mesh node, which allow them to act either as a source node to transmit to the smart meter or as a relay node to forward other devices' data to the smart meter.

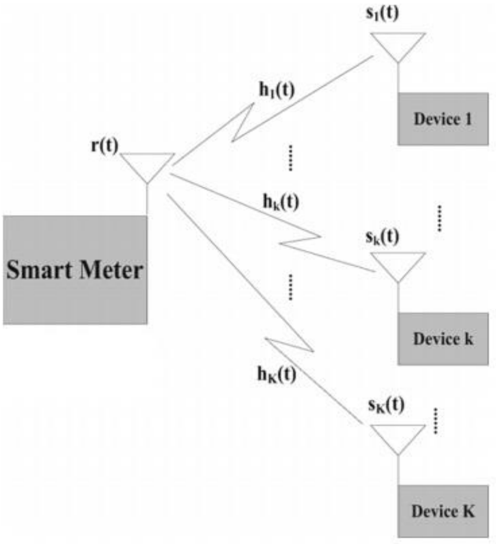


Figure 3.1 Home area network of a smart grid

Assume that all nodes work in half-duplex mode. Each transmission link suffers from independent and identically distributed Rayleigh flat fading. We propose a cooperative user-relay selection scheme. In the first stage, which is for user selection, the smart meter selects the user device that has the best link quality as the source node to transmit to the smart meter. If the direct transmission failed in the first stage, then it proceeds to the second stage, which is cooperative relay transmission, and the smart meter will select a node from the available devices that can overhear the transmission from the source node to the smart meter in the first stage as a relay node. The relay node should have the best communication link to the smart meter between all remaining active devices. The selected relay node will forward the overhead data message from the source node to the smart meter. There exists some protocols such as ARQ and HARQ, which allow the source node to retransmit when the direct transmission is failed, however, these protocols are mainly error-control methods for data transmission, and focusing on reducing the received error in the receiver. These protocols are insufficient for increasing the reliability of the network system in some cases, for example, when the source node is far away from the destination node or with strong path loss affects, the retransmission between the source node and the destination will not be efficient. Instead of simply retransmitting the message between the transmitter and receiver, our proposed cooperative scheme will more focus on the realiability of the system, by allowing the relay node to participate in the transmission, it can provide extra transmition route between the transmitter and the receiver, so that the reliabity will be increased. The details of the two steps are presented in the following.

In the following work, we consider a centralised user selection and radio resource management scenario. All devices are fully controlled by a smart meter in the network. The smart meter can be a Zigbee Router in Zigbee network, the access point (AP) in a Wi-Fi network and the base station (BS) in NB-IoT network [50,51].

### 3.2.1 User Selection Process

In the first stage, the source node is selected from all the available devices based on the channel quality of their link to the smart meter. We assume that in each transmission time slot only one device is allowed to transmit, therefore there is no interference during the transmission. The received signal-to-noise ratio ($SNR$) at the smart meter from the $k$th device $(k = 1, \dots, K)$ is:

$$\gamma_k = \frac{|h|^2{}_k P_k d^{-\alpha}}{N_0} \qquad (3.1)$$

where $P_k$ is the transmission power of the $k$th user device, which is assumed to be the same for all the user devices, and $|h|^2_k$ is the unit mean exponentially distributed channel power gain from the $k$th user device to the smart meter, $d$ is the distance between the transmitter and receiver, $\alpha$ is the pathloss exponent and $N_0$ is the noise power.

According to the user-selection-only transmission scheme [41], the device with the strongest channel to the smart meter among all devices is selected to transmit, and the received $SNR$ at the smart meter is given by:

$$\gamma_s = \max\{\gamma_k\} \qquad (3.2)$$

where $\{\gamma_k\}$ is the set of the *SNR*s of all the user devices given in (3.1).

### 3.2.2 Relay Selection Process

Relay selection is a difficult task in cooperative communication system. Appropriate relay selection will effectively enhance network's performance [77]. Relay selection schemes are designed to satisfy different system requirement. In [78] The authors proposed a joint user-relay selection and association in multi-user multi-relay cooperative wireless relay uplinks with multi-antenna nodes with reduced feedback and overhead. In [79] the author formulated the relay selection with partial (statistical) CSI as a a multiple-decision problem, and proposed two relay selection scheme for improving the spectrum efficiency. In [80] the author combines relay selection with power allocation for two-way Decode-and-Forward (DF) relay channels to achieve a better BER performance with total transmit power constraint. In our proposed system, we focus on the link reliability of the smart grid HAN, once the user selection process finished, a device is selected to act as source node to transmit data to the smart meter, cooperative relay transmission can be used to improve the communication reliability between the selected device and the smart meter by allowing the idle devices to overhear the transmission during the first stage. If the direct transmission in the first stage has failed, the devices that overheard the information in the first stage can act as a relay to help the transmission between the selected source node and the smart meter.

The received $SNR$s for the amplified-and-forwarded and decoded-and-forwarded cooperative transmission schemes are given respectively as:

$$\gamma_{AF} = \max\left(\gamma_s, \max\{\gamma_{AF_k}\}\right) \tag{3.3}$$

$$\gamma_{DF} = \max\left(\gamma_s, \max\{\gamma_{DF_k}\}\right) \tag{3.4}$$

where $\gamma_s$ represents the user-selection-only $SNR$, the two sets $\{\gamma_{AF_k}\}$ and $\{\gamma_{DF_k}\}$ denote the vector of the $SNR$ of different smart grid devices utilizing $AF$ scheme and $DF$ scheme, respectively.

By allowing the relay to participate in the communication, the reliability performance between the source node and the smart meter will not only depend on the direct transmission, but also the relay transmission link. There are advanced techniques in the traditional cooperative communication system,such as, MRC for diversity combining, M parallel direct transmissions and M cooperative transmission, however, they have more requirements on the transmission, such as multiple antennas, spectrum allocation etc. Since, it is early stage of developing cooperative communication in smart grid HAN, and the transmission nodes in the smart grid HAN network are mainly the the electricy devices which equiped with single antenna, our porposed scheme is cost effective, easy to install and also can significantly improve the reliability of the HAN.

Overall, we consider the following process for user selection and relay selection in our scheme.

Step 1: At stage 1, The smart meter selects a transmitter with the best link quality between itself and the receiver (smart meter in our scenario). The smart meter then choose a sub-set $(\leq \kappa)$ of idle devices which are within a range of $\theta$ m to the chosen transimitter to form a relay set, the selected nodes inside the relay set will overheard the direct transmission and buffer the message. Note that $\kappa$ and $\theta$ are two pre-set parameters that controlled the trade-off between reliability and the energy efficiency of the network. With higher $\kappa$ and $\theta$, more idle devices may be included into the buffer and relay actions, which can increase the reliability of the network while downgrade the energy efficiency of the system. Such parameter settings can achieved by intent-based networking (IBN) [84].

Step 2: The transmitter broadcasts its message. All the idle sources will receive and buffer the message if the direct transmission failed; the idle source that successfully received the information with the best the link to the receiver will act as a relay to re-transmit the information to the receiver..

Step 3: If the receiver (smart meter) successfully receives the message from the relay node, the transmission finishes. If not, the smart meter chooses another transmitter (among all the potential relays and the original transmitter) following the rule defined in Step 1.

We note that in our research, we more focus on applying the idea of cooperative transmission into the smart grid network, which leads a new deployment strategy of the smart grid HAN in later stage. The modulation and the coding schemes also have impact on the performance of the smart grid communication. In the [81] the authors evaluate the performance of the quadrature amplitude modulation (RQAM) and Gaussian minimum shift keying (GMSK) on Average symbol error rate (ASER) and average channel capacity (ACC) to show the efficiency of the modulation scheme in smart grid HAN, in [82], the authors propose a robust network coding protocol for enhancing the reliability and speed of data gathering in smart grids. The reserch on the modulation and the coding schemes are of great intersts in our furutre work to further impove the reliability performance of smart grid network.

## 3.3 Deployment Strategy Transmission Schemes in HAN

### 3.3.1 Outage Probability Analysis

The outage probability is the performance metric that is used to evaluate the reliability performance of the transmission schemes [52]. The outage probability of a transmission link is defined as:

$$OP(\gamma_{th}) = \Pr(\gamma \le \gamma_{th}) \qquad (3.5)$$

where $\gamma$ is the received $SNR$ at the destination node, and $\gamma_{th}$ is the threshold $SNR$. Following the channel model indicated in (3.1) and as we consider a Rayleigh fading in our work, the (3.5) is

$$\Pr(\gamma \le \gamma_{th}) = \int_0^{\gamma_{th}} f(\gamma)d\gamma = \frac{1}{N_0}\int_0^{\gamma_{th}} \frac{\gamma}{\sigma^2} e^{-\frac{\gamma^2}{2\sigma^2}} d^{-\alpha}\, d\gamma \qquad (3.6)$$

where $\sigma$ is the scale parameter of the Rayleigh distribution. Following (3.5), the outage probabilities corresponding to the received $SNRs$ in (3.2), (3.3) and (3.4) are given as:

$$OP_s(\gamma_{th}) = \prod \Pr(\gamma_k \le \gamma_{th}) = \prod_{k=1}^{K} \frac{1}{N_0}\int_0^{\gamma_{th}} \frac{\gamma_k}{\sigma^2} e^{-\frac{\gamma_k^2}{2\sigma^2}} d^{-\alpha}\, d\gamma_k \qquad (3.7)$$

$$OP_{AF}(\gamma_{th}) = \int_0^{\gamma_{th}}\int_0^{\gamma_{th}} f_{AF}(\gamma_{AF})f_r(\gamma)d\gamma d\gamma_{AF} \qquad (3.8)$$

$$OP_{DF}(\gamma_{th}) = \int_0^{\gamma_{th}} \int_0^{\gamma_{th}} f_{DF}(\gamma_{DF})f_r(\gamma)d\gamma d\gamma_{DF} \qquad (3.9)$$

where $f_r(\gamma)$ represents the probability density function (PDF) of the received $SNR$ as given in (3.1), which follows the distribution of the fading statistics of the channel, and $f_{AF}(\gamma_{AF})$ and $f_{DF}(\gamma_{DF})$ probability density function (PDF) of the received $SNR$ as given in （3.3），（3.4）, respectively. We note that, for (3.7), (3.8) and (3.9), there is no closed form expression, thus we utilize numerical integration in our work.

### 3.3.2 Outage Analysis for HAN, Considering Locations of Devices

In this subsection, we analyse the impacts of device locations on the outage probability performance of HAN communications by including path loss in the channel model as follows:

$$h(m,l) = PL(m.l) * f \qquad (3.10)$$

where $m$ and $l$ denote the locations of the transmitter and the receiver, respectively, $PL(m.l)$ is the path loss in the channel between locations $m$ and $l$, and $f$ is a random variable representing the small-scale fading. Here we consider a 2-D coordinate system, where $m$ is $(x_m, y_m)$ and $l$ is $(x_l, y_l)$, the distance between $m$ and $l$ can be calculated,with unit meter, as demonstrated in Fig. 3.2. Comparing this channel model with the fading-only model, we see that this model incorporates the receiver-location-induced channel variation through the path loss values at various locations. Thus, this composite fading channel model takes the receiver-location channel variation into account [53].

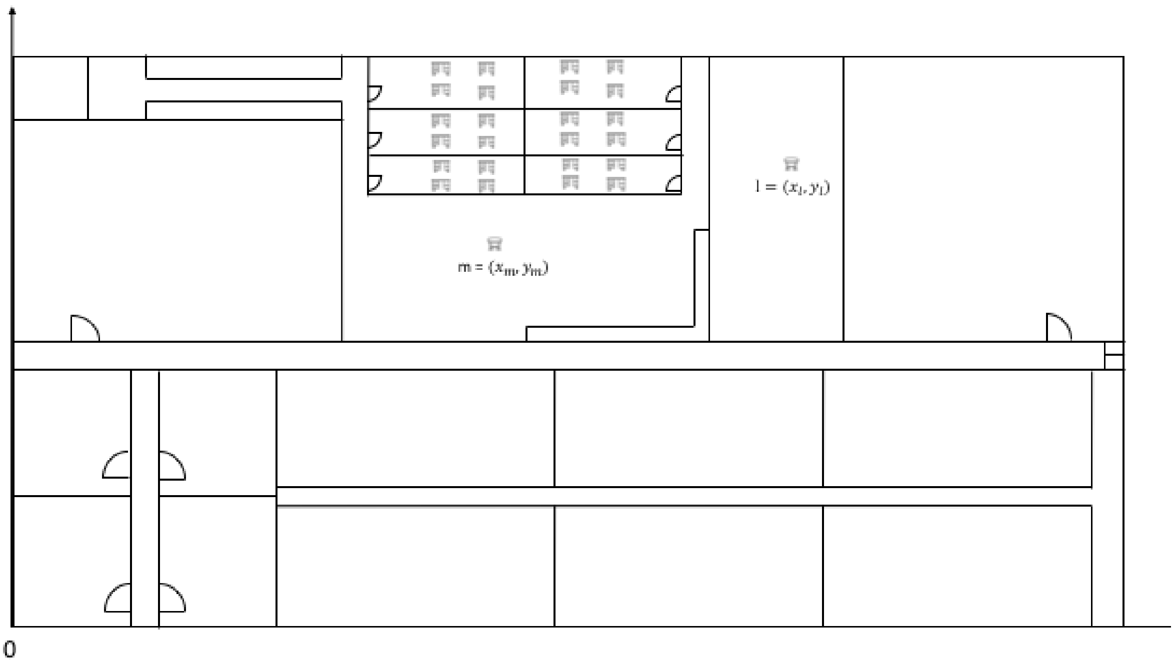


Figure 3.2 Demonstration of $m$ and $l$

Since in the network deployment problem, the locations of network nodes are yet to be determined, we model the path loss value $PL(m.l)$ as a random variable. By fixing a receiver location at $l_f$, the random sample space is the set of the path loss values over all the transmitter locations $\{PL(m.l_f)\}$. The probability density is the likelihood that a certain path loss value appears in the environment. Thus, the path loss value can be seen as a random variable distributed over the transmitter location space. Therefore, for each fixed transmitter location $l$, we have a random variable distributed over all possible receiver locations in the space. In this regard, the channel model in (3.9) is the product of two random variables, the random path loss values over the transmitter locations and the fading component.

Thus, by assuming a fixed possible transmitter location set for all the possible receiver locations, we can rewrite the channel gain as a function of the receiver location $l$ as:

$$h(l) = PL(l) * f \quad (3.11)$$

Thus, the PDF of the product of two independent random variables in (3.9) is given as [54]:

$$f_h(h(l)) = \int_{-\infty}^{\infty} f_f(f) f_{PL}\left(\frac{h(l)}{f}\right) \frac{1}{|f|} df \quad (3.12)$$

where $f_h(h(l))$ is the PDF of the channel gain $h$ with a receiver at location $l$, and $f_f(f)$ and $f_{PL}(x)$ are the PDF of the small-scale fading and the PDF of the path loss values, respectively.

This distribution of the composite channel results from the multiplication of both the channel fading and the location-induced channel variation. Therefore, when we use this distribution of the composite channel to evaluate the outage performance in (3.7), (3.8) and (3.9), the outage probability also captures the location induced outage, which will be utilized in network deployment.

Under the channel model in (3.9), the outage probabilities in (3.6), (3.7) and (3.8) can be rewritten as the function of the channel gain $h$ and the meter location $l$ as follows:

$$OP_s(\gamma_{th}, l) = \prod_{k=1}^{K} \int_0^{\gamma_{th}} f_{h_k}(h_k, l) dh_k \quad (3.13)$$

$$OP_{AF}(\gamma_{th}, l) = \int_0^{\gamma_{th}} \Pr_{AF}(h, l) f_r(h, l) dh \qquad (3.14)$$

$$OP_{DF}(\gamma_{th}, l) = \int_0^{\gamma_{th}} \Pr_{DF}(h, l) f_r(h, l) dh \qquad (3.15)$$

where the distribution of the channel gain $h$ is given in (3.12).

### 3.3.3 Deployment Strategy for HAN

In this subsection, we propose a network deployment strategy for finding the optimal location of the smart meter that minimizes the outage probability in a HAN network. Accordingly, the smart meter deployment optimization can be expressed as:

$$l^* = \arg\ min\, max OP(\gamma_{th}, l) \qquad (3.16)$$

where $OP(\gamma_{th}, l)$ can be substituted by (3.13), (3.14) or (3.15), according to the transmission scheme. The distribution of the channel gain $h$ follows (3.10).

By solving the above optimization problem, the optimal location for the smart meter which achieves the minimum outage probability can be identified.

### 3.3.4 Demonstration of the Impact of Smart Meter Location

In the following section, computer simulations are performed that model a home environment to evaluate the performance of the proposed HAN deployment strategy. We will demonstrate how the location of the smart meter may impact the performance of the system, while we leave the solution of the optimization problem (3.16) and further numerical simulations in Sections 3.4 and 3.5. Some important simulation parameters are listed in the following table.

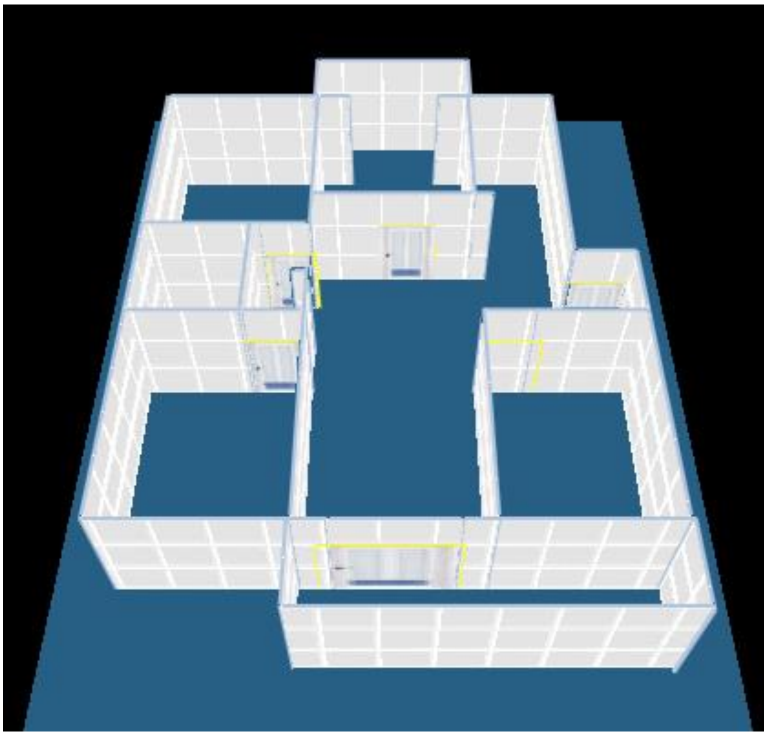

Figure 3.3 3D View of the home environment

Table 1 Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Transmit power | 0.1 W |
| Pathloss exponent | 3.5 |
| Noise level | −111 dBm |
| Frequency | 2.4 GHz |
| Bandwidth | 2 MHz |
| Number of Transmitters | 1, 2, 3, 4 |

### 3.3.5 Environment for Simulation

We choose a home environment to simulate the path loss values. The floor plan used in the simulation is shown in Figure 3.3. It is a typical home environment. We use a ray tracing model to predict the path loss values in the environment [55]. The whole floor area is evenly divided into 100 grids. Each grid provides one randomly selected candidate location within it for the user devices. For simplicity, we choose four candidate locations for the smart meters to be optimized. The ray-tracing simulated path loss maps of the four candidate meters are plotted in Figure 3.4.

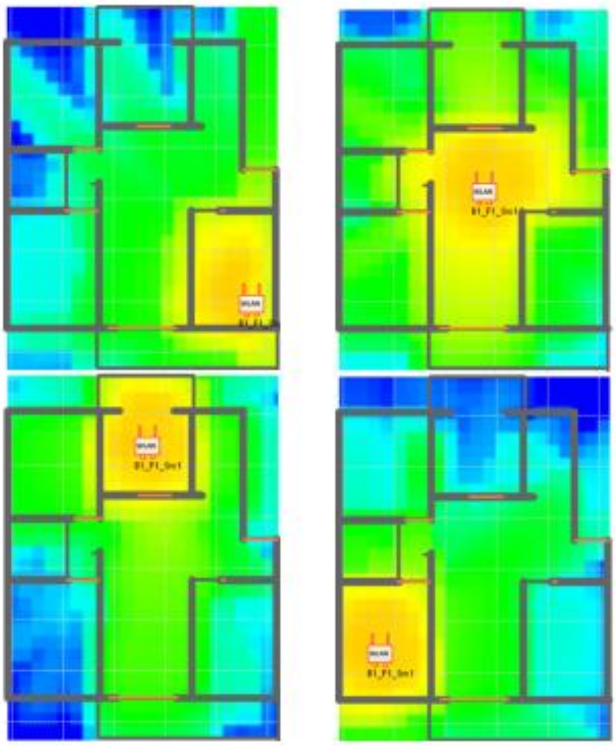

Figure 3.4 Simulated channel at four transmitter locations

### 3.3.6 Distribution of Simulated Channels

Using the simulated path loss values, we plot the cumulated distribution function (CDF) of the simulated path loss values in Figure 3.5.

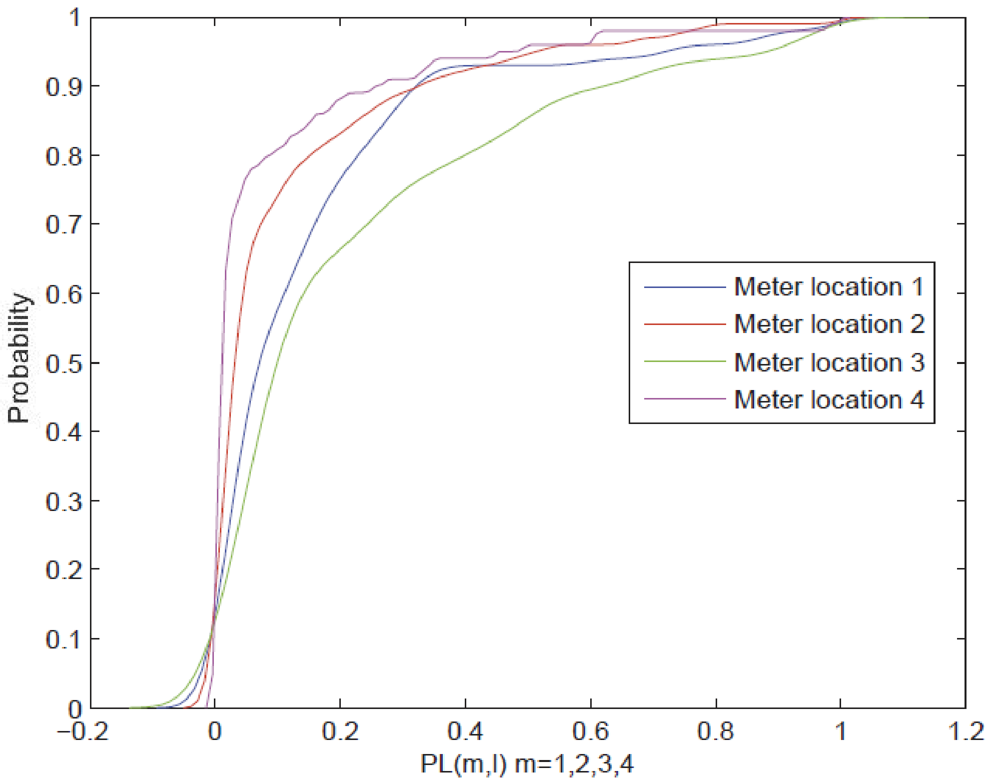


Figure 3.5 CDF of simulated normalized path loss values

To evaluate the outage performance, we need the distribution of the composite channel in (3.2). By using the channel gain distribution in Figure 3.5, and under the assumption that the fading is Rayleigh, the channel gain CDF is plotted in Figure 3.6.

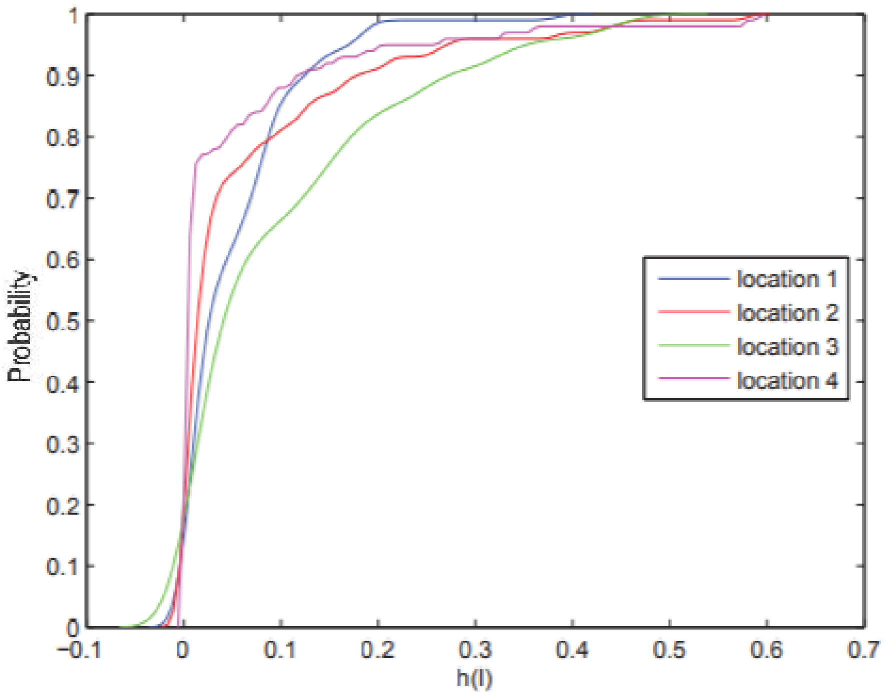


Figure 3.6 CDF of normalized channel gain

For a total number $M$ of locations in the coverage space, if we choose the number of user devices as $L$, then the possible number of location combinations is $C_M^L$, each representing one possible location combination to deploy the $L$ devices. We assume equal probability among all the location combinations. Thus, the probability for each possible location combination is $P_i = \frac{1}{C_M^L}$.

To calculate the distribution of the maximum user-selection $SNR$ in (3.2), we choose the maximum channel value from each possible location combination. Each set $\{\gamma_i\}$ consists of $L$ channel values from $L$ possible locations. Thus, the quantity $\max\{\gamma_i\}$ forms a set that consists of the maximum values of all the possible location combinations. The cardinality of the set is $C_M^L$. Following the equal probability assumption, the probability value assigned to each element in the set is:

$$P_r\left(\max\{\gamma_i\}\right) = \frac{1}{C_M^L} \quad (3.17)$$

where $\{\gamma_i\}$ is the set of the $SNRs$ from all possible location combinations.

In our example, we fix the number of devices $L = 4$. The CDF of the maximum $SNR$ values in (3.2) is plotted in Figure 3.8 based on the simulated channel in Figure 3.7.

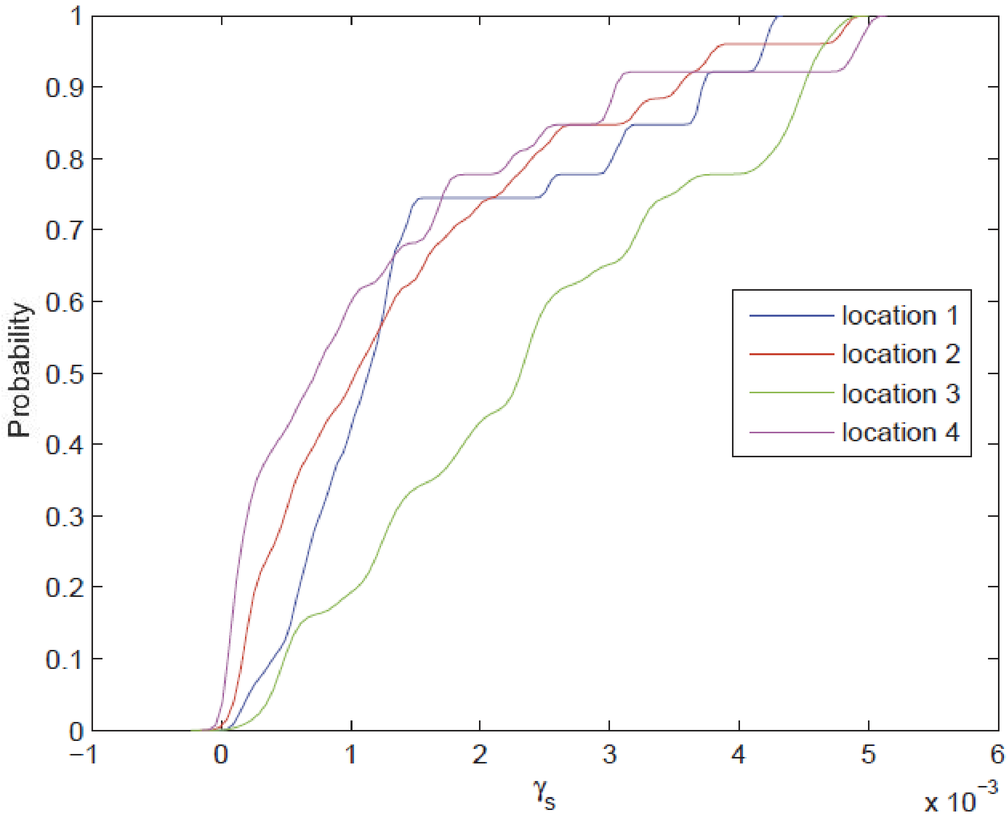


Figure 3.7 CDF of the maximum user selection $SNR$

Next, we calculate the distribution of the maximum $SNR$ in the cooperative transmission schemes in (3.3) and (3.4). Similar to the calculation of the direct link $SNR$ in (3.2), the distribution of the maximum $SNR$ in the cooperative transmission schemes can also be calculated based on the simulation channel information.

Following the realization of user-selection and cooperative transmission schemes [41], we choose the channel value that maximizes the total $SNR$ of the cooperative link, excluding the chosen source user device. The operation is written as:

$$\begin{cases} \max\{\gamma_{AF}\}, & for\ AF\ scheme \\ \max\{\gamma_{DF}\}, & for\ DF\ scheme \end{cases} \tag{3.18}$$

where $\gamma_{AF}$ and $\gamma_{DF}$ are the AF $SNR$ and DF $SNR$, respectively.

The relay selection operation chooses the device which maximizes the total $SNR$ between the source and the smart meter. Using the simulated channel information set, we implement this operation on the simulated channel information set.

Using the simulated channel information set, and the set of all the possible location combinations, we select the relay that maximizes the overall $SNR$ between the source device and the smart meter. Following the same simulated channel information with $L = 4$, the CDFs of the selected $AF\ SNR$ and the $DF\ SNR$ are plotted in Figures 3.7 and 3.8, respectively.

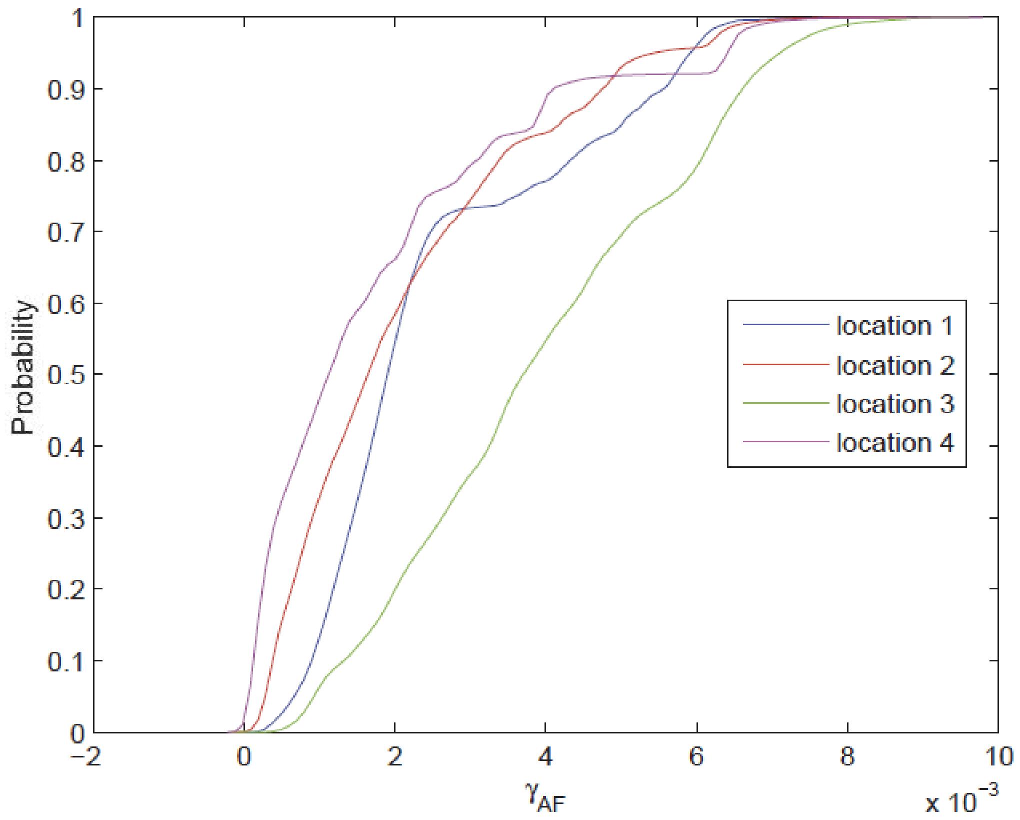


Figure 3.8 CDF of amplified-and-forwarded $SNR$

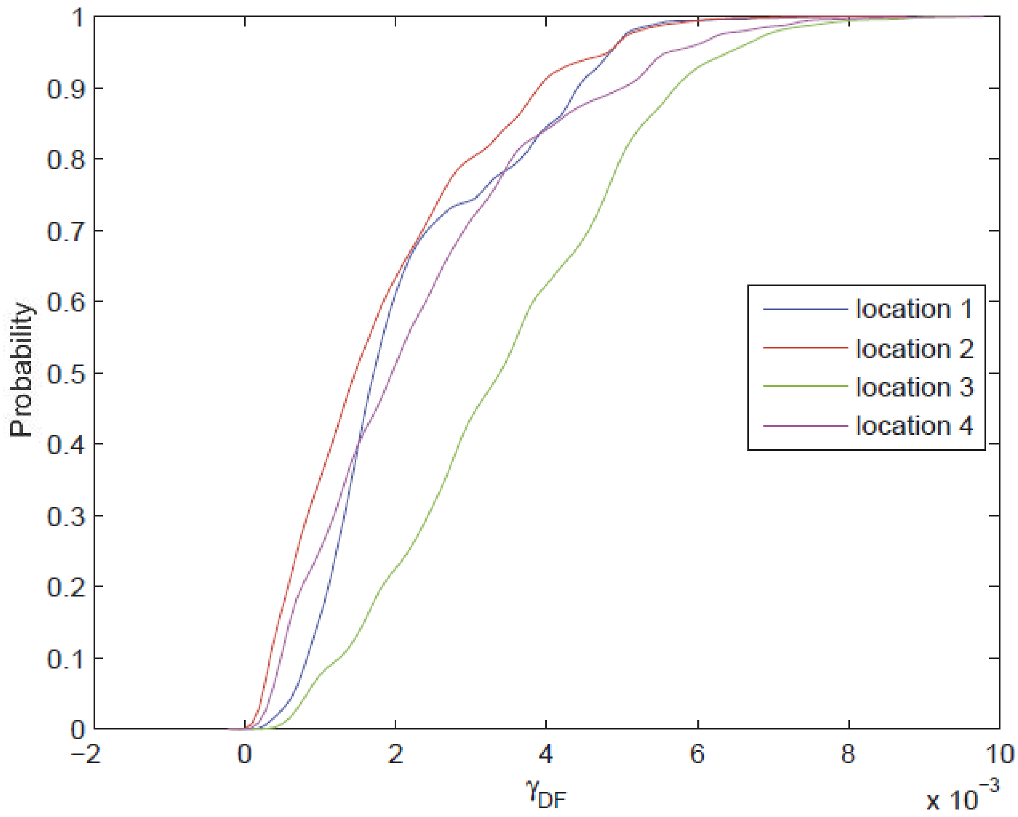


Figure 3.9 CDF of decoded-and-forwarded $SNR$

Thus, using the distribution of the cooperative transmission $SNR$ distribution plotted in Figures 3.8 and 3.9, and the channel gain distribution in Figure 3.7, we can calculate the outage probability according to (3.13), (3.14) and (3.15). The outage performance for the three transmission schemes is plotted in Figures 3.10, 3.11 and 3.12.

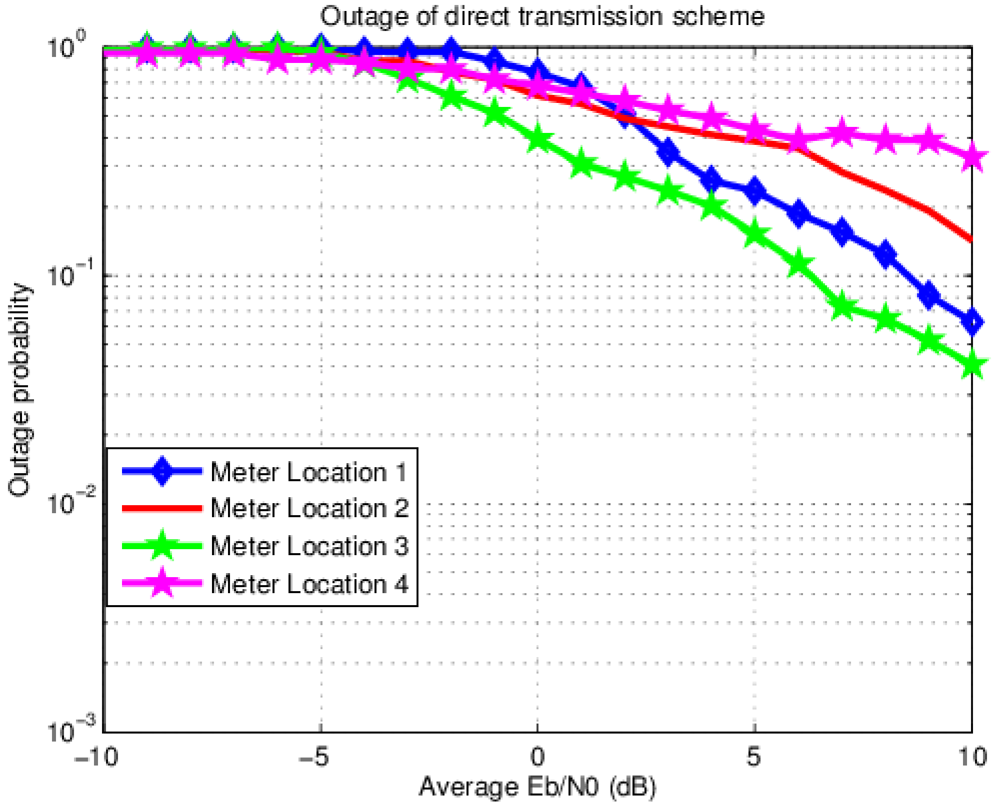


Figure 3.10 Outage of user selection only

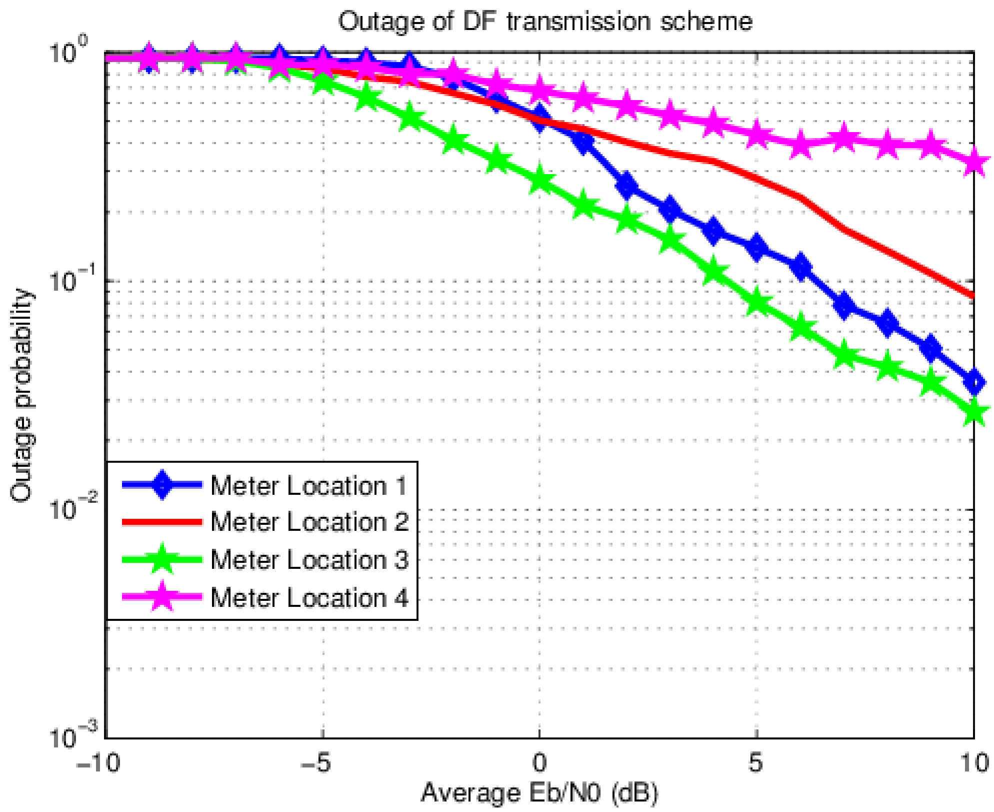


Figure 3.11 Outage of decoded-and-forwarded scheme

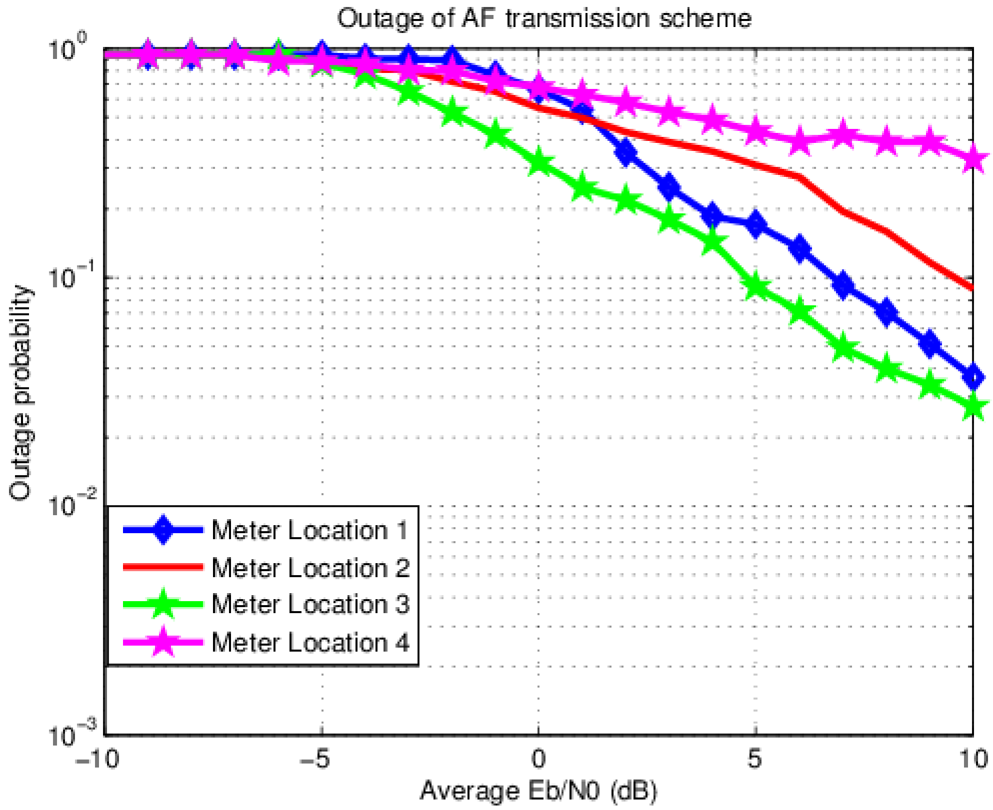


Figure 3.12 Outage of amplified-and-forwarded scheme

From the outage performance results, we can see that in all the three transmission schemes, deploying the smart meter at location 3 yields the minimum outage probability. In this regard, location 3 is the optimal location among the four candidate locations following the HAN deployment strategy. This demonstrates that the proposed HAN deployment strategy is effective in choosing the optimal location for the smart meter in HAN deployment.

# Chapter 4. Optimal Deployment Strategy for Home Area Network

## 4.1 Introduction

In this chapter, we consider the optimal deployment strategy for HAN. In the conventional wireless network, as the users are moving and require fast network service, the major goals of the deployment strategy are coverage and the network throughput [83]. Energy efficiency and deployment cost are two other major factors that are taken into consideration in conventional wireless network design [83-85]. This mainly because in conventional wireless networks, thousands of base stations should be deployed among a large area. For indoor environment, as the access points (APs) should provide the high-speed network service to users in a 24x7 manner. This leads to energy efficiency and deployment cost are two major additional factors to be considered in wireless network design. However, this is not the case for HAN, especially for the smart meters communications in HAN. We conclude that, for smart meter communciations in HAN, there are following characteristics:

1): The location of devices are determined. The devices which communicate to the smart metre are pre-located and maintain static during a long period, for example, the houlsehod appliances.

2) The transmit power of smart communications is low and the network design mainly focus on reducing the outage probability. The transmit power of smart communications should keep low to reduce the potential interference to other wireless network communications and for energy saving. In this case, the main goal of HAN design is to

reduce the outage probability of the smart meter communications.

As aforementioned in Chapter 3, the location of the smart meter significantly affect Thus, it is possible and it is critical to find a best location for smart meter in an area to guarantee the best communication quality for HAN. In this chapter, we propose an algorithm to find the best location for smart meter.

## 4.2 System Model and Problem Formulation

In this section, we demostrate the system model and present the problem we are investigating. We consider an indoor environment as shown in Fig. 3.2. We assume all walls are light walls in our model. We assume there are K devices in the environment, which all locations are determined. They need to communicate a smart meter, which location is optimised in this chapter.

We consider the WINNER II path loss model as following [86]

$$PL_{(LOS)} = 46.8 + 18.7\, log_{10}(d) + 20\, log_{10}(\frac{f_c}{5}) \qquad (4.1)$$

$$PL_{(NLOS)} = 46.4 + 20\, log_{10}(d) + 20\, log_{10}(\frac{f_c}{5}) + L_w \qquad (4.2)$$

where $f_c = 700M$hz, $d$ is the distance between transmitter and receiver (that is the device and the smart meter, respectively, in this chapter), and $L_w$ is the wall penetration losses which is $5(n_w - 1)$ when the signal penerates $\mathrm{n_w}$ walls. We then consider a Rayleigh fading channel. Thus the The received $SNR$ at the smart meter from the $k$th device $(k = 1, \dots, K)$ is:

$$\gamma_k = \frac{P_k |h|^2{}_k\, PL(k)}{N_0} \qquad (4.3)$$

where $P_k$ is the transmission power of the user device, which is assumed to be the same for all the user devices, and $|h|^2{}_k$ is the fading power gain from the $k$th user device to the smart meter, $PL(k)$ is the path loss defined in (4.1) and (4.2) and $N_0$ is the noise power.

In this chapter, we focus to minimise the outage probability of the network. The outage probability of a device can be express as

$$\Pr(k) = \Pr(\gamma_k < \gamma_{th}) = \frac{1}{N_0}\int_0^{\gamma_{th}} \frac{\gamma_k}{\sigma^2} e^{-\frac{\gamma_k^2}{2\sigma^2}} PL(k)\ d\gamma_k \quad (4.4)$$

We propose a network deployment strategy for finding the optimal location of the smart meter that minimizes the maximum outage probability in a HAN network. Accordingly, the smart meter deployment optimization can be expressed as:

$$l^* = arg\ min\,max\,\Pr\,(k) \quad (4.5)$$

By solving the above optimization problem, the optimal location for the smart meter which achieves the minimum outage probability can be identified.

## 4.3 Solution to the Optimal Location of the Smart Meter

We now consider the solution to find the optimal location of the smart meter. We propose an optimal solution by combining particle swarm optimization (PSO) [51] and the Rosenbrock searching algorithm [56].

### 4.3.1 Particle Swarm Optimization (PSO)

The PSO algorithm is originally defined in [51]. It solves a problem by having a population of candidate solutions, which are called “particles”, and moving these particles around in a search-space. For each particle, it can calculate its utility according to its current “position”. In addition, each particle has its own “velocity”, which consists of "speed" and "moving direction". The particle moves according to the velocity and adjusts its velocity according to the utility of its position. The algorithm tries to make all particles move towards their own best positions to maximize (or minimize) the total utility of all particles.

PSO algorithm typically contains the following variants: the number of particles S, inertia weight $w$, acceleration constants $c_1$ and $c_2$, and the terminate threshold $\phi$. For a particle at position $x$, it has utility $f(x)$. The algorithm maintains two result vectors, **pbest** and **gbest**. **pbest** records the positions of the particles for which they have the best utility $P_i = (p_{i1}, \ldots p_{iS})$. On the other hand, **gbest** records the positions of the particles for which the total utility is maximized (or minimized) $P_g = (p_{g1}, \ldots p_{gS})$. For an $i$ iteration, suppose the particles have a velocity vector $\mathrm{V_i} = (v_{i1}, v_{i2}, \ldots, v_{iS})$ and position vector $\mathrm{X}_i = (x_{i1}, x_{i2}, \ldots, x_{iS})$. Then for the iteration $i + 1$, it has

$$v_{(i+1)\mathrm{s}} = wv_{is} + c_1(p_{is} - x_{is})\sigma_1 + c_2(p_{gs} - x_{is})\sigma_2 \qquad (4.6)$$

$$x_{(i+1)s} = x_{is} + v_{is} \qquad (4.7)$$

where $\sigma_1$ and $\sigma_2$ are two adjustment variables that should be defined according to the actual application. In our work, we apply the Rosenbrock searching algorithm [56] for $c_1, c_2, \sigma_1$ and $\sigma_2$. The overall algorithm is described as following

Step 1: Initialize the particle's positions with any random distribution. Initialize the particle's velocity. Initialize iteration indicator $i = 0$.

Step 2: For iteration $i = 0, 1, \ldots$, calculate $f(X_i)$.

Step 3: For any particle $s$, if $f(x_{is}) > p_{is}$, set $p_{is} = f(x_{is})$ and record the position $x_{is}$. Otherwise, continue to Step 4.

Step 4: For any particles with its current location $x_{is}$ fulfil $\sum f(X_i) > \mathbf{gbest}$, then set **gbest** as $\sum f(X_i)$ and record the location $x_{is}$. Otherwise, continue to Step 5.

Step 5: Update the particle's velocity and positions according to (3.18) and (3.19).

Step 6: If $\left|X_{(i+1)} - X_i\right| < \phi$, then terminate, otherwise set $i = i + 1$ and go through Step 2–6.

### 4.3.2 Optimal Solution

The solution to the optimization problem defined in (4.7) is described in this subsection. In our work, the utility function for a location $x_{is}$ of smart meter is given as following:

$$f(x_{is}) = \frac{1}{max\, Pr(k)}, \forall k = 1, \ldots, K \qquad (4.8)$$

In our work, the particle is the smart meter, and the search-space is all the available locations for the smart meter. As mentioned in the previous subsection, the PSO requires $c_1, c_2, \sigma_1$ and $\sigma_2$. We define this according to Rosenbrock searching algorithm [56]. The initial velocity vector $V_0$ does follow the uniform distribution. $c_1 = 1$ and $c_2 = -0.5$. We define

$$\begin{cases} \sigma_1 = 2,\ \ \sigma_2 = 0, & \text{if } f(x_{is}) > p_{is} \\ \sigma_1 = 0,\ \sigma_2 = 0.5, & \text{if } f(x_{is}) < p_{is} \end{cases} \quad (4.9)$$

The combination of Rosenbrock searching algorithm and PSO is describe as follows:

Step 1: PSO initialization and Rosenbrock searching initialization

Step 2: PSO iteration

Step 3: Rosenbrock adjust new direction. For iteration $j$, suppose after Step 2, we have velocity vector $\mathrm{V}_j = (x_j, y_j)$. Then we do a Gram–Schmidt process to get the new searching direction. We consider a vector $v_2 = (0\,,1)$. Assume $V_j$ is not orthogonal with $u_2$, then according to the Gram–Schmidt process we have

$$\mathrm{u}_1 = V_j, \qquad \mathrm{e}_1 = \frac{u_1}{|u_1|} \quad (4.10)$$

$$\mathrm{u}_2 = V_j - proj_{u_1}(v_2),\ \ e_2 = \frac{e_2}{|e_2|} \quad (4.11)$$

where $proj_{x_j}(y_j)$ is the projection of $v_2$ to $\mathrm{u}_1$. Then we set $e_2$ as the initial velocity for the next iteration. If $V_j$ is orthogonal to $v_2$, then $v_2$ is the initial velocity for the next iteration.

Step 4: The iteration terminates if we cannot find a velocity to improve the total **gbest**, which is the optimal solution.

## 4.4 Simulations

In this section, we utilize numerical simulations to demonstrate the performance of our proposed algorithm. For simplicity, we consider the HAN as a $l * l$ square area, however, the proposed algorithm can be applied to HAN with any 2D-shape. In our simulations, 10 devices are randomly distributed in the square area following a uniform distribution. We compare our solution with the algorithm proposed in [57] and [58]. In [57], the authors consider a heuristic algorithm which is based on a greedy algorithm.

The algorithm is simple. The area is splited into a $l_x * l_y$ grid, and for each small rectangle (or cubic) the algorithm calculate the density of devices (number of devices per unit square). Then the algorithm choose the rectangle (cubic) with the highest density and locate the smart meter at the center of the rectangle. In [58], the authors choose a fixed number of locations for the base station, which then transform the optimization problem into a facility location problem (FLB).

That is, for each possible location i one smart meter can be located at that and denoted as i-th smart meter. The FLB can be modelled as following integer program

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}y_{ij} + \sum_{i=1}^{m} f_i x_i \qquad (4.12)$$

where m and n denote the number of smart meters and the devices, respectively, $c_{ij}$ is the cost defined in (4.3), $y_{ij}$is the amount of data transfer from j-th device to i-th smart meter, $x_i$ is {0, 1} indicator which demonstrates whether the i-th smart meter will be built, and $f_i$ is the cost to have the i-th smart meter. Here we will have fix cost of $f_i$ .

It is worth mentioning that in [58] the authors considered an energy-efficient optimization problem, so we change its objective to (3.16) defined in this paper for a fair comparison. The authors in [58] utilize the linprog in Mathlab to solve the problem, here we will follow the same procedure. Other critical simulation parameters are defined in Table 1 (please refer to Section 3.3.4).

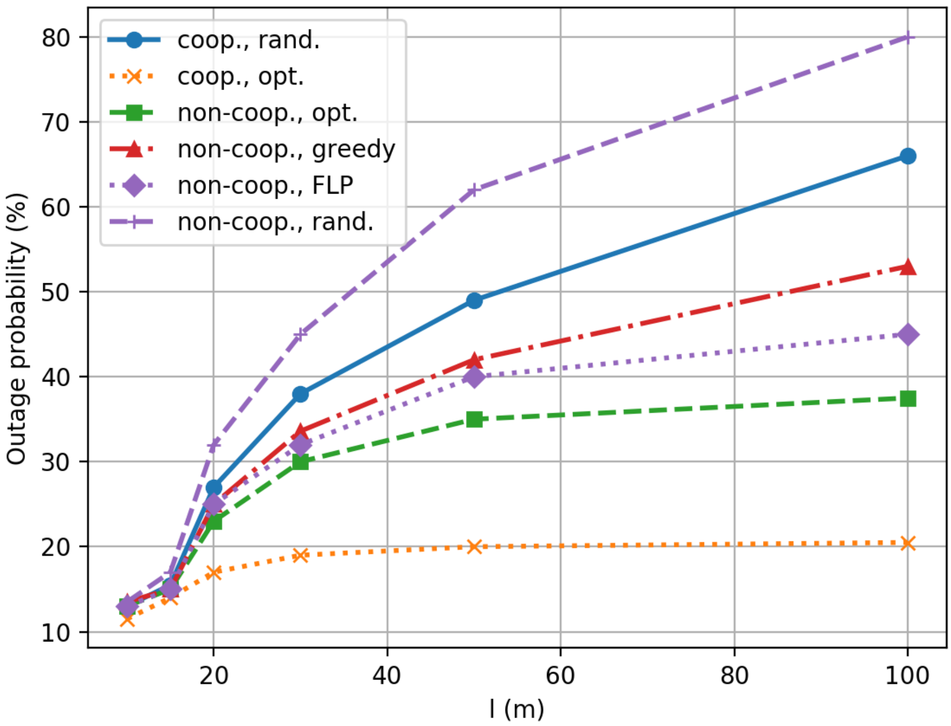


Figure 4.2 Outage probability vs. $l$ (the length of the HAN)

Figure 4.2 demonstrates the performance of the proposed algorithm in terms of $l = 10, 15, 20, 30, 50, 100$. The dashed line with '+' markers represents non-cooperative transmission with the smart meter randomly distributed in the area, while the solid line with circle markers denotes the cooperative transmission with the smart meter randomly distributed in the area. Comparing these two lines, we can conclude that the cooperative transmission actually reduces the outage probability of the system, especially in a large area (when $l$ = 100, it achieves about 20% reduction in terms of outage probability). Then we see that the dashed line with the square markers represents the non-cooperative transmission but with the proposed location algorithm applied to the smart meter, and it shows that the proposed algorithm significantly reduces the outage probability compared to both cooperative and non-cooperative transmissions without the proposed algorithm (50% reduction at $l = 100$). It is not surprising that our proposed algorithm outperforms the algorithms proposed in [57] and [58] (achieving 10–20% reduction in terms of outage probability). Finally, the cooperative transmission with the proposed location algorithm achieves a very good performance (dotted line with ‘x’ markers). It keeps the outage probability lower than 20% even when $l = 100$. Thus we have the following conclusions:

(1) The proposed optimal location algorithm for the smart meter can significantly reduce the outage probability of the system. The improvement is more than the cooperative transmission can bring in.

(2) In a relative large area ($l > 20$), the cooperative transmission and the optimal location for the smart meter are critical to the system.

(3) By combining the cooperative transmission and the proposed location searching algorithm, we can achieve very good performance, which keeps the outage probability always lower than 20%. Thus our overall system design is efficient.

(4) Finally, we demonstrate the computation complexity of the proposed algorithm. In the following table. Each column demonstrate the average computation loops required to achieve the results. We note that, although the solution is not an polynomial algorithm in terms of the number of devices, the algorithm is quite efficient when the searching area increases. As it can be seen from the table, with an area as large as 100m x 100m, it only requires about 212 loops to achieve the optimal solution, only four times as it does with a 10m x 10m area.

Table 2 Loops with length of HAN $l$

| | **10M** | **15M** | **20M** | **30M** | **50M** | **100M** |
|---|---|---|---|---|---|---|
| **LOOPS** | 57 | 82 | 93 | 136 | 157 | 212 |

# Chapter 5. Joint Optimization of Power Allocation and Relay Selection for Smart Grid Neighbourhood Area Networks

## 5.1 Introduction

The power allocation and relay selection problems in cooperative communications need to be considered jointly for achieving optimized performance [12]. The joint power allocation and relay selection have been mainly studied in cellular networks, e.g. to maximize the network capacity [59]. In [60], the authors design an optimal sleep mode selection scheme to maximize the energy efficiency in a mobile WiMAX system while providing a certain QoS guarantee. In [61], the authors considered a two-stage Stackelberg game-based algorithm for the relay selection and power control problem in conventional wireless networks. However, it is not a joint optimal solution. Then in [62], the authors consider a joint optimal algorithm for relay selection and power control in cellular networks based on coalition game. Furthermore, in [63] and [64], the authors consider a joint optimal optimisation for relay selection and power control for wireless networks utilising decoded-and-forwarded (DF) and amplified-and-forwarded (AF), respectively. Due to the high complexity associated with the joint optimization problem, sub-optimal solutions to the optimization problems are sought [65]. None of these previous works focused on the joint relay selection and power control problem in smart grid networks. This is mainly because in the conventional smart grid network, computation resource is very limited, especially compared to those in wireless networks.

Thus it is not possible to apply complex optimal algorithms in smart grid networks. However, as edge computing and 5G network technology are emerging, there is no doubt that the future smart grid network will be equipped with more computation power and thus it is worthwhile to consider joint optimal algorithms for relay selection and power control in smart grid networks [66]. And to the best of our knowledge, our work is the very earliest comprehensive research on this optimisation problem in smart grid networks.

In this chapter we focus on the joint power allocation and relay selection problem for smart grid NANs. The NANs were modelled as a wireless mesh network, and the smart meters and a data aggregator unit are modelled as wireless mesh nodes, which have the ability to act as a relay node to help transmission. Once a smart meter has been selected as the source node to transmit to the data aggregator unit, the remaining smart meters form a relay group, which allows the nodes to act as a relay to help the transmission between the source node and the data aggregator unit. In order to achieve an energy-efficient and high-reliability transmission, we propose to minimize the total transmission power of the system while guaranteeing the transmission reliability between the smart meter and the data aggregator unit. Two low-complexity solutions have been devised to solve the joint optimization problem. As there is no other related works in smart grid networks, we compare our algorithms with the adopted algorithm proposed in [62]. Extensive simulations were carried out to evaluate the performance of the solutions. The simulation results show that our solutions can minimize the total transmission power while satisfying the NAN transmission reliability requirement [67].

## 5.2 System Model

Consider a typical smart grid NAN consisting of multiple smart meters and one data aggregator unit, each equipped with a single antenna. We model the smart grid NAN network as a wireless mesh network [12], and the smart meters within the NAN will have the features of the wireless mesh nodes, which allows them to act either as a source node to transmit its data or as a relay node to help the transmission between other smart meters and the data aggregator unit. During each transmission, only one smart meter is allowed to act as the source node to transmit, and the remaining smart meters will form a relay set. The smart meters from the relay set are able to act as relay to help the transmission between the selected source node and the data aggregator unit. The location of each smart meter and the channel state information (CSI) are assumed to be known perfectly at the data aggregator unit, and the scheduling algorithm is centrally implemented.

We defined two transmission modes: direct transmission (DT) and cooperative transmission (CT). By applying the cooperative modified decoded-and-forwarded relaying scheme [44], which allows the source to transmit in the first time slot, both the relay and data aggregator unit will receive noisy copies of the transmitted data due to the broadcast nature. If the data aggregator unit decodes the data correctly, then it will send an acknowledgment (ACK) to the source and to the relay to confirm successful reception. Otherwise, it will send a negative acknowledgment (NACK) to inform the relay to forward the data to the data aggregator unit in the second time slot.

# 5.3 Performance Metrics

## 5.3.1 Transmission Reliability

### 5.3.1.1 Direct Transmission

In direct transmission mode, we defined that a transmission should be considered as reliable if the received signal-to-noise ratio ($SNR$) at the destination node is higher than the given $SNR$ threshold $\beta$. The transmission reliability for direct transmission can be obtained as:

$$p^D = P(\gamma_{sd} \geq \beta) \qquad (5.1)$$

where $\gamma_{sd}$ is the received $SNR$ at the data aggregator unit from the selected smart meter. The reliability $P_r^D$ represents the probability of the received $SNR$ being higher than the threshold $\beta$. We defined that if the received $SNR$ at the data aggregator unit is higher than the $SNR$ threshold $\beta$, then the data aggregator unit can receive the data with negligible error probability, otherwise, an outage may happen. The transmission is considered to have failed if an outage occurs. The $SNR$ threshold $\beta$ is based on the different application requirements and the receiver's sensitivity. A higher quality of service (QoS) will have a larger value of $\beta$ [68].

For a direct transmission between source and destination, the $SNR$ at the destination node $D$ from the source node $s$ is given by [42]:

$$\gamma_{SD} = \frac{|h_{SD}|^2 r_{SD}^{-k} P_S^D}{N_0} \tag{5.2}$$

where $P_S^D$ is the transmission power in the DT mode, $r_{SD}$ is the distance between $S$ and $D$, $h_{SD}$ is the channel fading coefficient between the $S$ and $D$, $N_0$ is the power of the additive white Gaussian noise (AWGN) and $k$ is the path loss exponent. The channel fading is modelled as a zero-mean circularly symmetric complex Gaussian random variable with unit variance, therefore $|h_{SD}|^2$ follows an exponential distribution with unit mean. Hence, the reliability probability for the direct transmission mode $p^D$ can be calculated as [42]:

$$p^D = P(\gamma_{sd} \geq \beta) = exp\,(-\frac{N_0 \beta r_{sd}^k}{P_S^D}) \tag{5.3}$$

#### 5.3.1.2 Cooperative Transmission

For cooperative transmission, a relay node $R$ is selected during the first time slot, when the source $S$ transmits to the destination node $D$, and the relay $R$ will overhear the transmission, then the received $SNRs$ at the destination $D$ and at the relay $R$ can be expressed respectively as:

$$\gamma_{SD} = \frac{|h_{SD}|^2 r_{SD}^{-k} P_S^C}{N_0} \tag{5.4}$$

$$\gamma_{SR} = \frac{|h_{SR}|^2 r_{SR}^{-k} P_S^C}{N_0} \quad (5.5)$$

where $P_S^C$ is the transmission power of the source node in the $CT$ model, $|h_{SD}|^2$, $|h_{SR}|^2$ are the channel gain for the $S-D$ and $S-R$ links, $r_{SD}$ and $r_{SR}$ are the distances for the $S-D$ and $S-R$ links, $k$ is the path loss exponent and $N_0$ is the noise power. In the second time slot, the relay $R$ retransmits the data to the destination node $D$, and the $SNR$ received at the destination from the relay $R$ is given by:

$$\gamma_{RD} = \frac{|h_{RD}|^2 r_{RD}^{-k} P_R^C}{N_0} \quad (5.6)$$

where $P_R^C$ is the transmission power at the relay node in the *CT* model, and $|h_{SD}|^2$, $|h_{SR}|^2$ and $|h_{SR}|^2$ are independent exponentially distributed random variables with unit mean.

The transmission reliability probability of the cooperative transmission $p^C$ can be calculated as follows [44]:

$$\begin{aligned} p^C &= 1 - Pr((\gamma_{SD} \leq \beta) \cap (\gamma_{SR} \leq \beta)) \\ &+ Pr((\gamma_{SD} \leq \beta) \cap (\gamma_{RD} \leq \beta) \cap (\gamma_{SR} \geq \beta)) \\ &= 1 - (1 - f(r_{SD}, P_S^C)) \times (1 - f(r_{SR}, P_S^C) f(r_{RD}, P_R^C)) \end{aligned} \quad (5.7)$$

where $f(x,y) = exp\,(-\frac{N_0 \beta x^k}{y})$, $Pr((\gamma_{SD} \leq \beta) \cap (\gamma_{SR} \leq \beta))$ denotes the probability that both the source to destination link and the source to relay link are in outage, $Pr((\gamma_{SD} \leq \beta) \cap (\gamma_{RD} \leq \beta) \cap (\gamma_{SR} \geq \beta))$ represents the probability that both the source to destination link and the relay to destination link are in outage while the source to relay link is not.

### 5.3.2 Power Consumption Model

The total transmission power $P_{power}^{D}$ under the $DT$ mode equals to the transmission power of the source node in the *DT* mode. The total transmission power $P_{power}^{C}$ under the $CT$ mode can be obtained by [44]:

$$
\begin{aligned}
& P_{power}^{C} = P_S^C Pr(\gamma_{SD} > \beta)) + P_S^C Pr(\gamma_{SD} < \beta) \\
& \times Pr(\gamma_{SR} < \beta) + (P_S^C + P_R^C) Pr(\gamma_{SD} < \beta) \\
& \times Pr(\gamma_{SR} > \beta)
\end{aligned}
\tag{5.8}
$$

where the $P_S^C Pr(\gamma_{SD} > \beta))$ corresponds to the event that the direct link is reliable; therefore, the total transmission power equals the transmission power of the source node. The $P_S^C Pr(\gamma_{SD} < \beta) Pr(\gamma_{SR} < \beta)$ accounts for the event that the direct source-destination and the source-relay links are both in the outage, therefore the total transmission power still equals the transmit power of the source node. The last term in the summation $(P_S^C + P_R^C) Pr(\gamma_{SD} < \beta) Pr(\gamma_{SR} > \beta)$ corresponds to the event that the source-destination link is in outage while the source-relay link is not, and in this case, because of the source-relay link is reliable, the relay will always transmit in the second time slot, therefore the transmit power of the relay node $P_R^C$ is included.

## 5.4 Problem Formulation

For a single pair of source-destination link, the diversity gain obtained by selecting the best possible relay node is higher than the diversity gain that is obtained by multiple relay nodes [69]. According to the facts, we assume that, each time, only the best relay node is selected among all $N$ available relays for each source-destination pair, and this can be expressed as：

$$\sum_{n=1}^{N} x_n = 1 \tag{5.9}$$

where $x_n = 1$ if the relay $n$ is selected; otherwise $x_n = 0$

The joint optimization problem can be formulated by minimizing the total transmission power while guaranteeing transmission reliability,

$$\arg\ \min_{P_S^C, P_R^C, n} \quad \sum_{l=1}^{L} x_n\, P_{power}^C(l) \tag{5.10}$$

$$\mathrm{s.t.} \qquad \sum_{l=1}^{L} p^C\,(l) x_n \geq p_{th} \tag{5.11}$$

$$P_{max} \geq P_s^C \geq 0 \tag{5.12}$$

$$P_{max} \geq P_R^C \geq 0 \tag{5.13}$$

$$\sum_{n=1}^{N} x_n = 1 \tag{5.14}$$

$$x_n \in \{0,1\}, n = 1,2,3 \dots, N \tag{5.15}$$

where $p_{max}$ is the maximum transmission power of a node, and $p_{th}$ is the reliability threshold that guarantees the QoS requirement of the smart grid communications.

# 5.5 Proposed Algorithms

## 5.5.1 Sub-Optimal: Approximation

According to the optimization problem in (5.10), it can be very complex to find the optimal solution to the problem, due to the fact that the transmission reliability constraint depends not only on relay selection but also on the power allocation,but also the computationa complexity which contains high order variables and the total number of the relays in the system, in order to solve the optimization problem, we propose to simplify the original optimization problem and devise a sub-optimal solution to solve it.

If the value of $x$ is small and close to 0, we can obtain the approximation, following [70]:

$$1 - exp(-x) \approx x \tag{5.16}$$

In a high $SNR$ situation, we can adopt the Lagrange multipliers method and substitute (5.12) into (5.3), (5.7) and (5.11), and the optimization problem in (5.10) can be set as follows:

$$L(P_S^C, P_R^C, \lambda) = P_{power}^C + \lambda(p_{th} - p^C) \tag{5.17}$$

where

$$\begin{aligned} P_{power}^C &= P_S^C(1 - \frac{N_0 \beta r_{SD}^k}{P_S^C}) + P_S^C(\frac{N_0 \beta r_{SD}^k}{P_S^C})(\frac{N_0 \beta r_{SR}^k}{P_S^C}) \\ &+ (P_S^C + P_R^C)(1 - \frac{N_0 \beta r_{SR}^k}{P_S^C})(\frac{N_0 \beta r_{SD}^k}{P_R^C}) \end{aligned} \tag{5.18}$$

$$\begin{aligned} p^C &= 1 - (\frac{N_0 \beta r_{SD}^k}{P_S^C}) \\ &\times (\frac{P_R^C N_0 \beta r_{SR}^k + P_S^C N_0 \beta r_{RD}^k - N_0^2 \beta_2 r_{SR}^k r_{RD}^k}{P_S^C P_R^C}) \end{aligned} \tag{5.19}$$

Now we prove the convexity of the $P_{power}^C$. We denote $P_{power}^C$ as y in the following provement. We firstly consider its first-order partial derivative.

$$\frac{\partial \mathrm{y}}{\partial \mathrm{P}_S^C} = 1 - N_0^2 \beta^2 r_{SD}^k r_{SR}^k (P_S^C)^{-2} + \frac{N_0 \beta r_{SD}^k}{P_R^C} \tag{5.20}$$

$$\frac{\partial \mathrm{y}}{\partial \mathrm{P}_R^C} = \frac{1}{(P_R^C)^2}\left(1 - \frac{N_0 \beta r_{SR}^k}{P_S^C}\right) + \frac{1}{(P_R^C)^2} N_0^2 \beta^2 r_{SD}^k r_{SR}^k \tag{5.21}$$

As we note that, we consider the situation where the SNR is relatively large, that is

$$\frac{N_0 \beta r_{SD}^k}{P_S^C} \ll 1 \tag{5.22}$$

$$\frac{N_0 \beta r_{SR}^k}{P_R^C} << 1 \tag{5.23}$$

With this two conditions, we conclude that

$$\frac{\partial y}{\partial P_S^C} > 0 \tag{5.24}$$

$$\frac{\partial y}{\partial P_R^C} > 0 \tag{5.25}$$

We then consider the second-order derivative of y

$$\frac{\partial^2 y}{\partial (P_S^C)^2} = (P_S^C)^{-4} N_0^2 \beta^2 r_{SD}^k r_{SR}^k \quad > 0 \tag{5.26}$$

$$\frac{\partial^2 y}{\partial (P_R^C)^2} = -(P_S^C)^{-4} \left(1 - \frac{N_0 \beta r_{SR}^k}{P_S^C} + N_0^2 \beta^2 r_{SD}^k r_{SR}^k\right) \quad < 0 \tag{5.27}$$

$$\frac{\partial^2 y}{\partial P_S^C \partial P_R^C} = -\frac{N_0 \beta r_{SD}^k}{\left(P_R^C\right)^2} < 0 \tag{5.28}$$

$$\frac{\partial^2 y}{\partial P_R^C \partial P_S^C} = \frac{N_0 \beta r_{SR}^k}{\left(P_R^C\right)^2} (P_S^C)^2 > 0 \tag{5.29}$$

Thus its Hessian matrix is as following

$$\begin{vmatrix} \frac{\partial^2 y}{\partial (P_S^C)^2} & \frac{\partial^2 y}{\partial P_S^C \partial P_R^C} \\ \frac{\partial^2 y}{\partial (P_R^C)^2} & \frac{\partial^2 y}{\partial P_R^C \partial P_S^C} \end{vmatrix} < 0 \tag{5.30}$$

Thus, we prove its convexity in our scenario. In the following part of this section, we utilize the Lagrange multiplier method to solve the optimisation problem.

Differentiating the $L(P_S^C, P_R^C, \lambda)$ with respect to $P_S^C, P_R^C, \lambda$ separately and letting the equations be equal to 0, we have:

$$\begin{aligned} &\frac{dL(P_S^C, P_R^C, \lambda)}{dP_S^C} \\ &= \frac{({P_S^C}^3 - 2N_0^2 r_{SD}^k r_{SR}^k \beta^2) P_R^C + N_0 r_{SD}^k \beta {P_S^C}^3 - \lambda N_0^2 r_{SD}^k r_{RD}^k \beta^2 P_S^C + 2\lambda N_0^3 r_{SD}^k r_{RD}^k r_{SR}^k \beta^2 r_{RD}^k \beta^3}{{P_S^C}^3 P_R^C} \\ &= 0 \end{aligned} \tag{5.31}$$

$$\frac{dL(P_S^C, P_R^C, \lambda)}{dP_R^C} = \frac{{P_S^C}^3 N_0 r_{SD} \beta - {P_S^C}^2 N_0^2\, r_{SD}^k r_{SR}^k \beta^2 + \lambda N_0^2 r_{SD}^k r_{RD}^k \beta^2 P_S^C \; - \lambda N_0^3 r_{SD}^k r_{RD}^k r_{SR}^k \beta^2 r_{RD}^k \beta^3}{{P_S^C}^2 {P_R^C}^2} = 0 \tag{5.32}$$

$$\frac{dL(P_S^C, P_R^C, \lambda)}{d\lambda} = \frac{({P_S^C}^2 (p_{th} - 1) + N_0^2\, r_{SD}^k r_{SR}^k \beta^2) P_R^C \; + N_0^2 r_{SD}^k r_{RD}^k \beta^2 P_S^C \; - N_0^3 r_{SD}^k r_{RD}^k r_{SR}^k \beta^2 r_{RD}^k \beta^3}{{P_S^C}^2 P_R^C} = 0 \tag{5.33}$$

With above Lagrange multiplier equation grop, the optimal power allocation for the source $S$ $P_S^C$ and the relay $R$ $P_R^C$ can be obtained By solving (5.31)–(5.33), the relay selection will perform according to the solution of the above equations, and the relay that provides the minimum values of $P_S^C$ and $P_R^C$ will be selected as the best relay. We note that, from (5.31)-(5.33), $P_S^C$ and $P_R^C$ may not be strictly postitive. However, we have the constraints (5.12) and (5.13), thus if one of them is negative, it means such pair cannot be chosen.

### 5.5.2 Sub-Optimal: Fixed Source Power

Although the Algorithm I gives the solution to the optimization problem, the computational complexity of the problem is still high, and the complexity also depends on the total number of the available relays in the network, so in order to further reduce the complexity, we proposed an $\alpha$-proportional fixed power algorithm, where the transmit power of the source node in the CT mode is scaled by a fixed factor $\alpha$ $(0 < \alpha \leq 1)$. Therefore, instead of the power allocation problem for both source node and relay node, we only need to solve the power allocation problem for the relay node.

The minimum total transmit power of a direct transmission link with reliability threshold $p_{th}$ can be obtained as:

$$P_S^{D^*} = \frac{p_{th} N_0 r_{SD}^k}{-ln(p_{th})} \tag{5.34}$$

By applying $\alpha$-proportional fixed power algorithm, the transmit power of the source node is set as:

$$P_S^C = \alpha P_S^{D^*} \tag{5.35}$$

where $0 < 0 < \alpha \leq 11$.

By substituting (5.35) into (5.7) and (5.8), we have:

$$\begin{aligned} p^C &= 1 - (1 - exp\,(-\frac{N_0 \beta r_{SD}^k}{\alpha p_S^{D^*}})) \\ &\times (1 - exp\,(-\frac{N_0 \beta r_{SR}^k}{\alpha p_S^{D^*}})\, exp\,(-\frac{N_0 \beta r_{RD}^k}{p_R^C}) \end{aligned} \tag{5.36}$$

$$P_{power}^{C} = \alpha P_S^{D^*} Pr(SNR_{SD} \geq \beta) + \alpha p_S^{D^*} Pr(SNR_{SD} \leq \beta)$$
$$\times Pr(SNR_{SR} \leq \beta) + (\alpha P_S^{D^*} + P_R^C) Pr(SNR_{SD} \leq \beta) \quad (5.37)$$
$$\times Pr(SNR_{SR} \geq \beta)$$

By letting $k_1 = exp\,(-\frac{N_0 \beta r_{SD}^k}{\alpha P_S^{D^*}})$, which is a value independent of the relay selection, we rewrite (5.36) as:

$$p^C = 1 - (1 - k_1)$$
$$\times (1 - exp\,(-\frac{N_0 \beta r_{SR}^k}{\alpha P_S^{D^*}})\, exp\,(-\frac{N_0 \beta r_{RD}^k}{P_R^C}) \quad (5.38)$$

Rearranging terms in (5.38), we have:

$$\frac{N_0 \beta (\alpha P_S^{D^*} r_{RD}^k + P_R^C r_{SR}^k)}{\alpha P_S^{D^*} P_R^C} = -\,ln\left(\frac{p_{th} - k_1}{1 - k_1}\right) \quad (5.39)$$

Let $A = -\frac{ln\left(\frac{p_{th} - k_1}{1 - k_1}\right)}{N_0 \beta}$

then we have:

$$P_R^C = \frac{\alpha P_S^{D^*} r_{RD}^k}{A \alpha P_S^{D^*} - r_{SR}^k} \quad (5.50)$$

From (5.40) we can conclude that the values of $P_R^C$ rely on $r_{SR}$ and $r_{RD}$, and are determined by the different locations of the relay nodes. Based on (5.40), the relay node that provides the smallest value of $P_R^C$ will be selected. The corresponding value of

$P_R^C$ will also give the optimal power allocation. For the relay selection, in order to find the optimal relay, the distance of $r_{SR}$ and $r_{RD}$ for each relay will need to be submitted to (5.40). Therefore, a full search of the relay locations is required. To further reduce the search complexity, a geographic search algorithm is proposed.

As shown in Figure 5.1, given a random relay $R$, two circles can be drawn centred at $S$ and $D$ with a radius of $r_{SR}$ and $r_{RD}$, respectively. Any relay node that is located outside the two circles will have a larger value of distance to $S$ and $D$ than the node that is located inside the two circles, thus any node that is outside the two circles will not be considered for a relay node. Because the location of each node is fixed and known to the data aggregator unit, there is no need to submit every relay's location to (5.40) to solve the optimal problem. We initialize the search from the relay node that has the smallest size of the two circles, and only the relay nodes located inside the two circles will be submitted to (5.40) to compare for the optimal allocation of the power. By applying the geographic search, and reducing the search area, the complexity of relay selection is reduced significantly.

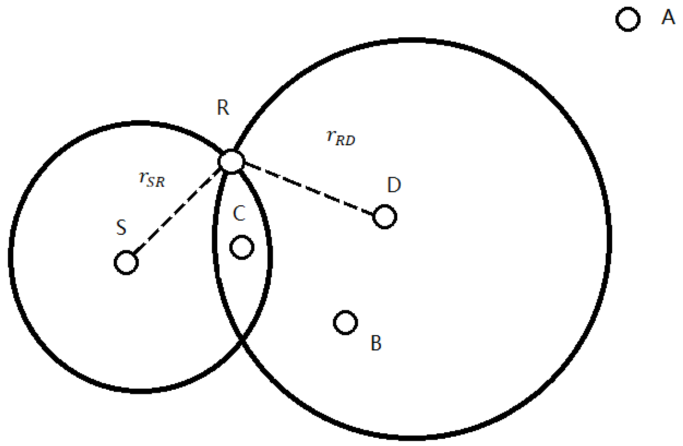


Figure 5.1 Geographic search algorithm

We conclude our proposed algorithm as following.

Step 0: for any pair of transmitter S and receiver (the smart meter) D, we randomly select a relay $R_0$. Set k=0. Step 1: for an iteration $k = 0,1 \ldots$, a relay $R_k$ is selected. We draw two circles which are centred at S and D with a radius of $r_{SR_k}$ and $r_{R_kD}$, respectively, as depicted in Fig. 5.1. Then we have a set of devices $\{T_k\}$ which are within the area of these two circles.

Step 2: For any device in $\{T_k\}$, we calculate the optimal transmit power according to the algorithms proposed in 5.5.1 and 5.5.2. If a relay $R_k^*$ has a better performance than $R_k$, stop Step 2 and go to Step 3.

Step 3: Set $R_{k+1} = R_k^*$. Set $k = k + 1$. Repeat Step 1-3 until there is no better relay can be found.

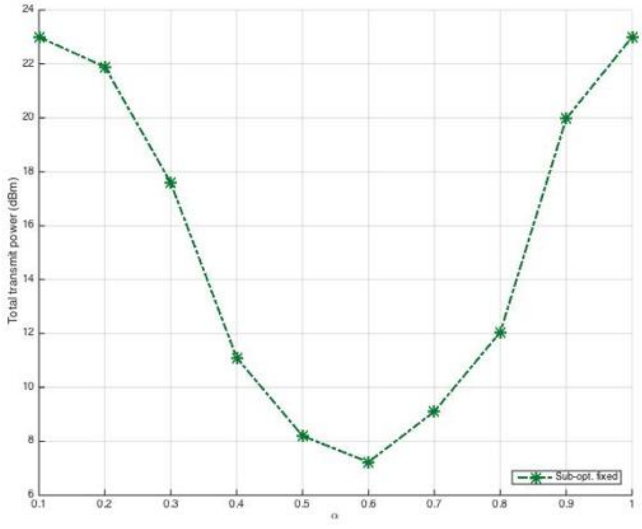


Figure 5.2 Total transmit power of Algorithm II with different values of α

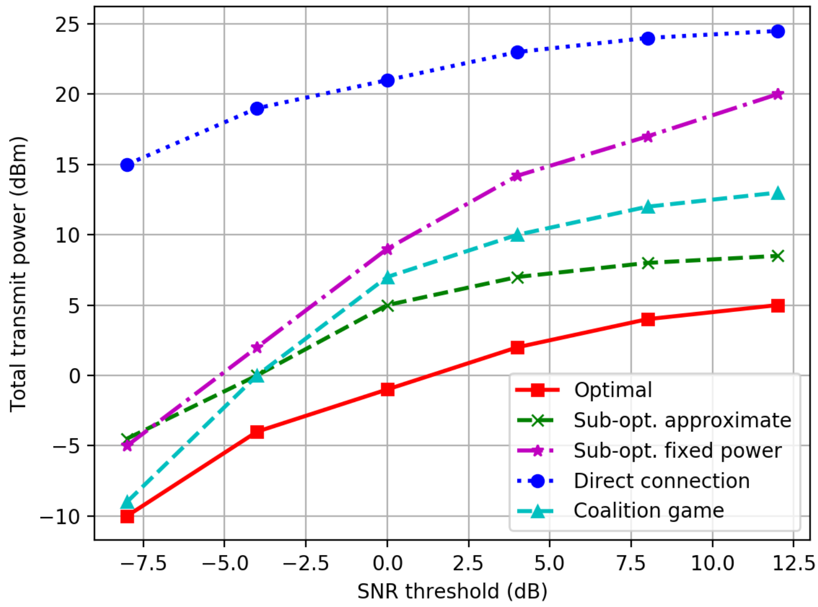


Figure 5.3 Total transmit power with different $SNR$ thresholds $\beta$

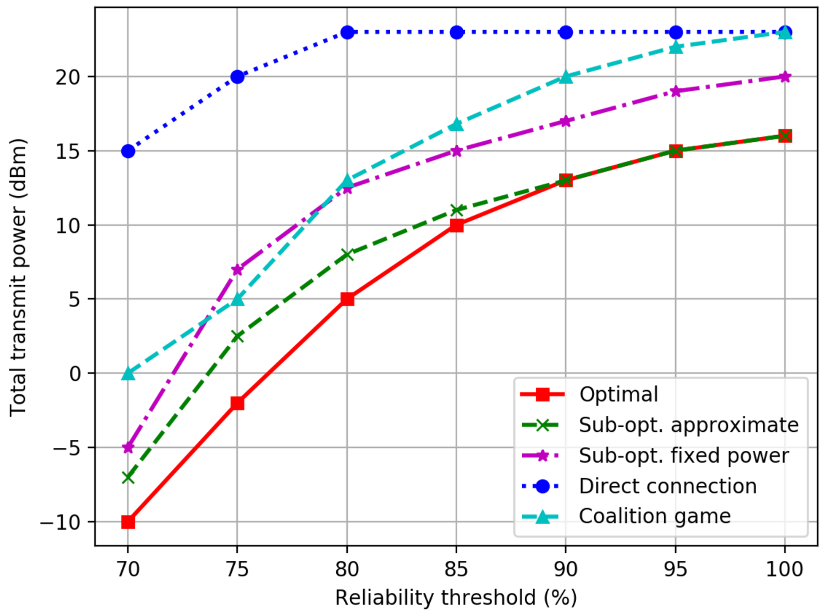


Figure 5.4 Total transmit power with different reliability thresholds $p_{th}$

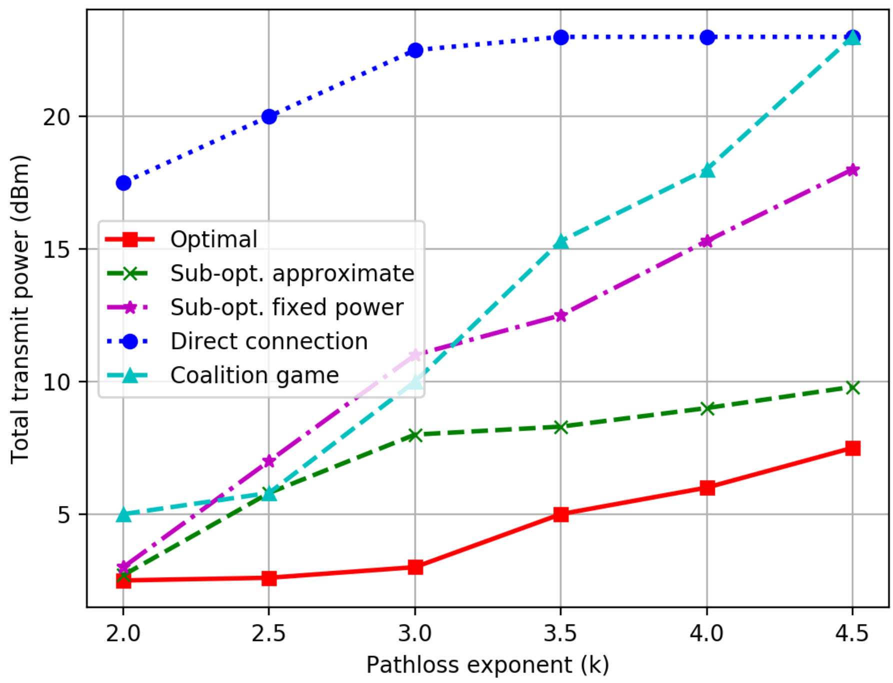


Figure 5.5 Total transmit power with the various values of path loss $k$

In this section, we conduct the simulation to evaluate the two proposed algorithms. We assume that the smart meters are uniformly distributed in a circular area centred at the data aggregator unit with a radius of 500 metres. We set the $P_{max}$ to 0.2 W as the maximum transmission power of a single node. The noise power density $N_0$ is set to $-170$ dBm/Hz.

We compared our work with the algorithm proposed in [62]. We would firstly describe the algorithm. In [62], it firstly assumes that a relay is selected, then it defines

$$\mathrm{P_K} = \frac{(n-1)\gamma_t\sigma^2}{G-(n-1)\gamma_t} + \sigma^2, \qquad (5.41)$$

where $n$ is 2 in our work, as we just consider one pair of single-hop transmission in the paper, while $G$ is the reward level in the coalition game. Then the transmit power for the transmitter $P_S$ and the relay's transmit power $P_R$ is calculated by the following

$$P_S + P_R = \frac{\gamma_t P_K}{\sum |h|^2{}_i} \qquad (5.42)$$

where $|h|^2{}_i$ is the channel gain of the transmitter channel and the relay channel, respectively. By exhaustively calculating all the combination of transmitter and the relay groups and finding the best pair, the relay is selected. Finally, we will evaluate the performance of our proposed algorithm and compare our algorithm with the one proposed in [62].

Figure 5.2 reflects the impact of $\alpha$ on the total transmit power of Algorithm II, with the parameter $SNR$ threshold $\beta$ set to $-4$ dB, the path loss exponent $k = 3.5$ and reliability threshold $p_{th} = 0.7$. We also set $G = 10$ in the algorithm proposed in [62]. It is clear that, when $\alpha = 0.7$ , the minimum total transmit power can be achieved for Algorithm II.

Figure 5.3 shows the impact of $SNR$ threshold $\beta$, on the total transmit power; we set path loss exponent $k = 3.5$ and reliability threshold $p_{th} = 0.7$. We also set $G = 10$ in the coalition game based algorithm proposed in [62] to achieve a similar QoS constraint effect as we did in our proposed algorithm. In the figure, 'Direct connection' refers to the direct transmission between the smart meter and the data aggregator unit where no relay node was involved in the direct transmission. By solving the optimization problem in (5.10) the optimal solution can obtained directly. The terms 'sub-optimal approximation' and 'sub-optimal fixed power' refer to Algorithm I and Algorithm II with $\alpha = 0.7$ respectively. The 'coalition game' refers to the algorithm proposed in [62]. It can be concluded that the increase of $\beta$ will lead to increases in total transmission power for all considered algorithms, also the two proposed sub-optimal algorithms will require less transmission power than the direct transmission. Algorithm I (sub-optimal approximation) performs closer to the optimal solution than Algorithm II (sub-optimal fixed power), but Algorithm II requires lower computational complexity. And compared to the coalition game based algorithm, our proposed Algorithm I outperforms the coalition game based algorithm, except when $\beta < -4$ ($SNR$ threshold is small). The low computation complexity Algorithm II is always worse than the coalition game algorithm. We can see almost a 20% improvement of Algorithm I comparing to the coalition game based algorithm, in terms of the saving of the total transmit power at $\beta = 12$.

Figure 5.4 shows total transmit power versus different reliability thresholds with $\alpha = 0.8$ for Algorithm II, $SNR$ threshold $\beta = -4$ dB, path loss exponent $k = 3.5$ and G = 12 for the coalition game based algorithm. By comparing the direct and cooperative transmission, we can see that the required total transmit power for cooperative transmission is always lower than that for direct transmission. For high-reliability thresholds over 90%, Algorithm I (sub-optimal approximation) performs very well and requires the same total transmit power as the optimal numerical result. We also compare our proposed algorithm with the coalition game based algorithm proposed in [62]. It can be found that our proposed Algorithm I can achieve a lower total transmit power than the coalition game based algorithm with reliability threshold ranges from 70% to

100%. And for the reliability threshold larger than 80%, even the low computation complexity Algorithm II has a better energy saving than the coalition game based algorithm.

Figure 5.5 shows the impact of the path loss exponent on the total transmit power, with $\alpha = 0.7$ for Algorithm II, $P_{th} = 0.7$, $\beta = -4$ dB and G = 12.8. With the increased value of the path loss exponent, the total transmission power increases for all considered algorithms. The direct transmission requires a higher total transmission power than that in our proposed cooperative transmission. Algorithm I (sub-optimal approximation) has better performance than Algorithm II (sub-optimal fixed power). With the increased value of the path loss exponent $k$ the gap between Algorithms I and II also increases; this indicates that the effect of path loss has a larger impact on Algorithm II than on Algorithm I. We can also see that, in a low pathloss exponent environment ($k \leq 2.5$), both of the two proposed algorithms outperform the coalition game based algorithm. Then in a median pathloss exponent environment ($2.5 \leq k \leq 3$), the proposed Algorithm I achieves a better energy saving performance than the coalition game based algorithm, while it outperforms Algorithm II. Finally, when $k \geq 3$, even the low computational complexity Algorithm II is better than the coalition game based algorithm.

It is worthwhile mentioning that the computation complexity of Algorithm II is $O(K)$, $K$ is the total number of devices in the network. This is the same as the coalition game based algorithm proposed in [62]. The theoretical computation complexity of Algorithm I is difficult to devise, but in our simulation, it requires about 1–2 times more computation processing than Algorithm I. Thus, we conclude that, with a little comprise in computation complexity, our proposed algorithms outperforms the coalition game based algorithm proposed in [62]. This also leads to the conclusion that we should propose a well optimised algorithm for the cooperation transmission in the smart grid scenario, instead of simply adopting the algorithms proposed for the cellular network.

# Chapter 6. Conclusion

In this thesis, cooperative communication in smart grids has been comprehensively studied. The concepts of smart grid and the cooperative communication have been reviewed. According to the smart grid's network features, we applied cooperative communication to wireless smart grid communication to enhance the reliability performance of the communication activities. Our research started with the application of the cooperative relay transmission, then we designed a new network deployment strategy based on the outage probability, the smart meter location optimization problem has been identified and solved. The simulation results show that the proposed deployment strategy is effective and can guarantee high reliability for smart grid communications in home area networks. We also proposed a way to solve a joint optimization problem of power allocation and relay selection in the NAN of a smart grid.

Specifically, we considered the deployment of the smart meter in a HAN for smart grid communications. We applied cooperative relay transmission to the current use selection scheme in the smart grid HAN to improve the transmission reliability between the smart meter and the user equipment.

By incorporating indoor path loss values in the outage probability analysis [71], we proposed a smart meter deployment strategy to minimize the outage probability in a HAN that employs cooperative transmission schemes. We performed a ray-tracing simulation example based on a real HAN deployment scenario. The smart meter location optimization problem has been identified and solved. The simulation results show that the proposed deployment strategy is effective and can guarantee high reliability for smart grid communications in home area networks.

We propose to jointly optimize relay selection and power allocation for achieving energy-efficient and reliable smart grid communications. To reduce the computational complexity, we devised two sub-optimal algorithms to solve the joint optimization problem. The performance evaluation results demonstrate the effectiveness of our proposed sub-optimal algorithms for energy-efficient and reliable smart grid NAN communications.

By the step-by-step studies, our results can contribute to the current and future research of the wireless smart grid communication.

# Chapter 7. Future Works

We can further develop our research to a multi-disciplinary level. Since the current power grid is experiencing a significant shift from the traditional electricity grid to the smart grid, it brings a brand-new view of power consumption: for example, the energy efficiency will not always mean reducing the power consumption, but using the power more efficiently. We combined together the cooperative relay communication and dynamic demand side management (DSM) of the smart grid. The cooperative relay communication will provide high reliability for supporting the communication activities within the smart grid system. The smart grid system can use the data to provide highly accurate prediction of the power usage so that the power consumption can be adjusted to achieve a high energy efficiency. On the other hand, the demand side management can also help the communication to reduce the communication power cost and increase the communication reliability by providing dynamic power supply. Motivated by the multi-disciplinary concept, our research will focus not only on the reliable communications but also on the dynamics demand side management of the smart grid. Specifically, cooperative relay communication is used in the system to ensure acceptable service reliability in the wireless smart grid network. The DSM network provides the power supply to the communication system, and it decides on which retailers to procure electricity from, and how much electricity to procure to support the communication activity. We can jointly optimize the power allocation, relay selection and dynamic power supply to give a more comprehensive analysis of the reliable and energy-efficient wireless communication for a smart grid network.

For the network deployment strategy, more location and path loss models can be taken into account to evaluate the impact of the location of the smart meter on the reliability of the HAN. The idea of the network development strategy based on the link reliability can be extended to other networks in smart grid system.

For the joint optimization problem, further work can be done to extend the current joint optimization of power allocation and relay selection: for example, to apply the cognitive ratio together to jointly consider the channel selection, power allocation and relay selection.

Based on the research content mentioned above, the future research on the cooperative communications on smart grid network has a great potential.

# Publications

- Li D, Chu X & Zhang J (2016) Joint optimization of power allocation and relay selection for smart grid neighborhood area networks. 2015 IEEE International Conference on Smart Grid Communications, SmartGridComm 2015 (pp 217–222).
- Li D, Weng J, Chu X & Zhang J (2015) A network deployment strategy for home area networks in smart grid. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, Vol. 2015-December (pp 2160–2165)

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