Cooperative Communications in Wireless Sensor Networks

Doctoral Thesis
to obtain the academic degree of
Doktor der technischen Wissenschaften
in the Doctoral Program
Technische Wissenschaften
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Abstract

An efficient utilization of electrical energy is imperative for wireless sensor networks because the sensor nodes are often battery-driven with no access to main power. Hence, to improve the lifetime of the network and decrease the overall expenditure on electrical energy, the nodes are required to use only sufficient transmit power that is necessary to fulfill the designed performance criteria. An accurate estimation of channel parameters and calculation of optimum transmit power is, therefore, required. Cooperation within the nodes using relaying is also helpful to improve the lifetime of the network by helping the nodes confronting poor channel conditions. The problem of optimum power calculation is exacerbated due to the limited computational capabilities of the nodes. Most of the existing algorithms are either too complex that they may not be implemented on the available commercial hardware or they are based on assumptions that may not be true in practical scenarios.

The work presented in this thesis contributes to overcome these problems. A novel received signal strength indicator (RSSI)-based estimator is proposed to estimate the mean pathloss and Rician K factor in Rician channels. The algorithm is designed to be simple enough to be implementable on nodes with limited computational capabilities. An approximation to the model is presented and practically implemented on simple nodes to demonstrate its effectiveness. A novel approximate algorithm is proposed to calculate transmit power for direct and relay links using the channel parameters. The proposed algorithm has a computational complexity comparable to the already existing approximate algorithms but shows a much superior performance. The estimated optimum transmit power is used in a cooperative communication-based network where nodes can assist each other by acting as relays. The calculated transmit power for direct and relayed communication is used by the partner selection algorithms to decide which node can act as a relay so that the overall energy expenditure is reduced or the lifetime of the network is improved. The idea of lifetime gain and energy expenditures is investigated using the developed MATLAB simulator for IEEE 802.15.4. A comparison of existing partner selection algorithms is performed. Modifications to the existing algorithm are proposed and their performance is demonstrated using simulations. A new distributed algorithm is also proposed to select the best partners without the need of a central entity. The practical implementation aspects are covered and different simulation environments are used for true comparison of the existing and proposed partner selection schemes.
It is shown that for a network of more than 30 nodes, a reduction of more than 1000 times in energy expenditure on transmission is realizable in some scenarios. A similar improvement in the lifetime of the network is also possible. The reduction in transmit power also leads to decreased interference with other co-existing systems. The findings are very significant for the emerging Internet of Things (IoT).
Kurzfassung


Acknowledgement

All praise be to the Creator of this universe, who provided me the strength to complete this task. He is the most merciful and the all-knowing. He guided mankind with the help of Prophets and Imams, who are the rightly-guided individuals. Peace be upon all of them.

While approaching the completion of my Doctoral work, it is my duty to thank all those who have made this achievement possible. There are many individuals who have directly or indirectly helped me during the course of this work or have made the foundations on which I could base this work. I must also clarify that there can also be many shortcomings but they are due to my own weaknesses and negligence and others may not, in any way, be held responsible for that.

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<th>Definition</th>
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<tbody>
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<td>AF</td>
<td>amplify and forward</td>
</tr>
<tr>
<td>AP</td>
<td>access point</td>
</tr>
<tr>
<td>AWGN</td>
<td>additive white Gaussian noise</td>
</tr>
<tr>
<td>BER</td>
<td>bit error rate</td>
</tr>
<tr>
<td>CRC</td>
<td>cyclic redundancy check</td>
</tr>
<tr>
<td>DF</td>
<td>decode and forward</td>
</tr>
<tr>
<td>ED</td>
<td>energy detection</td>
</tr>
<tr>
<td>FCS</td>
<td>frame check sequence</td>
</tr>
<tr>
<td>IoT</td>
<td>internet of things</td>
</tr>
<tr>
<td>IQ</td>
<td>in-phase and quadrature</td>
</tr>
<tr>
<td>ISM</td>
<td>industrial, scientific, and medical</td>
</tr>
<tr>
<td>LOS</td>
<td>line-of-sight</td>
</tr>
<tr>
<td>LQI</td>
<td>link quality indication</td>
</tr>
<tr>
<td>LR-WPAN</td>
<td>low-rate wireless personal area network</td>
</tr>
<tr>
<td>MAC</td>
<td>medium access control</td>
</tr>
<tr>
<td>MIMO</td>
<td>multiple-input and multiple-output</td>
</tr>
<tr>
<td>MRC</td>
<td>maximal-ratio combining</td>
</tr>
<tr>
<td>NLOS</td>
<td>non-line-of-sight</td>
</tr>
<tr>
<td>O-QPSK</td>
<td>offset quadrature phase-shift keying</td>
</tr>
<tr>
<td>OLG</td>
<td>optimum lifetime gain</td>
</tr>
<tr>
<td>OTE</td>
<td>optimum total energy</td>
</tr>
<tr>
<td>PDF</td>
<td>probability density function</td>
</tr>
<tr>
<td>PHR</td>
<td>PHY header</td>
</tr>
<tr>
<td>PHY</td>
<td>physical layer</td>
</tr>
<tr>
<td>PPDU</td>
<td>PHY protocol data unit</td>
</tr>
<tr>
<td>RSSI</td>
<td>received signal strength indicator</td>
</tr>
<tr>
<td>SC</td>
<td>selection combining</td>
</tr>
<tr>
<td>SDR</td>
<td>software defined radio</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SER</td>
<td>symbol error rate</td>
</tr>
<tr>
<td>SFD</td>
<td>start-of-frame delimiter</td>
</tr>
<tr>
<td>SHR</td>
<td>synchronization header</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SoC</td>
<td>system-on-chip</td>
</tr>
<tr>
<td>SPI</td>
<td>serial peripheral interface</td>
</tr>
<tr>
<td>TDMA</td>
<td>time division multiple access</td>
</tr>
<tr>
<td>USB</td>
<td>universal serial bus</td>
</tr>
<tr>
<td>USRP</td>
<td>universal software radio peripheral</td>
</tr>
<tr>
<td>WLF</td>
<td>worst link first</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Communication is an important part of animal behavior. Production of different sounds, gestures, changing of colors, and production of chemicals are some of the various methods by which animals communicate [2]. Animals mostly communicate with each other to guide their fellows towards food, to warn against impending dangers or during the mating rituals. Human beings, being more advanced, are distinguished from other animals by their ability to connect sounds to form words, connecting words to form sentences and thereby communicate ideas and information that could not otherwise be conveyed [3]. The desire to communicate at large distances ushered in the field of telecommunications that has markedly evolved from the prehistoric smoke and drum signals to the modern-world wired and wireless communications. The scope of communications that once consisted of voice and message exchange between humans, now even includes machines and devices. It has been an enthralling journey from the telegraph and telephone to the internet of things (IoT). The ever increasing number of devices, with largely differing needs and abilities, communicating to each other in diversified ways makes the scenario on one hand fascinating but on the other hand challenging for scientists and engineers. The present work outlines the challenge of efficient energy utilization in simple wireless nodes and contributes to provide its solution in the form of simple algorithms.

1.1 Industrial Communications

Communication between machines and devices finds its applications in home automation, sensor networks used in environmental monitoring, body area networks, and vehicular communication etc. One of the biggest beneficiary of communication
technologies is the modern industry. Industrial control and automation is based on a reliable communication between the different entities. The collection of data from different sensors, conveying the control signals to the actuators, and human machine interface cannot be realized without an effective communication system. Industrial environment, however, offers some unique challenges and requirements that can have different significance when compared to other telecommunication scenarios. Following we list some of the important characteristics of industrial communications [4–6]:

- Process control applications require an utmost reliability as any communication failure can lead to catastrophic consequences.
- Most of the applications are time-critical and have strict real-time requirements.
- The environment is generally replete with electromagnetic interference, which is likely to jeopardize data integrity and reliability.
- Energy-efficiency is much desirable to reduce the financial expenses incurred in communications. Since the sensor nodes are often battery-driven, changing the batteries frequently might be undesirable or even impossible.
- Security is important due to the importance of the data from a business perspective and protecting the system from an intrusion leading to any system shutdown or other catastrophic consequences is of utmost significance.

Although industrial communication has traditionally been mostly wired, wireless communication offers some unique advantages [7]:

- One of the major advantages of wireless communications is the inherent flexibility to deploy or upgrade the system.
- The deployment and maintenance costs for a wireless network are generally less than for a wired network.
- Wireless communication is the only choice for moving and rotating equipment.
- Wireless communication provides opportunity to communicate to remote and not so easily accessible parts and components.
- The availability of simple and cheap sensor node hardware offers the possibility of more proactive data collection that can lead to better system maintenance.

Due to these advantages, wireless communication is becoming popular for industrial communications and a number of wireless communications standards have evolved.
1.1 Industrial Communications

1.1.1 Industrial Wireless Communication Standards and Technologies

Following is a brief overview of some of the different wireless communications standards and technologies being used in the industry:

IEEE 802.15.4
IEEE 802.15.4 is a low-rate wireless personal area network (LR-WPAN) standard that was first released in 2003 [8]. The standard targets low complexity, low power consumption and low data rate transceivers. The standard specifies the physical layer (PHY) and the medium access control (MAC) layer for LR-WPANs. Some other standards like ZigBee, WirelessHART and ISA100.11a are also based on the PHY and MAC layers of IEEE 802.15.4 standard. Due to this fact, this standard is very popular in commercial hardware. Further details are provided in Section 1.2.

ZigBee
ZigBee is a personal area network standard, which is developed by the ZigBee Alliance [9]. It is based on IEEE 802.15.4 PHY and MAC layers and is suitable for small and low-power radios that can be used for data collection and home automation applications.

6LoWPAN
6LoWPAN or IPv6 over Wireless Personal Area Network is developed by a working group of IETF (Internet Engineering Task Force) using which IPv6 packets may be transmitted over IEEE 802.15.4 networks [10]. The basic idea of 6LoWPAN is to allow low-power devices to form part of the IoT. Devices compatible with 6LoWPAN are available in the market.

WirelessHART
WirelessHART is based on the Highway Addressable Remote Transducer (HART) Protocol, which is a popular industrial process communication protocol that was designed for 4 – 20 mA current loops. WirelessHART allows wireless communication using the IEEE 802.15.4 standard. It was developed by 37 HART Communications Foundation companies. The standard is also approved by the International Electrotechnical Commission (IEC) as IEC 62591. The standard is popular for industrial process control applications. See [11] for more details.

ISA100.11a
ISA 100.11a is developed by the International Society of Automation (ISA). It is
based on IEEE 802.15.4 standard and 6LoWPAN. Industrial products compatible with this standard are available in the market. For more detailed information on WirelessHART and ISA100.11a and their comparison, see [12].

**Bluetooth**

Bluetooth is developed by the Bluetooth Special Interest Group for exchanging data over short distances. Bluetooth has been a popular standard for exchanging data between mobile devices. The low-energy operation mode and recently released Bluetooth 5 offers some new services targeting Internet of Things (IoT) applications. See [13] for more details.

**Wi-Fi**

Wi-Fi is developed by the Wi-Fi Alliance and is based on IEEE 802.11 Wireless Local Area Network (WLAN) standard. IEEE 802.11ac, which is one of the latest versions of Wi-Fi, can transfer data up to many gigabit per second. This can even allow high resolution multimedia streaming. See [14] for further information. The use of Wi-Fi for sensor nodes is limited due to the high energy requirements of Wi-Fi.

There are also some other technologies and proprietary protocols that can be used for process control and wireless sensor communications (e.g. Industrial Wireless LAN by Siemens [15] etc.). It is also interesting to see from the above discussion that IEEE 802.15.4 forms a very popular base for many standards.

### 1.2 IEEE 802.15.4 Standard

IEEE 802.15.4 is a LR-WPAN standard that is very popular due to its usage in ZigBee, 6LoWPAN, WirelessHART and ISA100.11a. Some of the main characteristics of this standard are as follows:

- The standard specifies the PHY and the MAC layer for LR-WPANs.
- It targets low complexity, very low power consumption and low data rate (up to 250kbps) transceivers.
- It offers star or peer-to-peer connection topologies.
- The standard was first released in 2003 [8] and was later on, amended and revised.
- The latest version of the standard was released in 2015. [1]
All the discussion in the thesis is compatible with the first release [8] as well as the subsequent revisions. The exceptions are clearly mentioned.

1.2.1 Physical Layer

The standard specifies different options for the physical layer. Different modulation schemes are possible for different bands. According to the latest revision of the standard, 19 different types of PHY are possible [1]. One of the most popular options is the offset quadrature phase-shift keying (O-QPSK) PHY. It uses O-QPSK as the modulation scheme. It can be used in different designated bands. The most commonly used band is the 2.4 GHz industrial, scientific, and medical (ISM) band, which is freely available worldwide. The standard specifies the PHY protocol data unit (PPDU) as shown in Fig. 1.1.

```
SHR  PHR  PHY payload
```

**Fig. 1.1:** Format of the PHY protocol data unit [1]

The synchronization header (SHR) has a length of 5 octets. The first 4 octets make the preamble with all bits equal to zero and the fifth octet is the start-of-frame delimiter (SFD) with the known binary sequence of 11100101. The PHY header (PHR) has 7-bits representing the frame length and one reserved bit. It should be noted that the maximum number expressed in the 7-bit length field is 127. The PHY payload has a variable length as specified in the length field.

The modulation and spreading is shown in Fig. 1.2.

```
Binary data from PPDU → Bit-to-Symbol → Symbol-to-Chip → OQPSK Modulator → Modulated Signal
```

**Fig. 1.2:** Modulation and spreading functions in IEEE 802.15.4 standard [1]

Every 4-bits of the PPDU represent one of the sixteen possible symbols. Each symbol is converted to a chip sequence of length 32 as shown in Table 1.1.

O-QPSK modulation is performed on the chip sequence in the following way. The odd- and even-indexed chips are separated in two streams i.e. in-phase and quadrature
Table 1.1: Symbol-to-chip mapping for the 2.4GHz O-QPSK [1]

<table>
<thead>
<tr>
<th>Data symbol</th>
<th>Chip values ((c_0 \ c_1 \ldots c_{30} \ c_{31}))</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>1 1 0 1 1 0 0 1 1 1 0 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 0 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0</td>
</tr>
<tr>
<td>2</td>
<td>0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 0 1 0 1 0 0 1 0 0 1 0</td>
</tr>
<tr>
<td>3</td>
<td>0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 0 1 0 1 1 1 0</td>
</tr>
<tr>
<td>4</td>
<td>0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 1 1 0 1 1 1 0 0 0 1 1 1</td>
</tr>
<tr>
<td>5</td>
<td>0 0 1 1 0 1 0 1 0 0 1 0 0 1 0 1 1 1 0 1 1 0 1 1 0 1 1 0 1 1 0 1 1 0</td>
</tr>
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<td>6</td>
<td>1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 1 1 0 1</td>
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<td>7</td>
<td>1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 1 0 1 1 1 0 1 1 0 1 1 0 1</td>
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<td>8</td>
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<td>9</td>
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<td>15</td>
<td>1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 0 1 1 1 0 1 1 1 0 0 0</td>
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</tbody>
</table>

sequences. The quadrature sequence is delayed by one chip interval, which is given by the reciprocal of the chip rate \(T_c\) \((T_c = 2 \text{ Mcps} \text{ and therefore, } 1/T_c = 0.5 \mu s)\). Each baseband chip is converted to a half-sine pulse shape \(p(t)\) as given by [1], such that

\[
p(t) = \begin{cases} 
\sin \left( \frac{\pi}{2T_c} t \right), & 0 \leq t \leq 2T_c \\
0, & \text{else} 
\end{cases} \tag{1.1}
\]

The transmit power for a compliant device should be at least \(-3 \text{ dBm}\) and the receiver sensitivity should be at least \(-85 \text{ dBm}\). Two useful parameters that are required to be measured by the receiver are the receiver energy detection (ED) and the link quality indication (LQI). ED is the measure of the received signal energy averaged over 8 symbol periods, while the LQI is a measure of the signal strength, an estimate of the received signal-to-noise ratio or a combination of both as implemented by the hardware. Each receiver must perform the two measures for each received packet. For further details about ED and LQI, please refer to [1, Ch. 10] and for further information regarding the O-QPSK PHY, please refer to [1, Ch. 12].
1.2.2 MAC Sublayer

The MAC sublayer performs the following functions [1]:

- Beacon management
- Channel access
- Time slot management
- Frame validation
- Acknowledged frame delivery
- Association and disassociation etc.

The MAC frame consists of a variable length header that contains the source and destination addresses and some control information, variable length payload and a 2-byte footer. The footer contains the frame check sequence (FCS) consisting of a 16-bit cyclic redundancy check (CRC) computed over the MAC header and payload.

1.3 Cooperative Communication

As stated in Section 1.1, communicating devices may face difficult channel conditions that, in order to achieve the desired signal quality at the receiver, demand high values of transmit power that may not be achievable or are a huge burden on the storage batteries. The idea of cooperative communication helps in such scenarios such that the nodes support each other in delivering the messages of each other. The support or cooperation is, usually, in the form of relaying. [16]. Cooperative systems are differentiated from the simple relay-based systems (also termed as supportive relaying [16]) in which a fixed relay always exists and always relays the signal from the source. In the case of cooperative communication, either there are no fixed relays and the normal nodes act as relays when demanded or if there are already designated relays, they cooperate with each other depending upon the requirements. Apart from energy-saving, cooperative communication can be used to improve the capacity and coverage of the network. It also helps to deploy a communication system without any existing infrastructure and at a reduced cost [16]. Further details on relaying and cooperating strategies are provided in chapter 3 and 4.
1.4 Outline of the Thesis

The thesis investigates the different aspects of cooperative communication in wireless sensor networks. The major contributions are:

- A novel estimator and its very low-complexity approximation for channel parameter estimation in Rician channels are presented. Another proposed method uses the estimated parameters to calculate optimum transmit power for direct links.

- A novel approximation is proposed to calculate transmit power in relay channels.

- Novel partner selection algorithms for improving the network lifetime and decreasing the overall energy consumption of a wireless sensor network are presented. A comprehensive comparison of partner selection algorithms is also given.

The MATLAB simulator for IEEE 802.15.4 standard, which was developed during the course of this work, is used to verify the performance of the proposed algorithms. Some of the proposed algorithms are also implemented on simple sensor node hardware and practical results are presented.

After introducing some of the basic concepts related to industrial communications and the associated communication standards, the thesis elaborates some of the challenges confronted by wireless nodes’ communication in a more specific way. Already proposed solutions available in the literature are discussed and new solutions, that are better than the already existing solutions in some respects, are then proposed. Simulation results and practical results substantiate the stated claims.

An efficient utilization of the available electrical energy is of paramount importance in a wireless node. The calculation of optimum transmit power also requires an accurate estimation of the channel parameters. Chap. 2 deals with the problem of parameter estimation and optimum power calculation in a single link. Algorithms are proposed and comparisons are made with the existing methods using simulations and practical results.

The work presented in Chap. 2 is extended to incorporate the idea of relaying. Relaying is an important strategy that can be used for mitigating the effects caused by poor channel conditions as well as for improving the lifetime of a network. The calculation of optimum transmit power in relay channels is extremely complex and
the available coding gain approximation technique does not provide accurate results in most of the practical scenarios. This discussion as well as the proposed transmit power calculation algorithms form Chap. 3.

In networks consisting of many nodes, the selection of an appropriate cooperation partner can further optimize the desired benefits of a relaying network. This leads to the concept of cooperative communication where nodes cooperate with each other in an optimum way. Chap. 4 describes the existing and proposed partner selection algorithms for optimizing the lifetime and overall energy expenditure of a wireless network.

Chap. 5 gives the final conclusions and summarizes the contributions that are made in this work.
Chapter 2

Optimum Transmit Power Calculation

The ever-increasing number of machines, devices, sensor and actuator nodes getting connected together for data exchange demands an efficient utilization of energy resources. The importance of efficient energy utilization is underlined by the following issues:

- For big networks consisting of a large number of nodes, the total energy requirement can itself be a problem in terms of availability as well as cost. Saving even a slight amount per node can translate to a significant saving for the overall network.

- Small sensor nodes and the nodes located in remote places with no connection to the main power supply are often battery driven. The cost and effort required for battery replacement also demand efficient energy utilization so that the frequency of battery replacements is reduced [17].

- Energy harvesting can provide a solution but the methods are still under development (e.g. EZ430-RF2500-SEH by Texas Instrument [18] is equipped with solar energy harvesting. It is, however, not compatible with IEEE 802.15.4 standard.). Efficient energy utilization can, nevertheless, complement energy harvesting solutions [19].

\[^1\]The terms mentioned here are generally used in different scenarios. Although they differ very much from each other in their functionality, they will be treated in a similar way from the communication perspective as far as the discussions in this thesis are concerned. The term 'node' or 'wireless node' when used in the thesis will represent any such object.
• Various standards often share the same part of the electromagnetic spectrum. Communication between two devices acts as an interference for others. The transmit power is hence limited, often by regulatory agencies, to reduce this interference. Hence, it is essential to use only the minimum possible transmit power that is required to fulfill the desired quality criteria [20].

The problem of optimum transmit power calculation for a communication link between two nodes is the main focus of this chapter. The chapter starts with some literature survey that highlights the importance of Rician fading in different practical scenarios. The calculation of transmit power depends on the channel characteristics. It is, therefore, very important to accurately estimate the channel parameters. After a brief literature survey, a proposed method is discussed that estimates the parameters using the received signal strength indicator (RSSI) information. An approximation to the proposed method is also presented. These methods are simple enough to be implemented on simple nodes with limited computational capabilities. All the claims are supported by simulations and practical results. The estimated parameters form the base for transmit power calculation, which is explained in Section 2.3. The exact solution to the problem is computationally complex. An approximate method that describes the channel response in terms of its coding and diversity gain, that already exists in literature, is described. Some limitations in the method are then explained. A complete transmit power calculation system based on a piecewise model is proposed. Simulations and practical results are used to verify the claims.

2.1 Fading Channel

The received signal in WSNs, after reflections from different objects, is usually a combination of several versions of the transmit signal with different delays and attenuation. The phenomenon is termed as multipath fading [21]. Time variations in the position of transmitter, receiver and/or reflecting objects further complicate the situation. The strength of the directly received (line-of-sight (LOS)) component without reflections gives rise to different channel characteristics. A very strong LOS component with negligible non-line-of-sight (NLOS) components, results in an additive white Gaussian noise (AWGN) channel, whereas a channel with a non-existing LOS component is termed as Rayleigh channel [22]. The variable strength of the LOS component can be best represented in terms of Rician fading, with
the received signal amplitude varying according to Rice distribution that is named after Stephen O. Rice [22]. Readers may refer to [23] for his short biography and contributions.

### 2.1.1 Examples of Rician Fading

Rician fading has been observed in a number of practical scenarios as listed below:

- Wireless body area networks [24]
- Underground tunnels [25]
- Indoor office channels [26]
- Industrial indoor channels [27]
- Shallow water acoustic channels [28]
- Agricultural farms [29]

### 2.1.2 Rician Distribution

As already stated, the received signal magnitude in many practical scenarios can be modeled as a Rician distribution. The transmission of a signal through a channel can be modeled as

\[
x = hw + n,
\]

where \( x \) is the received signal, \( h \) represents the complex path gain of the channel, \( w \) is the complex input symbol with power \( \rho \) and \( n \) represents the complex additive white Gaussian noise. The complex path gain of the channel results from a fixed LOS component and some NLOS components obtained from different fixed and/or moving scatterers.

The magnitude of the received signal can be obtained by the combination of two independent Gaussian random variables with the same variance and different means in the following way [21]. We consider two random variables \( U \) and \( V \), such that

\[
U = \mathcal{N}(m, \sigma^2)
\]
and

\[ V = \mathcal{N}(0, \sigma^2), \]

such that \( \sigma^2 \) denotes the variance of \( U \) and \( V \), whereas \( m \) represents the mean of \( U \).

We now define a random variable \( X \), such that

\[ X = \sqrt{(U^2 + V^2)}. \]  \hfill (2.2)

The random variable \( X \) follows a Rician distribution. The probability density function (PDF) for \( X \) is given by [21]

\[
 f_X(x; m, \sigma) = \frac{x}{\sigma^2} \exp \left[ -\frac{x^2 + m^2}{2\sigma^2} \right] I_0 \left( \frac{xm}{\sigma^2} \right),
\]  \hfill (2.3)

where \( I_0 \) is the modified Bessel function of the first kind and zero order. The same PDF can also be expressed in terms of new variables, i.e. Rician \( K \) factor denoted by \( K \) and a scale parameter \( \Omega \), as

\[
 f_X(x; K, \Omega) = \frac{2(K + 1)x}{\Omega} \exp \left[ -K - \frac{(K + 1)x^2}{\Omega} \right] I_0 \left( 2\sqrt{\frac{K(K + 1)x}{\Omega}} \right). \]  \hfill (2.4)

The parameters \( K \) and \( \Omega \) are obtained from \( m \) and \( \sigma \) as follows:

\[
 K = \frac{m^2}{2\sigma^2}, \]  \hfill (2.5)

\[
 \Omega = m^2 + 2\sigma^2. \]  \hfill (2.6)

With this formulation, \( \Omega \) represents the total mean power of the random variable \( X \), while \( K \) gives the ratio of the power in the LOS component to the power in the NLOS components. These two parameters are also beneficial from a communications perspective because of their straightforward physical interpretation. It should also be noted that a \( K \) factor value of 0 implies a Rayleigh channel without any LOS component, whereas a value of \( K = \infty \) implies an AWGN channel. Putting \( K = 0 \) in (2.4) leads to the PDF for a Rayleigh distributed random variable, as

\[
 f_X(x; \Omega) = \frac{2x}{\Omega} \exp \left[ -\frac{x^2}{\Omega} \right]. \]  \hfill (2.7)
Using (2.4), Fig. 2.1 shows the PDF of Rician distributions for different values of $K$. We take $\Omega = 1$. It can also be seen from the figure and (2.5) that for a constant value of $\Omega$, a smaller $K$ means more randomness in the channel parameters and increasing $K$ decreases the randomness and leads to an impulse centered around $\sqrt{\Omega}$. This means that, for a very high value of $K$, there is a 100% probability that the received signal amplitude is $\sqrt{\Omega}$. This means that the mean received signal power is $\Omega$. Thus, the channel is an AWGN channel and there is no fading.

It is convenient to find the mean power gain of the channel by dividing $\Omega$ by the average transmit power (denoted by $\rho$). According to (2.1), the mean path gain of
the channel will be given as $\mathbb{E}|h|^2$. Therefore,

$$\mathbb{E}|h|^2 = \frac{\Omega}{\rho} \quad (2.8)$$

Mean pathloss of the channel in decibels is often found by converting the mean power gain of the channel to decibels i.e.

$$L = -10\log_{10}(\mathbb{E}|h|^2) \quad (2.9)$$

### 2.1.3 Simulation Model

For all the simulations given in this thesis, we use the channel model proposed by Castiglione et al. [30]. The model is used in a scenario where multiple resource-constrained nodes are placed in an indoor environment. These nodes communicate with an access point that is placed outside. The communication channels between the resource-constrained nodes are purely indoor, whereas the channels between the nodes and the access point can be divided into an indoor part from the nodes to the nearest wall, transmission through the wall and the outdoor part from the wall to the access point. For indoor communication, a bivariate Gaussian model is constructed that is based on experimental measurements conducted at Stanford University [31]. The model generates the pathloss and Rician $K$ factor for a given distance between the nodes. For the outdoor component of indoor-to-outdoor communication, the bivariate Gaussian model is based on WINNER-II channel models [32]. The pathloss through the wall is given as 14 dB. The mean values of Rician $K$ factor and pathloss for these models are shown in Figs. 2.2 and 2.3. It can be seen that mean value of the $K$ factor decreases and the mean pathloss increases with increasing distance for both the scenarios. The outdoor model results in higher pathloss values when compared with the indoor model (75.4 dB pathloss for the indoor model as compared to 96.9 dB for the outdoor model at a distance of 100 m). Including the effect of the wall for indoor to outdoor communication further increases the pathloss. The Rician $K$ factor values for the indoor model are also slightly lower than the values for the outdoor model. The differences in the two models can be attributed to much more reflections indoors than outdoors. It should also be noted that for the indoor model, the mean values of Rician $K$ factor and pathloss are expected to be about 10 dB and 63 dB respectively at a
2.1 Fading Channel

Fig. 2.2: Mean values of Rician $K$ factor and pathloss against distance for the indoor model

Fig. 2.3: Mean values of Rician $K$ factor and pathloss against distance for the outdoor model

distance of 20 m. At shorter distances, the mean values of Rician $K$ factor increase exponentially, whereas the pathloss decreases exponentially. The expected values of the two parameters will have an important role in the forthcoming discussions.
2.2 Estimation of Rician Parameters

As discussed previously, the allocation of optimum transmit power is very essential for a wireless node. If the transmit power is more than what is required, the node quickly runs out of its stored energy and if it is less than the required, the received signal is too weak, causing errors at the receiver. In order to obtain a desired signal power at the receiver, the transmit power is adjusted according to the characteristics of the channel. The statistical properties of the channel determine how much the power of the transmitted signal is attenuated and how much variations are expected in the amount of attenuation. For a Rician channel, the two parameters that determine this behavior are the pathloss and the Rician $K$ factor. An accurate estimation of these two parameters\(^2\) is, therefore, essential for the calculation of optimum transmit power. An error in the estimation of these parameters, leads to an error in the calculation of transmit power, which will either result in excessive energy consumption at the transmitter or a poor error performance at the receiver.

2.2.1 Literature Survey

Channel parameters can be estimated for a Rician fading channel by using the received signal. Various characteristics of the signal may be utilized for this purpose and hence several estimators exist in the literature. Following is a brief overview of already proposed parameter estimators that have been grouped according to the characteristic of the received signal on which they are based. It should also be noted that the estimation of the mean pathloss is trivial (mean value of the difference between transmit power and received power) and hence the following discussion only considers the estimation of Rician $K$ factor.

The power of the received signal forms a very convenient characteristic to be used for $K$ factor estimation due to the fact that most of the commercial hardware comes with a capability to determine received power. As discussed in Sec. 1.2, IEEE 802.15.4 also requires the hardware to perform energy detection and link quality indication, which is often based on the received signal power. The moment-based estimator proposed by Greenstein et al. [33] is based on the received signal power. It uses the first and

\(^2\)The term channel parameters in the subsequent discussion whenever done with reference to Rician fading channels will refer to Rician $K$ factor and mean pathloss.
second moments of the received signal power to compute the Rician $K$ factor. The work was later on validated using experimental measurements [34].

The received signal amplitude, although not directly available in most commercial hardware, may also be used to estimate the $K$ factor. Two moment-based estimators were proposed by Bhattacharjea et al. [35]. One of them is based on the first and second moments of the received signal amplitude while the second one is based on the second and fourth moments of the received signal amplitude. Another estimator, proposed by Naimi and Azemi, is also based on the second and fourth moments [36]. Liu et al. used Kolmogorov-Smirnov statistics to estimate the $K$ factor [37]. Sadowski collected measurement results in the 424 MHz band using channel sounding and estimated the $K$ factor using already existing estimators as well as curve fitting with the amplitude data [38]. He found that the two approaches differ for high values of Rician $K$ factors and the amplitude estimators sometimes erroneously lead to negative or complex values of $K$ factor.

The in-phase and quadrature (IQ) components of the signal may also be used for $K$ factor estimation. The components may not be available in most of the commercial hardware. However, software-defined radio platforms can provide access to these components. An estimator proposed by Baddour and Willink uses the IQ components of the received signal to estimate the $K$ factor [39].

Sasaoka et al. presented a method for $K$ factor estimation in multiple-input and multiple output (MIMO) channels, which is based on the Frobenius norm of the complex channel matrix [40]. Azemi et al. proposed an estimator that uses the first moment and zero crossing rate of the instantaneous frequency of the received signal [41]. Similarly, channel phase has been used for $K$ factor estimation as proposed by Ren and Vaughan [42].

The literature survey yields the following important conclusion: Most of the proposed estimators are based on some received signal characteristics that are not directly available in the commercial hardware. The low-cost hardware does not provide access to the IQ components of the signal or the phase or frequency of the received signal. Amplitude values can be calculated from the signal power but at an additional computational cost. The information that is readily available in all the commercial hardware is the RSSI signal. RSSI is a measure of the received signal power. The receivers estimate the RSSI value for every received packet. It can be concluded that most of the proposed estimators will either not be implementable on the available
commercial hardware or will require some additional complexity. Only the estimators that are based on the signal power or energy can be implemented without additional overhead.

2.2.2 Proposed Method

The above-mentioned reason motivated the development of a $K$ factor estimator that is based on the strength of the received signal (i.e. RSSI). Additionally, it was desired to be simple enough to be implementable on nodes with limited memory and computational capabilities. The proposed algorithm is based on the statistical distribution of the received signal power which is shown to be a scaled non-central chi-squared distribution.

2.2.3 Derivation

With a Rician distributed received signal magnitude, we are interested in finding the distribution of the received power. With Rician distributed random variable $X$ having a PDF as given in (2.3), we define a random variable $Y$, such that $Y = X^2$. The PDF of $Y$ can be obtained from (2.3) as

$$f_Y(y) = \frac{1}{2\sigma^2} \exp\left[-\frac{1}{2\sigma^2}(y + m^2)\right] I_0\left(\frac{\sqrt{m^2y}}{\sigma^2}\right),$$

(2.10)

and with rearrangement can be written as

$$f_Y(y) = \frac{1}{\sigma^2} \left\{ \frac{1}{2} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma^2} + \frac{m^2}{\sigma^2}\right)\right] I_0\left(\sqrt{\frac{m^2y}{\sigma^2}}\right) \right\}.$$  

(2.11)

It can be seen that (2.11) is similar to a non-central chi-squared distribution for a degree of freedom equal to 2, which for a random variable $Z$ can be written as [43]

$$f_Z(z; 2, \lambda) = \frac{1}{2} \exp\left[-\frac{1}{2}(z + \lambda)\right] I_0\left(\sqrt{\lambda z}\right).$$

(2.12)

The parameter $\lambda$ is termed as the non-centrality parameter. The mean and variance of $Z$ are given by

$$\mu_z = 2 + \lambda$$

(2.13)
and
\[ \sigma_z^2 = 2(2 + 2\lambda) = 4 + 4\lambda. \] (2.14)

The comparison of (2.11) and (2.12) yields the following.

\[ f_Y(y) = \frac{1}{\sigma^2} f_Z \left( z; 2, \frac{m^2}{\sigma^2} \right), \] (2.15)

with \( z = \frac{y}{\sigma^2} \) and \( \lambda = \frac{m^2}{\sigma^2} \). So using (2.13) and (2.14), the mean and variance of \( Y \) are

\[ \mu_Y = \sigma^2 \left( 2 + \frac{m^2}{\sigma^2} \right), \] (2.16)

\[ \sigma_Y^2 = \sigma^4 \left( 4 + 4 \frac{m^2}{\sigma^2} \right). \] (2.17)

We can use (2.5) to get the mean and variance in terms of \( K \) and \( \sigma \),

\[ \mu_Y = \sigma^2 (2 + 2K), \] (2.18)

\[ \sigma_Y^2 = \sigma^4 (4 + 8K). \] (2.19)

The two equations relate the mean and variance of \( Y \) (power of a Rician random variable) in terms of the parameters of \( X \) (Rician random variable). Since \( \mu_Y \) and \( \sigma_Y^2 \) can be calculated from the observed received power as will be explained later, it can be seen that (2.18) and (2.19) can be manipulated to yield the Rician \( K \) factor in terms of \( \mu_Y \) and \( \sigma_Y^2 \). To remove \( \sigma_Y^2 \), we square (2.18) and divide it by (2.19) and get

\[ \frac{\mu_Y^2}{\sigma_Y^2} = \frac{(2 + 2K)^2}{4 + 8K}. \] (2.20)

Denoting this ratio by \( A \) and doing simple algebraic manipulation, we get

\[ A = \frac{(4 + 8K + 4K^2)}{4 + 8K}, \]

\[ (4 + 8K)A = 4 + 8K + 4K^2 \]

\[ 4A + 8KA = 4 + 8K + 4K^2. \]
Further rearrangement gives

\[ 4K^2 + 8K - 8KA + 4 - 4A = 0 \]
\[ K^2 + 2(1 - A)K + (1 - A) = 0. \]  \hspace{1cm} (2.21)

The quadratic equation can be solved to get \( K \) in terms of \( A \) i.e.

\[ K = (A - 1) \pm \sqrt{A^2 - A} = (A - 1) \pm A\sqrt{1 - \frac{1}{A}}. \]  \hspace{1cm} (2.22)

Following points are very important about (2.22):

Since the Rician \( K \) factor is always positive, \( \mu_Y^2 = 4 + 8K + 4K^2 \) is larger than \( \sigma_Y^2 = 4 + 8K \). This means that \( A > 1 \). So, \((1 - 1/A) > 0 \) and hence the square root in (2.22) will always yield a real result.

Secondly, the first part of (2.22) can be written as \((A - 1) = \sqrt{A-1} \times \sqrt{A-1}\). On the other hand, the second part of (2.22) is \( \sqrt{A^2 - A} = \sqrt{A} \times \sqrt{A - 1} \), which is larger than the first part. Hence, a negative sign with the square root term will yield a negative value of \( K \), whereas a positive sign results in a positive \( K \). We, therefore, consider the positive sign to write the final expression as

\[ K = (A - 1) + A\sqrt{1 - \frac{1}{A}}. \]  \hspace{1cm} (2.23)

2.2.4 Approximate \( K \) Factor Estimation

Using Taylor’s series expansion [44],

\[ \sqrt{1 - \frac{1}{A}} = 1 - \frac{1}{2A} - \frac{1}{8A^2} - \frac{1}{16A^3} - \frac{5}{128A^4} - \cdots \]  \hspace{1cm} (2.24)

For large values of \( A \), the second and higher order terms in (2.24) may be ignored and the result is substituted in (2.23) to get

\[ K \approx (A - 1) + A \left(1 - \frac{1}{2A}\right) \]
\[ = 2A - 1.5. \]  \hspace{1cm} (2.25)
2.2 Estimation of Rician Parameters

The result in (2.25), although looking very simple, will be subsequently shown to result in negligible error at $K$ factor values greater than 2. The simple equation is very much advantageous for implementation in sensor nodes with limited computational capabilities.

2.2.5 Pathloss Estimation

Pathloss in decibels, denoted by $L$, can be computed from $\mu_Y$, as

$$L = -10\log_{10}(\frac{\mu_Y}{\rho}),$$

(2.26)

where $\rho$ is the transmit power.

2.2.6 Simulation Results

![Graph showing symbol and bit error rates for the IEEE 802.15.4 simulator in AWGN channel](image)

**Fig. 2.4:** Symbol and bit error rates for the IEEE 802.15.4 simulator in AWGN channel

To simulate the behavior of wireless nodes operating according to the IEEE 802.15.4 standard, a MATLAB simulator has been developed. The simulator incorporates all
the physical layer (PHY) features for 2.4 GHz offset quadrature phase-shift keying (O-QPSK) and the medium access control (MAC) features that are essential for packet exchange between two nodes. The receiver is designed as a coherent receiver. To verify the working of the simulator, symbol error rate (SER) is simulated for the AWGN channel. Gupta and Wilson presented the SER in AWGN channel, denoted by $P_s$, as \[ P_s \leq 3Q \left( \sqrt{\frac{4E_b}{N_0}} \right) + 6Q \left( \sqrt{\frac{5E_b}{N_0}} \right) + 2Q \left( \sqrt{\frac{4.5E_b}{N_0}} \right) + 2Q \left( \sqrt{\frac{3E_b}{N_0}} \right) + 2Q \left( \sqrt{\frac{3.5E_b}{N_0}} \right), \] (2.27)

where $E_b$ denotes the bit energy, $N_0$ is the noise variance and $Q(x)$ is the Q-function defined as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du$.

The simulated SER, the SER obtained from (2.27) and the simulated bit error rate (BER) are plotted in Fig. 2.4. It can be observed that the results obtained from the simulator are close to the bound given by (2.27) at high $E_b/N_0$ values. This simulator is used for all the work presented in this thesis.

In order to verify the performance of the proposed estimator and its approximation, channel conditions are simulated with different Rician $K$ factor values. The mean pathloss for these simulations is held constant at 0 dB, whereas $K$ values are varied from 0 to 10 with an increment of 0.1. The amplitude of the transmit signal is set equal to 1. The proposed algorithms work by first finding the mean and variance of received signal power and then using (2.23) and (2.25) for the proposed algorithm and its approximation respectively. Results are averaged over $10^5$ different simulations. For comparison, the following two already proposed estimators are considered:

The $K$ factor estimator proposed by Greenstein et al. [34] is considered because it is also based on the received signal power.

The estimator proposed by Bhattacharjea et al. [35] is considered for its superior performance as will be shown shortly. The algorithm, however, uses the second and fourth moments of the signal amplitude and is thus more complex than our proposed algorithms.

Other algorithms (e.g., IQ-based) are not considered for comparison due to their low implementation potential for low-cost simple commercial hardware.

The comparison is shown in Fig. 2.5. It can be observed that the proposed estimator
and the estimator proposed by Bhattacharjea et al. [35] result in the estimated $K$ factor values that are very close to the actual values and their curves almost overlap. It should, however, be reiterated that the proposed algorithm is computationally simpler as compared to the other algorithm which requires the second and fourth moments of the amplitude signal and the amplitude signal itself also needs to be computed in practical hardware from the available power information (RSSI). The estimator that was proposed by Greenstein et al. [34], which was also based on the power information, under-estimates the $K$ factor values. This effect, although
negligible at very high values of $K$, is significant at low values of $K$. The proposed approximation gives very good results at $K$ factor values larger than 2. For values less than 2, the use of the approximation is not justifiable.

### 2.2.7 Hardware Implementation

The proposed algorithm computes the Rician $K$ factor and pathloss from the mean and variance of the received signal power, which is practically obtained in the form of RSSI information that is present in most of the commercially available transceiver hardware. Transmit power of the transmitted signal is also needed, which can be communicated to the receiver by reserving a single byte in each transmit packet. The sequence of RSSI values is the random variable $Y$, as described in the derivation. The computation of its mean and variance may be done in two ways:

In what can be termed as block computation, the receiver can collect a certain number of packets and hence the power values of the received signal and then compute their mean and variance. In such a scheme, there will be a certain waiting time during which the parameter values cannot be computed. The process should be repeated after some time to account for time-variations in the channel. The frequency of repetition depends on how fast the channel is changing.

The other approach can be termed as online computation, in which, each newly obtained power value is used to compute a new mean and variance from the previous values. Several such algorithms already exist in literature. With this approach, some of the initially computed values may deviate from the actual but as more and more packets are received, the algorithms converge to the actual value.

The present work uses the online computation approach. The algorithm presented by Welford [46] and analyzed by Chan et al. [47] is used to compute the mean and variance of signal power ($\mu_Y$ and $\sigma^2_Y$). The calculations are performed iteratively. On receiving the $i$th value of the received signal power ($y_i$), the values of mean and variance, denoted by $\mu_i$ and $\sigma^2_i$, respectively, are calculated as

$$\mu_i = \mu_{i-1} + \frac{(y_i - \mu_{i-1})}{i}$$

(2.28)
2.2 Estimation of Rician Parameters

![Graph showing sequential calculation of Rician $K$ factor.](image)

**Fig. 2.6:** Sequential calculation of Rician $K$ factor.

and

$$
\sigma_i^2 = \frac{(i - 1) \sigma_{i-1}^2 + (y_i - \mu_i)(y_i - \mu_{i-1})}{i}.
$$

(2.29)

The two are then used to calculate the mean pathloss and the Rician $K$ factor.

For practical demonstration of the proposed algorithms, IEEE 802.15.4 compatible hardware is used. Such a hardware is readily available and often comes with integrated microcontroller units for easy programming. It should also be noted that a number of transceivers that are compatible with ZigBee are also compatible with IEEE 802.15.4
Fig. 2.7: Sequential calculation of mean pathloss.

because, as stated earlier, ZigBee utilizes the PHY and MAC provided by IEEE 802.15.4. ZigBit modules by Atmel (e.g. AT86RF212B [48]), XBee ZigBee [49] and XBee 802.15.4 [50] by Digi International, PAN4561 by Panasonic [51], JN5161 from NXP [52], EasyBee by Flexipanel [53] are some of the many available hardware solutions compatible with IEEE 802.15.4. Texas Instruments also offers many ZigBee compatible transceivers\(^3\). Following is a brief overview of two such transceivers that are used in the subsequent work.

\(^3\)http://www.ti.com/lads/ti/wireless-connectivity/zigbee/overview.page
2.2 Estimation of Rician Parameters

**CC2520**

CC2520 is a 2.4 GHz transceiver that is compatible with ZigBee and IEEE 802.15.4. The physical layer complies with the 2.4 GHz O-QPSK PHY of the standard. The transmit power can be programmed from $-18$ dBm to $5$ dBm by setting the TXPOWER register in the transceiver. The receiver sensitivity is $-98$ dBm. The transceiver generates the RSSI and the link quality indication (LQI) signals for every received packet. The received packet is also appended with its cyclic redundancy check (CRC). Most of the functions can be programmed through a serial peripheral interface (SPI) using microcontroller. For further details, please refer to the CC2520 datasheet [54].

**CC2531**

CC2531 is a system-on-chip (SoC) solution for ZigBee and IEEE 802.15.4. With its universal serial bus (USB) interface, it is also available as a USB Evaluation Module Kit. This kit can be easily plugged into the computer and programmed. It also comes with some example programs including a packet sniffer. The packet sniffer can be readily used to collect IEEE 802.15.4 compatible packets and save them to the computer for analysis. For further information, please refer to CC2531 USB hardware user’s guide [55].

![Fig. 2.8: CC2531 USB Evaluation Kit.](image)

The CC2531-based USB evaluation module kit is mostly used in the current work as a packet sniffer for saving all packets being exchanged by other nodes in a passive way i.e with the node itself not being part of the network. CC2520 transceivers are used with MSP430-based microcontroller boards for testing the proposed algorithms.
The proposed approximate algorithm was implemented on evaluation boards MSP-EXP430F5438 [56] and MSP-EXP5529LP [57] with IEEE 802.15.4 compatible CC2520 [54] transceivers. Experiments were conducted in the lab and office environments (Rooms 348 and 349 of Science Park 1, JKU). Typical distances were 1 m to 3 m within the same room and 5 m for communication between two different rooms. Even for the same distance, the placement of the nodes relative to the already existing objects generated different channel conditions. The movement of people also resulted in variations. One node that was also connected to a computer was programmed to transmit packets every 2 sec with a transmit power that was included
in the packet payload. The other node, termed as the remote node, was placed at a distance, which was varied for different setups (however, constant for a complete run consisting of several packet exchanges) in order to create channels with different mean pathloss and Rician $K$ factors. The remote node, on receiving packets, used the online computation algorithm to calculate the mean and variance of the received signal power obtained through RSSI values. The calculated mean and variance along with the transmit power conveyed to the node in the received packets are used to calculate the mean pathloss and the Rician $K$ factor of the channel. All these computations were performed on the node itself. On completion, the remote node transmitted a packet, consisting of its computed parameters and other variables, which could be received at the first node connected to the computer. This allowed the received packets to be saved in the computer for future reference and analysis. As a part of the analysis, the algorithm presented by Bhattacharjea et al. [35] was run offline, due to its complexity, on the computer to compare the results produced by our proposed algorithm. The results for one such scenario are shown in Figs. 2.6 and 2.7 for the Rician $K$ factor and the mean pathloss, respectively. It can be seen that results for $K$ factor estimation are in perfect agreement with each other. Moreover, it can be seen that the initial $K$ factor estimate is very large. So, the channel is assumed to be an AWGN channel. As more and more packets arrive, the estimate converges to the true value. However, if the channel characteristics vary with time, the estimates will continue to change.

The mean pathloss and the Rician $K$ factor computed from the proposed algorithm were used to compute the optimum transmit power, which is discussed in the next section.

### 2.3 Transmit Power Calculation

The calculated transmit power is said to be optimum if it fulfills some desired performance criteria. Outage probability, bit error rate, and symbol error rate are some of the most commonly used performance criteria. In the present work, we use outage probability as the performance criterion to calculate the transmit power. Outage probability can be defined as the probability that the received signal-to-noise ratio (SNR) falls below a certain desired threshold. In this work, without loss of generality, the threshold is considered to be 1. With a threshold of 1, the outage
probability may be redefined as the probability that the received signal power falls below the noise level. It should also be noted that the condition when the received SNR is below the threshold is termed as an outage.

Calculating the transmit power when the randomness of the channel parameters has been taken into account results in a better outage performance as compared to the case when the transmit power is based only on the pathloss value [30].

The probability that the received SNR $x$ is below a threshold $\xi$ in a Rician channel, is given by [58, Eq. 8],

$$P_{\text{out}} = P(x \leq \xi) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(1 + K)\xi}{\Omega}}\right),$$

(2.30)

where $P_{\text{out}}$ is the outage probability and $Q(\cdot, \cdot)$ is the first-order Marcum Q function. The first-order Marcum Q function is defined as [22]

$$Q(a,b) = \int_{b}^{\infty} x \exp\left(-\frac{x^2 + a^2}{2}\right) I_0(ax)dx,$$

(2.31)

with $I_0(\cdot)$ as the zero-order modified Bessel function of the first kind. The problem of obtaining a desired outage probability for a certain SNR threshold can be done by iteratively solving (2.30), to obtain the value of $\Omega$, i.e. total mean received power. It should be noted that, according to (2.8), the total mean received power is the product of the transmit power and the mean power gain of the channel. To summarize, we can solve (2.30) to find the value of transmit power to have a required outage probability with a given SNR threshold. The process is computationally prohibitive, especially with the presence of Marcum Q function, for sensor nodes with limited computational capabilities.

It is, therefore, desired to find an alternate approach to solve the optimum transmit power calculation problem in Rician channels. The alternate approach, although approximate, should be computationally simple.

### 2.3.1 Coding Gain Approach

The idea of coding and diversity gains, as proposed by Wang and Giannakis [59], may be used to approximate the channel behavior at high SNR. According to this approach, the error or outage behavior of a channel is inversely related to the average
SNR ($\gamma$) with a multiplicative term, called the coding gain ($G_c$), raised to an exponent term, called the diversity gain ($G_d$) i.e.

$$P_E \approx (G_c \gamma)^{-G_d} \quad (2.32)$$

The approximation is justified at high values of SNR. It should be noted that the term coding gain in this approach refers to the behavior of the whole system and is applicable to both uncoded and coded systems. For an uncoded system, the approach describes the effect of the channel on the error or outage performance and must not be confused with the normal usage of the term in coded systems where it describes the advantage of coding. For a single, point-to-point link between two nodes, the diversity gain is equal to 1. The coding gain can be calculated from the channel parameters and is different for different types of channel. Savazzi and Spagnolini gave an expression for the coding gain of a Rician fading channel [60], denoted by $c$ as

$$c = e^{K \frac{L}{10 \log(1+K)}} \quad (2.33)$$

where $K$ and $L$ are the Rician $K$ factor and the mean pathloss respectively.

Modifying (2.32) for outage probability by introducing the SNR threshold, the relationship between the coding gain and the outage probability can be found in [30] as

$$P_{out} \approx \frac{\gamma_{th} \sigma^2}{c \rho} \quad (2.34)$$

where $P_{out}$ is the outage probability, $\gamma_{th}$ is the SNR threshold, $\sigma^2$ represents the noise variance, and $\rho$ is the transmit power. The $\approx$ sign indicates that the expression is asymptotically true at high SNR values.

To get an insight into the equation, we rearrange (2.34) to get

$$\frac{P_{out} \rho}{\sigma^2} \approx \gamma_{th} \quad (2.35)$$

With this formulation, the right hand side of the equation is the SNR threshold for the outage probability. The left hand side has the signal power in the numerator while the noise variance in the denominator and there are the multiplicative terms, $P_{out}$ and $c$. From a physical perspective, the multiplicative terms represent the effect
of the channel on the input power (transmit power) and hence, correspond to the power gain of the channel that will be expected at the limit for outage. This can be explained as follows. If, for example, the outage probability is chosen as 0.01, the power gain of the channel will be 1% of the time below this value and for the remaining 99%, the power gain of the channel will be more than this value. Thus, the transmit power, hence chosen, will be able to meet the required outage criterion. This interpretation is, however, true only asymptotically at high SNR.

It is interesting to further explore the validity of the coding gain expression. According to [30], the approximation is valid at high SNR, which is true at outage probabilities less than 0.01. We, however, found that the validity of the expression strongly depends on the Rician $K$ factor. For large $K$ factors, extremely small outage probabilities are required to justify its use, which in some cases may not even be practical. It should also be noted that the mean pathloss value has no effect on the validity of coding gain expression because it only acts as an overall shifting factor without changing the shape of the performance curves.

The effect of Rician $K$ factor on the coding gain is investigated using simulations. For these simulations, we consider a mean pathloss value of 0 dB. A different mean pathloss value just changes the values of the plotted power gain values without changing the shapes of the curves or the inferred results. For reference, we use (2.30) to find the mean power gain of the channel for different values of $K$ factor at outage probabilities of $10^{-1}$, $10^{-2}$ and $10^{-3}$. The resulting values are termed as the theoretical results. The power gain of the channel is important due to the fact that it relates to the outage performance of the channel in a very simple way. E.g. doubling of the power gain of the channel at a certain outage probability allows the transmit power to be halved for a similar performance. For the coding gain approach, we calculate the coding gains using (2.33) for different $K$ factor values and multiply them by the outage probability values of $10^{-1}$, $10^{-2}$ and $10^{-3}$ to get the plotted curves.

The comparison shown in Fig. 2.11 reveals the following interesting points:

For $K$ factor values below 1, both the approaches give almost identical results. For large values of $K$ factors, the power gain values obtained from the coding gain approach exponentially deviate from the theoretical values. However, the $K$ factor value at which the two results deviate, depends on the outage probability. E.g. at an outage probability of 0.1, the coding gain approach deviates for $K$ factor values
2.3 Transmit Power Calculation

Fig. 2.11: Comparison of the power gain of the channel determined from Marcum Q function (shown with solid lines and denoted by 'Th') with the power gain determined from coding gain approach (shown with dashed lines and denoted by 'CG'), done at different outage probability values and Rician $K$-factors.

of greater than 1, while for an outage probability of 0.01, they deviate for $K$ factor values greater than 2 and for an outage probability of 0.001, the deviation is at around $K$ factor value of 4. The deviation indicates that the coding gain approximation is not valid for these parameter values. To make the approximation hold for these high $K$ factor values requires even lower outage probability values. For example, we calculated that a Rician $K$ factor value of 40 requires an outage probability
value of $10^{-15}$ to have similar results for the coding gain value and the actual value. Such exceedingly low values are not practically achievable. From Sec. 2.1.3, it can be recalled that the $K$ factor values may be expected to be over 40 for practical scenarios. Thus, in such cases, using the coding gain approximation may not be justifiable.

### 2.3.2 Proposed Power Calculation Method

As stated in the previous subsection, the power gain of the channel can be a suitable parameter to calculate the optimum transmit power of a node for a given outage probability. Due to the invalidity of the coding gain approximation at practical values of the Rician $K$ factor and the complexity of the exact solution, an alternative approach is desirable especially for simple low-cost sensor nodes with limited computational capabilities. A simple look-up table-based approach is hence proposed along with a method to use it in simple nodes. Simulations and hardware results validate the effectiveness of this approach.

The complete method for calculating optimum transmit power for a Rician channel was presented in [61]. The main idea was that, the power gain values can be pre-computed using Marcum Q function at different values of Rician $K$ factor. Since, the mean pathloss acts as a scaling factor (additive factor when considered in decibels) only, the computations are performed at a single mean pathloss value of 0 dB. These precomputed values can be stored in the node in the form of a table and a table look-up approach is used to access these values for the given $K$ factor value. Knowing the desired received power, transmit power can be calculated using the power gain of the channel. Following modifications are proposed in the method presented in [61]:

In [61], it was proposed that the Rician $K$ factor values for which the channel power gain values are computed can be considered in decibels and the range may be chosen from $-15$ dB to 25 dB with non-linear spacing such that only 16 points are considered. Linear interpolation was proposed for calculating the power gain at the values not listed in the table. Simulations proved that the output power calculated from the proposed method performed almost equal to the case when the channel power gains were computed according to the Marcum Q relationship and this was achieved at negligible computational costs.

A modification to [61] is proposed, by considering the initial used $K$ factor values not
in decibels. Since the results of $K$ factor calculation obtained by (2.23) or (2.25) are not in decibels, the additional cost of converting the results to decibels are avoided when the channel power gain table is computed at the $K$ factor values that are not in decibels.

An additional improvement is proposed to avoid the complexity of linear interpolation by increasing the size of the look-up table such that the power gains are computed at integer values of the $K$ factors starting from 0. The 0 value corresponds to the Rayleigh fading channel and is followed by Rician channels with increasing $K$ factors. It is also found that after a certain $K$ factor value, the channel may be considered as an AWGN channel and the Rician effect is negligible i.e. considering it as a Rician channel does not change the output power requirement by more than 2 dB when compared to an AWGN channel with the same mean pathloss value. E.g. the difference in calculated power from the two approaches is 2 dB or less for Rician $K$ factor values greater than 44, when considered at an outage probability of 0.01. Thus, in this case, the size of the table is only 44. Arranging the look-up table for integer values of $K$ factors also allows the table to be accessed as a simple array where the $K$ factor value, for which the channel power gain is to be calculated, acts as an index to the array and the returned content from the array represents the channel power gain.

Since the RSSI values in commercial hardware are generally in decibels and hence the computed mean pathloss is also conveniently expressed in decibels, the values generated from the look-up table are expressed in decibels to further reduce the computational overhead. It should be noted that since the table is computed at a mean pathloss of 0 dB, the channel power gain values represent the difference of power requirement for the Rician channel at the desired $K$ factor as compared to an AWGN channel.

### 2.3.3 Hardware Implementation

The proposed algorithm and the $K$ factor estimation method proposed in the previous section are implemented on MSP-EXP430F5438 [56] and MSP-EXP5529LP [57]-based nodes with IEEE 802.15.4 compatible CC2520 [54] transceivers. The setup is done as described in Section 2.2.7 with one node connected to a computer programmed to periodically send dummy packets and save the received packets to the computer for analysis. The remote node on receiving packets, uses the RSSI value to estimate
Chapter 2  Optimum Transmit Power Calculation

Fig. 2.12: Observed outage ratio for the proposed power calculation algorithm for different Rician $K$ factors.

Fig. 2.12: Observed outage ratio for the proposed power calculation algorithm for different Rician $K$ factors.

the mean pathloss and the Rician $K$ factor of its channel to the first node. The estimation is done using (2.25). The estimated parameters are then used to calculate the optimum transmit power using the proposed approach, presented in Section 2.3.2. I.e. look-up tables are computed for integer values of Rician $K$ factor (not in decibels) and interpolation is not required. The size of the table is 44. The computed channel gain values are already in decibels. The transmit power is designed to ensure an outage probability of 0.01 at the destination. All the calculations are verified by sending the calculated values as a part of the payload in packets that are sent to
the node connected to the computer. The use of the actually calculated transmit power is hampered by the fact that the used transceiver (i.e. CC2520) allows the transmit power to be set from a limited number of possible values (According to the datasheet [54], the output power values in dBm can be 5, 3, 2, 1, 0, −2, −4, −7 and −18). Thus, in the case that the calculated optimum power is not exactly equal to the allowed value, the nearest value needs to be chosen. The choice of the next higher power level is logical so that the minimum performance requirement (outage probability in our case) is met. However, this may result in a power level that is
much higher than the required and hence the expected performance can be much better than the one for which the system is actually designed. A fair performance assessment in such a case is not possible. It should also be noted that such a problem may not happen if the transceiver allows a more or less continuous setting of transmit power within its range. Nevertheless, to assess the performance of the proposed power calculation algorithm, we develop the following strategy. The remote node runs the optimum power calculation algorithm, sets its output power according to the calculated power and next allowed power level and sends a packet that contains the actually calculated power value as a part of its payload. The node connected to the computer receives these packets and computes the RSSI value and determines the pathloss encountered in that transmission. A comparison is made to find if the calculated transmit power at the remote node is sufficient for the encountered pathloss or not. In the case that it is not sufficient, outage would be caused if the calculated value is used. In this way, outage ratios are computed for different placements of the remote node. The different placements are done to generate channels with different mean pathloss and Rician $K$ factors. The number of packets transmitted by the remote node in each node placement is on average equal to 2000. The combined outage ratio performance is shown in Figs. 2.12 and 2.13 against the estimated Rician $K$ factors and mean pathloss values respectively. It can be seen that the algorithm works independent of the mean pathloss and the Rician $K$ factor. The mean outage ratio is observed to be equal to 0.009, which is slightly less than the design value of 0.01. The small discrepancy can be attributed to the fact that, in some cases, especially with long runs, it is possible that there are some early disturbances in the channel that prompt the node to use higher transmit power. Even though the disturbances, later on, cease, the transmit power continues to remain high due to the overall average behavior of the channel. A sliding window can be beneficial in such scenarios. However, its performance is not evaluated.

2.4 Summary

The chapter outlined the issue of calculating the optimum transmit power in a point-to-point link, where the channel is modeled by a Rician distribution. The power calculation requires an accurate estimation of the channel parameters, which are the Rician $K$ factor and the mean pathloss. A method was proposed that uses the RSSI value, which is present in most of the commercial hardware and is required to
be present in IEEE 802.15.4 compatible hardware, to estimate the two parameters. An approximation to the method was also proposed that is computationally very simple for practical nodes with limited computational capabilities. The mathematical derivation was followed by simulation results to verify the effectiveness of the proposed methods. The approximate method is also implemented on practical nodes and the performance is observed to be equal to the state-of-the-art estimators albeit at a much lower computational complexity. The topic of optimum power calculation was discussed and it was found that the actual method is too complicated. It was also found that the already proposed approximation of coding gain could not be applied in channels with $K$ factor values that are likely to exist in practical environments. A practical scheme based on a look-up table was proposed and was implemented on nodes. The effectiveness of the method was hence proved.
Chapter 3

Relaying

Relaying is a useful technique to enable data transfer between two nodes that are experiencing poor channel conditions that otherwise would make the transfer impossible or require excessively high transmit power. In this chapter, we present some basic information regarding relaying and also present the communication scenario that will be used further in the remaining work. Then, we shall deal with the optimum power calculation problem in relayed transmission. The existing solutions as well as our proposed solutions will be presented. Simulations and practical results will be used to verify the claims. The topic of energy saving using relaying will also be introduced.

3.1 Basics

According to Oxford dictionary, the word relay originated in Late Middle English\(^1\), which is much before the discovery of electricity by Benjamin Franklin. The term describes a group of people or animals who help each other in an activity by doing a part of that activity one after the other. In telecommunications, relaying is also an old technique for transmitting signal to a distance which may not otherwise be achievable by the source. Intermediate node(s), called relay(s), can help the source to deliver the signal to the destination.

The idea of relaying is not necessarily applicable to long-distance communication only. Relying is applicable even when the distance is not too large but the channel conditions are poor enough to require other nodes to assist the source node in

\(^1\)https://en.oxforddictionaries.com/definition/relay
conveying its message to the destination. In such cases, relay channels use the idea of cooperative diversity to mitigate the fading effects that are caused by multipath propagation [62]. The same idea can also be used to decrease the power consumption of the nodes that are facing poor channel conditions and hence increase the lifetime of the network [63].

### 3.1.1 Types of Relaying

Relays can function in a number of ways. Following are the most commonly used types of relaying:

**Amplify and Forward Relaying**

The simplest type of relaying is the amplify and forward (AF) relaying, in which the relaying node receives the message and relays it without decoding its contents. Such a relaying can be fast and the job of the relay node is much simplified. The incoming signal and the relayed signal are differentiated either by using different frequencies for the two or using time division by first receiving the whole frame and then relaying it afterwards (possibly in a different slot or sub-slot) [16].

**Decode and Forward Relaying**

The other major type of relaying is termed as the decode and forward (DF) relaying. In this type of relaying, the relay first decodes the signal and then regenerates the frame for transmission. The process requires more functionality in the node as compared to AF relaying and takes more time. Different strategies may be adopted if the relay node is unable to decode the received frame. In some cases, it is deemed useful that the node resorts to AF strategy if it is unable to fully decode the received frame [16].

Some other relaying schemes (e.g. compress and forward [64]) also exist in literature but their use in the literature is much limited. From a practical perspective and considering the commercial sensor node hardware available in the market, if ordinary nodes are used as relay nodes, DF can be a possible choice. With software defined radio (SDR), other relaying schemes can also be implemented.
3.1 Basics

3.1.2 Relaying Strategies

Different relaying strategies exist in the literature. According to Laneman et al. [62], relaying may be done in the following ways:

- **Fixed Relaying** - In this scheme, the relay node always forwards the received message from the source node.
- **Selection Relaying** - In this scheme, the relay adapts its transmission mechanism according to the channel conditions with the source. Nevertheless, relaying always takes place.
- **Incremental Relaying** - This scheme circumvents the problem of always relaying by doing it only when it is required. In this case, the feedback from the destination determines if relaying is required or not.

3.1.3 Combination at the Destination

The signal directly received from the source and the signal relayed by the relay node can be combined at the destination in a number of ways. The optimum combination technique that is also widely used in literature is the maximal-ratio combining (MRC). In MRC, the received signals from the direct path and the relayed path are weighted according to their signal strength and added to make the combined signal. MRC is an optimum combining technique and this is the reason of its wide use in the relaying literature. Another scheme that can be of interest from a practical point of view is selection combining (SC), in which the best received signal is selected. With simple transceivers, SC can be used by selecting the error-free received packet from the direct or the relayed path, if available. Other combination techniques like equal gain combining are seldom used in the relaying literature.

3.1.4 Relay Model

For the forthcoming discussions in the thesis, we shall consider the communication scenario, in which the resource-constrained sensor nodes, as denoted by $i$ and $j$ in Fig. 3.1 transfer data to a single destination node that may be termed as an access point (AP). The index 0 denotes the AP and the $N$ resource-constrained nodes are numbered from 1 to $N$. In the current chapter, we take $N = 2$ to describe the power
Fig. 3.1: Source, relay and destination links

calculation problem. The case of \( N > 2 \) will be discussed afterwards. The channel impulse responses for the different links are denoted by \( h \) and the indices are used to indicate the particular link.

It is very important to note that, in this work, we consider the case where there are no special relay nodes. Ordinary nodes can help other nodes to act as relays for their communication. Such a scenario is hence termed as cooperative communication. More will be discussed about cooperative communication in the next chapter. In Fig. 3.1, node \( j \) acts as a relay for node \( i \). This cooperation may also be reciprocal, in which, node \( i \) may also act as a relay for node \( j \).

### 3.2 Power Calculation

As discussed in chapter 2, the calculation of optimum transmit power is very important for wireless nodes and hence the already existing methods were discussed and a proposed approach was presented to calculate optimum transmit power in Rician fading channels. The calculation of optimum power is equally important for relay channels. As will be shown shortly, the calculation of optimum power in Rician fading relay channels is even more complicated.

In this discussion, we assume that the Rician channel parameters (i.e. mean pathloss and Rician \( K \) factor) are already estimated by the nodes (using the method proposed in chapter 2) for their links to each other and to the AP. With the current scenario
3.2 Power Calculation

of transferring data to an AP, all the nodes can estimate the channel parameters to the AP by using the beacon signals that are usually transmitted periodically by the AP for management purposes. The channel parameters for the links between the nodes are estimated using the overheard signals. Hence, the estimation of channel parameters does not require any special packet exchange between the nodes.

3.2.1 Exact Calculation

For the scenario shown in Fig. 3.1, the signal directly received at the AP from node \(i\) is given by

\[ y_{i,0} = h_{i,0} x_i + n_0, \]  

(3.1)

where \(x_i\) is the signal generated by node \(i\), \(h_{i,0}\) is the complex frequency-flat, block fading channel coefficient between node \(i\) and the AP and \(n_0\) is the symmetric, complex, additive white Gaussian noise with variance \(\sigma^2\).

The same signal is also received at node \(j\) and given by

\[ y_{i,j} = h_{i,j} x_i + n_j, \]  

(3.2)

with the indices changed to reflect node \(j\) instead of the AP.

In order to perform AF relaying, the relay node \(j\) amplifies the signal received from node \(i\) using a gain factor \(\alpha_j\) and transmits it. This relayed signal is received at the AP as

\[ y_{j,0} = \alpha_j h_{j,0} y_{i,j} + n_0. \]  

(3.3)

The AP combines the two signals (i.e. directly received \(y_{i,0}\) and relayed \(y_{j,0}\)) to extract the information. With MRC at the AP, it can be proved that the combined signal-to-noise ratio (SNR) is given by [65]

\[ \gamma(i,j),0 = \gamma_{i,0} + \left( \frac{\gamma_{i,j} \gamma_{j,0}}{1 + \gamma_{i,j} + \gamma_{j,0}} \right), \]  

(3.4)

where \(\gamma\) represents the SNR and the subscripts represent the various links. The subscript \((i,j),0\) indicates the SNR for node \(i\) as the source with node \(j\) acting as relay and node 0 i.e. AP as the destination. Allocating equal power to the source and
the relay has been found to be useful for improving the lifetime of the network [66].

Denoting the transmit power by $\rho$ and assuming the same noise variance $\sigma^2$ for all nodes, (3.4) becomes

$$
\gamma(i,j,0) = \frac{\rho}{\sigma^2} \left[ |h|_{i,0}^2 + \left( \frac{|h|_{i,j}^2}{\rho} + |h|_{i,j}^2 + |h|_{j,0}^2 \right) \right].
$$

(3.5)

The equation can be used to find a value of $\rho$ to achieve the desired SNR at the destination for given channel parameters. With a statistical distribution for the channel response, (3.5) ends up in a distribution for SNR, which can be used to find the outage probability. However, for a Rician fading channel, such an expression is too complex. Limpakom et al. [65] provided an expression for the SNR probability density function (PDF) of the relayed path (excluding the direct link)

$$
p_{\gamma_r}(\gamma) = \frac{(1 + K_{sr})(1 + K_{rd})}{\tilde{\gamma}_{sr} \tilde{\gamma}_{rd}} \exp \left( -K_{sr} - K_{rd} - \frac{(1 + K_{sr})\gamma}{\tilde{\gamma}_{sr}} - \frac{(1 + K_{rd})\gamma}{\tilde{\gamma}_{rd}} \right)
\times \sum_{m=0}^{\infty} \sum_{n=0}^{m} \frac{1}{[n!(m-n)]^2} \left[ \frac{K_{sr}(K_{sr} + 1)}{\tilde{\gamma}_{sr}} \right]^n \left[ \frac{K_{rd}(K_{rd} + 1)}{\tilde{\gamma}_{rd}} \right]^{m-n}
\times \sum_{k=0}^{m+2} \left( \frac{m+2}{k} \right) 2^{\gamma m+1} \left( \frac{\tilde{\gamma}_{sr} \tilde{\gamma}_{rd}}{1 + K_{sr} + K_{rd}} \right)^{(m-n-k+1)}
\times K_{m-n-k+1} \left( 2^\gamma \sqrt{\frac{(1 + K_{sr})(1 + K_{rd})}{\tilde{\gamma}_{sr} \tilde{\gamma}_{rd}}} \right).
$$

(3.6)

The expression even excluding the direct link is so complex that using it to compute the transmit power in sensor nodes with limited capabilities is not feasible. It is, therefore, essential to develop some approximate solutions that may be implementable on available hardware.

### 3.2.2 Coding Gain Approach

As already discussed in the previous chapter, the coding gain approach provides an approximate solution to calculate the power required for the channel conditions approximated in the form of coding and diversity gains as proposed by Wang and Giannakis [59]. As stated previously, the coding gain of a link can be calculated using
3.2 Power Calculation

the Rician $K$ factor and the pathloss using (2.33). The coding gain of the direct, source to relay and relay to destination links can be combined to form the total coding gain (Node $i$ as source, node $j$ as relay and AP as destination) [30]

$$c_{(i,j),0} = \left[ \frac{1}{c_{i,0}} \left( \frac{1}{c_{i,j}} + \frac{1}{c_{j,0}} \right) \right]^{-\frac{1}{2}}.$$  \hspace{1cm} (3.7)

The outage probability for the overall link is given by [30]

$$P_{\text{outage}} \approx \frac{1}{2} \left( \frac{\gamma_{\text{th}} \sigma^2}{c_{(i,j),0} \rho} \right)^2.$$  \hspace{1cm} (3.8)

In (3.8), the SNR threshold for outage is represented by $\gamma_{\text{th}}$, noise variance by $\sigma^2$ and the transmit power by $\rho$. Unlike (2.34), it can be seen in (3.8) that the outage probability is proportional to the square of the given parameters. This is due to the diversity gain of the relay link which is equal to 2.

Manipulating (3.8), the transmit power is obtained as

$$\rho \approx \frac{\gamma_{\text{th}} \sigma^2}{c_{(i,j),0} \sqrt{2P_{\text{outage}}}}.$$  \hspace{1cm} (3.9)

The following points are worth consideration in order to better understand the forthcoming discussion:

Considering that the mean pathloss and the Rician $K$ factor of the links are known, calculating the transmit power requires the following steps:

- Coding gains of the individual links are calculated using (2.33) that involves one conversion from decibels, an exponent and one division and multiplication (There is also one addition but the computational cost of addition may be neglected when compared to the other mathematical operations). The process is required for the three links i.e. node $i$ to 0, node $i$ to $j$ and node $j$ to 0.

- Combined coding gain is obtained using (3.7). The equation can be rearranged to require two multiplications, one division and a square root operation.

- The required transmit power is calculated using (3.9). The execution requires one square root, four multiplications and one division.
So, the first step requires more complex operations while the next steps require division, multiplication and square root operations. The computational complexity is much lower than for the computation of (3.6).

Another important behavior of the coding gain approximation, which was explored in Sec. 2.3.1, is the dependence on the value of the Rician $K$ factor that determines the validity or invalidity of the approximation. The conclusions obtained for the direct link are extendible to the relay links because the relay link is a combination of the individual link or, stated differently, since the overall coding gain is the combination of the three individual coding gains, the approximation will not yield good results if it is not true for any of the individual links. The claim will be substantiated when a comparison of the coding gain approach is presented later in this chapter.

### 3.2.3 Proposed Solution

As explained in Sec. 2.3.2, the channel power gain values to ensure the required outage probability can be obtained from a look-up table. For relaying, these channel power gains are calculated for the three links i.e. source to destination (node $i$ to node $0$), source to relay (node $i$ to node $j$) and relay to destination (node $j$ to node $0$) and denoted by $|h_{i,0}|^2_{P_{out}}$, $|h_{i,j}|^2_{P_{out}}$, and $|h_{j,0}|^2_{P_{out}}$ respectively. We divide these channel power gain values by the outage probability at which they were computed and term them as the modified channel gains. The three modified channel gains are denoted by $g_{i,j}$, $g_{i,0}$, and $g_{j,0}$. Considering (2.35) and the associated discussion, it can be seen that the modified channel gain has the following relation to the coding gain: At very low outage probabilities i.e. when the coding gain approximation is valid, the modified channel gain and the coding gain are equal. In this region, the modified channel gain will be a constant irrespective of the outage probability value similar to the coding gain value. When the coding gain approximation is not valid, coding gain and the modified channel gain values are different.

To derive the overall channel gain for the relay channel, we initially assume that the modified channel gains for the links are constant. From a physical perspective, the assumption means that the power gain of the channel is linearly related to the outage probability ($|h_{i,0}|^2_{P_{out}} \propto P_{out}$) such that if the outage probability is divided by 10, the power gain value of the channel is also divided by the same factor i.e. 10 times more transmit power is required to achieve the new outage probability. This scenario is exactly similar to the coding gain approach when it is valid to use the
approximation. Thus, similar to the coding gain, the combined modified channel gain for the relay-based link is expressed as

\[
g_{(i,j),0} = \left[ \frac{1}{g_{i,0}} \left( \frac{1}{g_{i,j}} + \frac{1}{g_{j,0}} \right) \right]^{-\frac{1}{2}}
\]  \tag{3.10}

However, the assumption of a constant modified channel gain is only valid at very low outage probability values. As described in Sec. 2.3.1, the validity also depends upon the Rician \(K\) factor value and therefore, for practical scenarios, the outage probability value required for the validity may be not achievable. To circumvent this problem, we propose the following strategy. We compensate the nonlinearity in the channel gain by computing the gain values at two outage probabilities and taking the harmonic mean of the two values. The selection of these values is based on the fact that the existence of an alternate path (relay channel) in addition to the source-to-destination channel makes the combined channel better than if only the direct link is used. This means that the transmit power requirement with a relay channel is always less than if only the direct path is used. Thus, if the transmit power required for the relay channel is used for the direct link, the outage probability is more. For the asymptotic case and when all the channels are similar, it can be easily proved from (3.7) and (3.8) that the outage probability for the direct link is equal to the square root of the outage probability for which the relay-based system was designed. The work presented in [61], computed the modified channel gain values at the desired outage probability and the square root of the desired outage probability. It was found through simulations that the designed system performed well at low to medium values of Rician \(K\) factor but deviated from the desired value for high values of Rician \(K\) factor. The results were, however, significantly better than that for the coding gain approach. Through simulations, we have observed that if the modified channel gain values are computed at 10 times and 40 times the outage probability, the observed performance is very close to the desired performance.

Thus, the modified channel gains \(g_c|_{P_{out1}}\) and \(g_c|_{P_{out2}}\) are computed using (3.10) such that \(P_{out1} = 10P_{outage}\) and \(P_{out2} = 40P_{outage}\).

We calculate the effective modified channel gain as the harmonic mean of the two values,
Chapter 3 Relaying

\[ g_{\text{effective}} = \frac{2}{\frac{1}{g_{i,j}|P_{\text{out}1}} + \frac{1}{g_{i,j}|P_{\text{out}2}}} \].

(3.11)

The reason to select the harmonic mean is that the harmonic mean of two numbers is always closer to the smaller number. Hence, for the two modified channel gain values, the harmonic mean results in a value that is closer to the worst modified channel gain. Similar to (3.9), we calculate the transmit power as

\[ \rho \approx \frac{\gamma_{\text{th}}\sigma^2}{g_{\text{effective}}\sqrt{2P_{\text{outage}}}}. \]

(3.12)

It is interesting to compare the proposed method with the coding gain approach. The proposed method utilizes a channel characteristic that is named as the modified channel gain whereas the other approach is based on the coding gain of the channel. The two terms are similar at low outage probability values but differ at other values. The proposed method requires an additional computation of the modified channel gain at a second outage probability value and an effective value is calculated using harmonic mean. The next step i.e. calculation of the transmit power is similar for both of the methods. Thus, from a computational complexity perspective, the additional overhead in the proposed method is only small.

From the performance point of view, at very low outage probability values, both the methods produce equal results and the calculated power will be close to optimum. However, at higher outage probability values, the coding gain approach suffers from two problems:

- The power gain values calculated for the channel segments, using the coding gain values, are much different from the actual values.
- The application of the power calculation formula assumes a constant slope for the channel power gain versus outage probability which is not true.

The proposed approach circumvents the problem by first using the modified channel gain parameter and hence removing the first above-stated drawback of the coding gain approach. The calculation of the modified channel gain at the second outage probability value and taking the harmonic means help to reduce the effect of the second above-stated problem. Hence, the performance of the proposed algorithm is expected to be better than the coding gain approach as will be shown in the next subsection.
3.2 Power Calculation

3.2.4 Simulation Results

The performance of the power calculation methods for AF relaying is compared using simulations. The IEEE 802.15.4 simulator (see Section 2.2.6) is used. We consider the problem of a source node sending data to a destination node with another node acting as a relay using AF, as shown in Fig. 3.1. Since the performance of the different methods is expected to be highly dependent on the Rician $K$ factors of the channel, channel conditions are created with different $K$ factor values for the source.
to destination, source to relay and relay to destination links. The $K$ factor values are varied from 0 to 100 for the three channels, such that same values are used for the three channels. It was also verified from the simulations that the mean pathloss values of the channels did not play any role in the results. Hence a constant value of 50 dB is chosen for the three channels. Transmit power values are calculated for the exact approach (described in Sec.3.2.1), coding gain approximation (described in Sec. 3.2.2) and the proposed approach (described in Sec. 3.2.3). The outage probability is targeted as 0.001. For each scenario, $10^5$ frames are transmitted and the received SNR is computed at the destination to identify if an outage occurs or not. An outage rate is computed for each scenario. The results are shown in Fig.3.2.

It can be observed that even for low values of $K$ factor, the coding gain approach causes outage rates approaching 1. The outage probability for the proposed approach, on the other hand, is very close to the outage probability for the exact calculation. As stated previously, the better performance of the proposed approach is achieved with a computational complexity similar to the coding gain approach.

### 3.3 Relaying and Energy Saving

Apart from overcoming the effect of multipath fading, relaying can also be used to improve the lifetime of the network and decrease the overall energy consumption of the nodes using optimum power allocation [63]. In this section, we consider the problem of two nodes sending data to an AP and both nodes, irrespective of the channel conditions, acting as relays for each other. The relays use AF relaying and the AP uses MRC to combine the received signal. The problem of having more than 2 nodes complicates the problem because in that case the selection of an optimum relay node is also required, which will be discussed in the next chapter. In this section, we will focus on the problem of lifetime improvement and the overall energy expenditure.

#### 3.3.1 Basic Definitions

As described in the previous chapter, efficient utilization of energy is very important for a wireless node. The importance of optimum energy utilization is even more significant for simple battery-driven sensor nodes because the costs and efforts of
battery replacement are not ignorable. The individual energy consumption of a node is reflected in the overall network in two ways:

1. **Total Energy Consumption:** The overall sum of individual energy consumption of nodes leads to the total energy consumption of the network. In case of a network owned by a single individual or company, the total energy consumption of the network is very important and for a large network consisting of many nodes, it is worthwhile to realize a significant saving in energy by small energy-savings in the individual nodes.

2. **Network Lifetime:** From the perspective of a network, a node running out of electrical energy makes the network incomplete. The complete network exists as long as all the nodes are operational. The time till it exists is termed as the network lifetime. The problem occurs only for battery-driven nodes because batteries have a limited charge capacity. The node that first consumes its available charge determines the network lifetime. With similar batteries for all nodes, the node consuming maximum energy is the first to run out of its stored energy.

Relaying makes use of diversity to decrease the energy consumption of a node. A node requiring large transmit power to send its data on a poor channel can be helped by a relay node to achieve a similar or a better signal quality at the destination, however, at a much reduced transmit power. Denoting the energy consumption of a node \( i \) with and without relaying by \( E_i^{\text{rel}} \) and \( E_i^{\text{dir}} \) respectively, the energy saving at an individual node leads to:

1. **Total Energy Saving Ratio:** It can be defined as the ratio of the total energy consumption of the network without relaying to the total energy consumption of the network using relaying. Mathematically, total energy saving ratio, denoted by \( \eta_E \) is

\[
\eta_E = \frac{\sum E_i^{\text{dir}}}{\sum E_i^{\text{rel}}}, \quad (3.13)
\]

2. **Network Lifetime Gain:** It gives the improvement in the lifetime of the network as a result of relaying. Since, the network lifetime depends on the node that consumes the maximum energy, network lifetime gain, denoted by \( \eta_L \) is

\[
\eta_L = \frac{\mathbb{E}(E_{\text{max}}^{\text{dir}})}{\mathbb{E}(E_{\text{max}}^{\text{rel}})}, \quad (3.14)
\]
where $E(\cdot)$ represents the expectation operation and the subscript ’max’ represents the node that consumes the maximum energy. The expectation operation is required since for a given number of nodes, due to change in the position of the node or the channel conditions, the node consuming the maximum energy may not be the same. The effect of relaying can thus be better estimated by considering all the possible scenarios and taking an expectation over them. A similar approach (i.e. taking the expectation over all possible scenarios) is also possible with the total energy saving ratio so as to consider the effect of different possible scenarios with a given number of nodes. However, since the number of scenarios is the same with and without relaying, (3.13) can be still used with the summation including the total energy consumption of each node for all possible scenarios.

### 3.3.2 Energy Model

Energy is required for the operation of a wireless node. A sensor node needs energy for its sensing function and associated computations. In this work, we only consider the energy that is required for the communication part. Since the radio transceivers often have an associated microcontroller, some of the energy is also consumed by it. Microcontrollers, however, draw much less current than the transceiver chips. E.g. MSP430F5529 microcontroller, which is used in the current work, draws 290 $\mu$A/MHz current at 3.0 V for flash program execution when all the system clocks are active [67]. The device can be driven to low-power modes when not in use and in that case the current required is around 1 $\mu$A. It is interesting to note that the latest MSP430-based microcontrollers released by Texas Instruments draw even lesser currents. E.g. one of the latest released microcontrollers, MSP430FR69891 draws 100 $\mu$A/MHz current in the active mode and the current in the low-power mode is only 0.4 $\mu$A [68]. The transceivers, on the other hand, require much more current for the transmission and reception of signals. CC2520 transceiver needs 18.5 mA current for reception and 33.6 mA current for transmission (at 5 dBm transmit power) [54]. The transceivers that were later on released have also similar values of current for transmission and reception. From these values, it is evident that the maximum amount of current is required for the signal transmission. Thus, in the forthcoming discussion, the work will be aimed to reduce the transmit energy. It is also pertinent to mention that the transmit energy can be calculated by multiplying the transmit current, voltage and
3.3 Relaying and Energy Saving

The time required for transmission. Since, in most cases, we calculate the required transmit power to achieve the desired outage probability, transmit energy can be calculated by multiplying transmit power by the time required for transmission. In the subsequent work, we assume the same packet size for all transmitting nodes and hence the propagation time is also constant for all nodes. In case of a node acting as a relay, it transmits its own data as well as the data of the other node for which it acts as a relay. Therefore, for such a node, the energy required for transmission is the sum of the energy required for its own transmission plus the energy required for relaying. If it uses the same transmit power for its own communication and the communication for which it acts as a relay, the transmission time is considered as two times the normal transmission time. Having considered this effect, the transmission time for a single transmission cancels out for the total energy saving ratio and the network lifetime gain calculations.

3.3.3 Simulation Results

We consider the scenario of two nodes sending data to the AP, as discussed in the last section. The nodes are randomly placed in an indoor environment with the AP placed in the center. The environment forms a square with each dimension ranging from 10 m to 50 m. The channel model is used as described in Sec. 2.1.3. Our MATLAB simulator is used to simulate transmission of 1000 IEEE 802.15.4 compatible packets by each node for each placement of nodes. The random placements of nodes are 1000 for each environment size. We compare the case of direct communication by the nodes and relaying. In case of relaying, both the nodes act as relays for each other. Optimum transmit power is calculated to design an outage probability of 0.001 using the methods discussed in the last section. The calculated powers are used to find the total energy saving ratio and the network lifetime gain as shown in Figs. 3.3 and 3.4. To compare the effect of relaying, we also simulate the bit error rate (BER), which is shown in Fig. 3.5. Following interesting observations can be made:

From Figs. 3.3 and 3.4, it can be observed that values of the network lifetime gain and energy saving ratio larger than one indicate a benefit of relaying. For all the given conditions, relaying helps to decrease the energy consumption of nodes, to increase the lifetime of the network and decrease the overall energy consumption of the network. Secondly, it can be seen that increasing the size of the environment helps to increase the value of both parameters. A larger environment size translates
Fig. 3.3: Energy saving ratio for different environment sizes with power calculated using the exact, proposed and coding gain approaches.

to more variation in the communication channels between the nodes and hence more advantage can be offered by relaying.

A comparison of the three power calculation schemes reveals almost identical values for energy saving ratios and network lifetime gains for the exact and the proposed schemes. The coding gain approach apparently offers some exceptionally high values of the energy saving ratio and the network lifetime but the associated BER curves for the same scenarios reveal the actual drawback of the approach. For the given
scenarios, with communication channels having moderate to high values of Rician $K$ factors, the coding gain approach models the channel behavior that significantly deviates from the true value. Although the model offers very large values of lifetime gain and energy saving ratio, the calculated powers are inadequate to support even moderate reception quality (BER). The BER values approaching 0.5 indicate that the coding gain approach is inappropriate for the given scenarios. As shown in Fig. 2.11, the coding gain approach provides accurate results for very small values of the $K$ factor only. Interestingly, the gain values with coding gain approach decrease as
Fig. 3.5: Bit error rates for different environment sizes with power calculated using the exact, proposed and coding gain approaches.

The size of the environment increases which is opposite to the behavior of the other two schemes. This is due to the fact that as the size of the environment increases the average length of the links increases. Larger distances result in larger mean pathloss values and smaller values of Rician $K$ factor. This enables coding gain approach to estimate the transmit power in a better way. It was determined through simulation that for a $100 \text{ m} \times 100 \text{ m}$ square, the error in the network lifetime gain for the coding gain approach is about 80%, which is still very high.
3.4 Summary

It is also interesting to see the behavior of the BER for the exact approach. Although the system is designed to operate at a constant outage probability, the condition does not translate to a constant BER performance. It is due to the fact that the calculated transmit power ensures that the received SNR does not fall below the threshold with a ratio as given by the outage probability. The probabilities to get all SNR values depend on the statistical characteristics of the channel and may not be determined by the outage probability only. The translation of the received SNR to the BER has a non-linear relation and depends on the modulation and coding schemes. Thus with two channels with different mean pathloss and Rician $K$ factor values, the same outage probability translates to different BER values. Relaying has an improved BER as compared to the direct links because the statistical behavior of relay channels has a steeper slope for the received SNR (diversity gain of 2) than the direct link (diversity gain of 1). Similarly, Rician channels with low values of $K$ factor result in higher BER than the channels with high values of $K$ factor. The slightly increasing trend for the BER with increasing distances is also due to the same effect, because large distances between the nodes allow channels with low $K$ factor values.

3.4 Summary

Relaying is a useful technique to assist a node to deliver its data in harsh channel conditions. It is shown that the technique also improves the lifetime of the network and decreases the amount of energy expended in transmission. A method to exactly calculate the transmit power in Rician fading channels is described. Due to the complexity of the method, the well-known coding gain approach is discussed and its limitations are pointed out. A method is proposed that is computationally simple and performs close to the exact approach. Simulation results are used for comparing the performance of the three approaches. Energy saving factor and network lifetime gain are then explained and simulated for environments of different sizes with two nodes reciprocating as relays for each other. It is observed that the benefit is increased with an increasing size of the environment as the number of possible channel conditions increases. These results with two cooperating nodes motivate us to consider the scenario with multiple nodes cooperating with each other and getting more advantage by appropriately selecting the relay nodes in the next chapter.
Chapter 4

Partner Selection

Nodes can assist each other in delivering each other’s message with the help of relaying. Relaying helps to reduce the overall energy consumption of the network and improves the lifetime of the network. When many nodes are available in the network, the allocation of an appropriate relaying partner can further increase the network lifetime [66]. Many partner selection algorithms have been proposed in the literature. This chapter covers some of the important methods of partner selection and compares their performance in improving the network lifetime and decreasing the overall energy consumption of the network. Modifications to existing algorithms and a new distributed approach is proposed and results are presented to verify their superior performance.

4.1 Literature Survey

Different algorithms have been proposed to address the problem of partner selection. Following is a brief overview of some of the important algorithms in a chronological order.

A distributed protocol for user cooperation in a multi-user wireless network was presented by Hunter and Nosratinia [69]. In this case, a user can select $n$ nodes in a Rayleigh fading environment. Partners are selected on the basis of received signal-to-noise ratio (SNR). For comparison, random and fixed priority selections were also used. Outage probability is used as the quality metric.

A centralized algorithm for partner selection was presented by Venturino et al. [70] for a synchronous direct-sequence code-division multiple-access system. Each node
can support one other node without reciprocating. Received power is used to make the selection decision. Farthest users are prioritized.

Another cooperation algorithm was presented by Nosratinia and Hunter [71] with a non-reciprocal scheme, thus one node can support \( n \) other nodes. Outage probability is used as a quality metric. The algorithm was proposed using a distributed as well as a centralized scheme.

Three partner selection schemes were presented by Chen et al. [72]. The schemes are based on maximizing system level efficiency, maximizing the minimum utility of the node and maximizing the product of all nodes’ utilities. Each node is used as a relay only once in a communication round. The problem of maximum total strategy was solved as an assignment problem using the Hungarian method [73].

A cooperative relaying scheme was proposed by Jing Shi et al. [74]. In this scheme each node can act as a relay for only one node and can also be assisted by one node. Outage probability is used as the quality metric. Bipartite graph is constructed to find the solution as a matching problem.

A partner selection algorithm was proposed by Mahinthan et al. [66]. The algorithm targets to maximize the lifetime of the network. Two nodes act as partners in a reciprocating manner. The proposed centralized algorithm was termed as worst link first (WLF) as it works by first considering the node with the worst link quality and assigns it the best partner and repeats the process with the remaining nodes.

A distributed partner selection algorithm for energy-efficiency was presented by Simic et al. [75]. It uses the mean pathloss of the channels for the partner selection decision. Two schemes were proposed. In one of the schemes, the number of nodes served by a node is 1 while in the other scheme, the number of nodes served by a node is unlimited.

A partner allocation, subcarrier allocation and packet scheduling scheme was presented by Ho Ting Cheng et al. [76] for a wireless mesh network employing orthogonal frequency division multiplexing. They used non-reciprocating partners. The two proposed schemes are based on Karush-Kuhn-Tucker interpretations and their throughput performance was compared.

To minimize the overall energy expenditure of the network, Cho Yiu Ng and Tat Ming Lok [77] proposed an algorithm. It is based on Gabow’s algorithm [78]. The algorithm uses reciprocal pairing.
An incentive-based auction strategy was used by Mukherjee and Kwon [79] for partner selection in ad-hoc networks. The algorithm is decentralized and in one of the schemes, a node can support one other node while in the other scheme, a node can be assisted by many other nodes.

Irving’s algorithm [80] that is used to solve the stable roommates matching problem was used by Hasan et al. [81] and Baidas and Afghah [82] for partner selection. In both these algorithms, reciprocating pairs are formed.

### 4.2 Possible Pairs

<table>
<thead>
<tr>
<th>Pairing</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
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<td>10</td>
<td>26</td>
<td>76</td>
<td>232</td>
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<td>120</td>
<td>720</td>
<td>5040</td>
<td>40320</td>
<td>362880</td>
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<td>780</td>
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<td>8361360</td>
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<tr>
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<td>256</td>
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<td>823543</td>
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</tr>
</tbody>
</table>

It is important to first find out the number of possible ways in which nodes may assist each other. We will term the source-relay association as pairing. Thus a source node and a relay node (which is also an ordinary node that acts as a relay) form a pair. For Rician fading channels when the time variations in the channel are incorporated in the calculation of transmit power with the help of the Rician $K$ factor, pairing once done may remain the same as long as the nodes are static. It should also be noted that we are considering the case of only one relay node assigned to each source node. Thus there are at the most two communication hops from the source to the destination. In each case, we also consider the possibility that a node may not need a relay node because its own channel conditions are good enough and in that case, using a relay may require more energy for transmission or deteriorate the network lifetime. Following are the possible ways in which pairing may be done:

**One-to-one Reciprocal pairing:**
In this type of pairing, one node acts as a relay for another node and that node also reciprocates by acting as a relay for the former. I.e. if node $i$ acts as a relay for node
j, node j will also act as a relay for node i. E.g. for 3 nodes, the possible groupings of source-relay pairs, denoted by \( \zeta \), are given by:

\[
\begin{align*}
\zeta_1 &= \{(1, 1), (2, 2), (3, 3)\} \\
\zeta_2 &= \{(1, 1), (2, 3), (3, 2)\} \\
\zeta_3 &= \{(1, 2), (2, 1), (3, 3)\} \\
\zeta_4 &= \{(1, 3), (2, 2), (3, 1)\}
\end{align*}
\]

The first number within the parenthesis indicates the source and the second number indicates the relay. Same numbers at the source and relay positions indicate that the node is using direct communication.

For a network with \( N \) nodes, the number of possible pairs using reciprocal pairing is given by [83]

\[
\nu_{\text{Recip}} = 1 + \sum_{k=1}^{\lfloor N/2 \rfloor} \frac{N!}{2k!(N-2k)!} \prod_{j=1}^{k} (2j-1)
\]

(4.1)

The equation is explained in the following way:

The 1 in the beginning of (4.1) indicates the possibility of no reciprocal pairs.

The variable \( k \) in the summation term is the number of reciprocal pairs being considered for the given number of nodes. I.e. when \( k = 1 \), we are considering the case of only one reciprocal pair being constructed from the given nodes. Similarly \( k = 2 \) implies the case of 2 reciprocal pairs and so on. The maximum number of pairs that can be constructed from \( N \) nodes is \( \lfloor N/2 \rfloor \), where \( \lfloor \cdot \rfloor \) is the floor operation.

\[
\frac{N!}{2k!(N-2k)!}
\]
gives the number of ways, \( 2k \) nodes can be chosen from \( N \) nodes.

The last product term indicates the number of ways, the chosen nodes can be arranged in the form of reciprocal pairs.

Following observations can be made:

- The number of reciprocating pairs increases with the number of nodes with a relationship involving the factorial term. The computational complexity with such a number of possible pairs is more than the polynomial order.

- With odd number of nodes, at least one node is always unpaired. This leads to a different behavior depending upon if the number of nodes is even or odd. E.g. if there are already 2 nodes and a third node is added to the system, it offers more flexibility to form reciprocating pairs but one of the nodes will still remain unpaired. On the other hand if a fourth node is subsequently added,
apart from the flexibility, the added node may be paired to an unpaired node to
get more advantage in terms of energy saving or lifetime improvement. Because
of this reason, the performance curves for odd and even number of nodes are
separately plotted.

- From Table 4.1, it can be seen that the number of possible pairs for the
reciprocating scheme is the least among the four schemes.

For a small number of nodes, it is manageable to apply exhaustive search methods.
Some of the algorithms like the Irving’s algorithm for stable roommates problem \[80\]
and the worst link first algorithm \[66\] inherently provide the solution for reciprocating
pairs with a computational complexity that is a polynomial function of the number
of nodes. Due to these reasons, reciprocating pairs are often found in the literature.

**Only One Pairing:** This type of pairing will result if the node is allowed to help
only one node if it is itself using any other node as a relay. In case it is not using any
other node as a relay, it does not help any other node. Relaying is also not necessarily
reciprocal. Such a pairing results from a conventional assignment problem with the
energies for transmission placed in the form of a matrix

\[
E_t = \begin{bmatrix}
E_{t11} & E_{t12} & \ldots & E_{t1N} \\
E_{t21} & E_{t22} & \ldots & E_{t2N} \\
\vdots & \vdots & \ddots & \vdots \\
E_{tN1} & E_{tN2} & \ldots & E_{tNN}
\end{bmatrix}.
\]

In (4.2), the row index indicates the source node and the column index indicates the
relay node. The diagonal gives the energy for the nodes when they are not using any
other node as a relay. Only one pairing will result when exactly one value is selected
from each row and column depending on some criteria (e.g. to minimize the total
sum of all energies). Algorithms that are used to solve the assignment problem result
in this type of pairing. The Hungarian algorithm \[73\] is one such algorithm.

E.g. for 3 nodes, the possible groupings are:
\[
\begin{align*}
\zeta_1 &= \{(1,1), (2,2), (3,3)\} \\
\zeta_2 &= \{(1,1), (2,3), (3,2)\} \\
\zeta_3 &= \{(1,2), (2,1), (3,3)\} \\
\zeta_4 &= \{(1,2), (2,3), (3,1)\} \\
\zeta_5 &= \{(1,3), (2,1), (3,2)\}
\end{align*}
\]
The number of possible pairing with this scheme is

\[ \nu_{\text{OnlyOne}} = N! . \]

The number of possibilities is more than the one-to-one reciprocal pairing. Even with 10 nodes, the number of possible pairs is 3628800 and exhaustive search with all the possible combinations is computationally not feasible.

**One Other Pairing:** The condition of not allowing the nodes to help other nodes when they are not being assisted is removed to form one other pairing scheme. Thus, in this case, a node can assist one other node without the obligation to reciprocate and irrespective of how its own communication takes place. E.g. for 3 nodes, the possible groupings are:

- \( \zeta_1 = \{(1, 1), (2, 1), (3, 2)\} \)
- \( \zeta_2 = \{(1, 1), (2, 1), (3, 3)\} \)
- \( \zeta_3 = \{(1, 1), (2, 2), (3, 1)\} \)
- \( \zeta_4 = \{(1, 1), (2, 2), (3, 2)\} \)
- \( \zeta_5 = \{(1, 1), (2, 2), (3, 3)\} \)
- \( \zeta_6 = \{(1, 1), (2, 3), (3, 1)\} \)
- \( \zeta_7 = \{(1, 1), (2, 3), (3, 2)\} \)
- \( \zeta_8 = \{(1, 1), (2, 3), (3, 3)\} \)
- \( \zeta_9 = \{(1, 2), (2, 1), (3, 3)\} \)
- \( \zeta_{10} = \{(1, 2), (2, 2), (3, 1)\} \)
- \( \zeta_{11} = \{(1, 2), (2, 2), (3, 3)\} \)
- \( \zeta_{12} = \{(1, 2), (2, 3), (3, 1)\} \)
- \( \zeta_{13} = \{(1, 2), (2, 3), (3, 3)\} \)
- \( \zeta_{14} = \{(1, 3), (2, 1), (3, 2)\} \)
- \( \zeta_{15} = \{(1, 3), (2, 1), (3, 3)\} \)
- \( \zeta_{16} = \{(1, 3), (2, 2), (3, 1)\} \)
- \( \zeta_{17} = \{(1, 3), (2, 2), (3, 2)\} \)
- \( \zeta_{18} = \{(1, 3), (2, 2), (3, 3)\} \)

With this approach, the number of possible groupings is \([83]\)

\[
\nu_{\text{OneOther}} = NN! + \sum_{k=2}^{[N/2]} \frac{N!}{k!(N-k)!} \prod_{j=1}^{k} (N-k+1-j) \prod_{i=1}^{N-2k} (N-k+1-i). \quad (4.4)
\]
4.2 Possible Pairs

We can also replace the product terms in (4.4) by factorials to get

\[ \nu_{\text{OneOther}} = NN! + \sum_{k=2}^{\lfloor N/2 \rfloor} \frac{N!}{k!(N-k)!} \frac{(N-k)!}{(N-2k)!} \frac{(N-k)!}{k!}, \]  

(4.5)

which can be further simplified to

\[ \nu_{\text{OneOther}} = NN! + \sum_{k=2}^{\lfloor N/2 \rfloor} \frac{N!(N-k)!}{k!(N-2k)!}. \]  

(4.6)

The equation can be explained in the following way:

If a node supports only one node, the number of possibilities are \( N! \) as given for the only one pairing.

Out of the \( N! \) possibilities, one node is supporting only itself in \( 1/N \) cases and supporting some other node in the remaining \( 1 - 1/N \) cases but not supporting itself. If we allow one node to also support itself in these \( 1 - 1/N \) cases, we can thus generate \( (1 - 1/N)N! \) additional possibilities for each node, which for \( N \) nodes is \( (N - 1)N! \). Thus, if exactly one node is allowed to support any other node and its own self, there are \( (N - 1)N! \) ways to do that.

Summing \( N! \) and \( (N - 1)N! \) yields \( NN! \), which is the first term in (4.6). This term, hence, gives the number of possible ways in which only one node is allowed to support any other node irrespective of its own status.

We then consider the case when 2 or more nodes are supporting any other node along with their own selves. This is given by the summation term and the index \( k \) starting from 2 indicates the number of nodes that are supporting any other nodes along themselves.

The term \( \frac{N!}{k!(N-2k)!} \) gives the number of ways, \( k \) nodes can be picked from the given \( N \) nodes. The first product term \( \prod_{j=1}^{k} (N - k + 1 - j) \) gives the ways in which these \( k \) nodes can be arranged in the remaining \( N - k \) places. \( N - k \) is done because, we are considering the cases when these nodes are supporting \( k \) other nodes excluding themselves. The last product term \( \prod_{i=1}^{N-2k} (N - k + 1 - i) \) gives the possible ways, the remaining nodes may be arranged in the remaining places.

It can be observed by comparing (4.3) and (4.6) that there is an additional \( N \) being multiplied with the factorial term and a sum term for the number of possibilities with the one other approach. Hence, the number of possibilities is much more and
with 10 nodes, the possible groupings are about $1.1 \times 10^8$. In this case, to search through all the possible combinations is not feasible.

Any Other Pairing: We term the case of one node supporting any number of other nodes as any other pairing. E.g. for 3 nodes, the possible groupings are:

\[
\begin{align*}
\zeta_1 &= \{(1,1), (2,1), (3,1)\} \\
\zeta_2 &= \{(1,1), (2,1), (3,2)\} \\
\zeta_3 &= \{(1,1), (2,1), (3,3)\} \\
\zeta_4 &= \{(1,1), (2,2), (3,1)\} \\
\zeta_5 &= \{(1,1), (2,2), (3,2)\} \\
\zeta_6 &= \{(1,1), (2,2), (3,3)\} \\
\zeta_7 &= \{(1,1), (2,3), (3,1)\} \\
\zeta_8 &= \{(1,1), (2,3), (3,2)\} \\
\zeta_9 &= \{(1,1), (2,3), (3,3)\} \\
\zeta_{10} &= \{(1,2), (2,1), (3,1)\} \\
\zeta_{11} &= \{(1,2), (2,1), (3,2)\} \\
\zeta_{12} &= \{(1,2), (2,1), (3,3)\} \\
\zeta_{13} &= \{(1,2), (2,2), (3,1)\} \\
\zeta_{14} &= \{(1,2), (2,2), (3,2)\} \\
\zeta_{15} &= \{(1,2), (2,2), (3,3)\} \\
\zeta_{16} &= \{(1,2), (2,3), (3,1)\} \\
\zeta_{17} &= \{(1,2), (2,3), (3,2)\} \\
\zeta_{18} &= \{(1,2), (2,3), (3,3)\} \\
\zeta_{19} &= \{(1,3), (2,1), (3,1)\} \\
\zeta_{20} &= \{(1,3), (2,1), (3,2)\} \\
\zeta_{21} &= \{(1,3), (2,1), (3,3)\} \\
\zeta_{22} &= \{(1,3), (2,2), (3,1)\} \\
\zeta_{23} &= \{(1,3), (2,2), (3,2)\} \\
\zeta_{24} &= \{(1,3), (2,2), (3,3)\} \\
\zeta_{25} &= \{(1,3), (2,3), (3,1)\} \\
\zeta_{26} &= \{(1,3), (2,3), (3,2)\} \\
\zeta_{27} &= \{(1,3), (2,3), (3,3)\}
\end{align*}
\]

The number of possible groupings for this approach is

$$
\nu_{\text{AnyOther}} = N^N. 
$$

(4.7)
It can be seen that the number of possible groupings with this approach is the most. An exhaustive search approach to find the optimum grouping with this node can only be done with a few nodes.

**Fig. 4.1:** Number of possible groupings against the number of nodes for different pairings. Also plotted are the linear, quadratic and fourth order polynomial for comparison.

The number of possible pair combinations are shown in Table 4.1 for number of nodes going from 3 to 10. The same is plotted for number of nodes ranging from 2 to 40 and shown in Fig. 4.1. For reference, the linear, quadratic and fourth order functions of the number of nodes are also plotted. It is evident that all the four schemes
end up with a very large number of possible groups even for a medium number of
nodes and any algorithm that uses extensive search to find the best pairing is not
computationally feasible. One-to-one reciprocal pairing may be used for exhaustive
search methods for number of nodes till about 15, whereas the other pairings can
undergo exhaustive search only when the number of nodes is less than 10. Thus, there
is a strong need of algorithms that do not test each and every possible combination
and provide the solution with a polynomial complexity in the number of nodes.

4.3 Partner Selection Algorithms

With the availability of numerous nodes, nodes may be appropriately paired to
achieve a better performance in terms of some quality criterion or criteria. Partner
selection algorithms aim to find this appropriate pairing. In this section, we compare
the performance of existing partner selection algorithms and propose modifications
to the existing algorithms as well as a new algorithm to find the best partnering
strategy. The aim of these partner selection strategies will be to either reduce the
overall energy consumption of the system or to improve the lifetime of the network.
Since the optimum partner selection using exhaustive search is only feasible for a
small number of nodes, we will use this method when the number of nodes is below
10 and it will be used as reference for comparing the performance of other algorithms.

4.3.1 Existing Algorithms

Optimum Lifetime Gain (OLG):
For this method, we do an exhaustive search through all the possible groupings for
the four possibilities i.e. one-to-one reciprocal, only one, one other and any other
schemes and name them as OLG Recip, OLG Only One, OLG One Other and OLG
Any Other respectively. The purpose of the exhaustive search is to find the grouping
for which we have the maximum network lifetime gain. Denoting the pairing by ζ,
the exhaustive search method finds the optimum pairing

$$ζ_{OLG} = \arg \max_ζ \eta_L(ζ) = \frac{E^\text{dir}_{\max}(ζ)}{E^\text{rel}_{\max}(ζ)},$$

(4.8)

where ζ is taken from the possible sets for the four different allowed pairing schemes,
$E^\text{dir}_{\max}$ denotes the maximum energy for the nodes without relaying and $E^\text{rel}_{\max}(ζ)$ is
the maximum energy required by a node with relaying, which is also a function of
the selected pairing.

**Optimum Total Energy (OTE):**

This algorithm also does an exhaustive search through all the possible combinations
such that the total energy for the network is the minimum. According to the four
pairing schemes, the algorithms are termed as OTE Recip, OTE Only One, OTE
One Other and OTE Any Other. Denoting the pairing by $\zeta$, the OTE method finds
the optimum pairing

$$\zeta_{OTE} = \arg \max_\zeta \eta_E(\zeta) = \frac{\sum E_i^{dir}}{\sum E_i^{rel}(\zeta)}, \quad (4.9)$$

where $\zeta$ is taken from the possible sets for the four different allowed pairing schemes,
$\sum E_i^{dir}$ denotes the total energy for the nodes without relaying and $\sum E_i^{rel}(\zeta)$ is the
total energy required by the nodes with relaying.

**Hungarian Algorithm:**

Hungarian algorithm [73] finds the solution of the assignment problem in a polynomial
time. The original algorithm has a complexity of $O(N^4)$ but modified versions exist
which can have a complexity of $O(N^3)$. The algorithm has been widely used to
find the solution of economic problems to find the assignment or grouping with
the minimum total cost. In such cases, the algorithm operates on a cost matrix.
The algorithm works by subtracting the minimum element of a row from all the
elements in the row and the minimum element in the column from all the elements
in the column, thus, creating zeros. The algorithm tries to cover these zeros with
the minimum number of lines. For our problem, we can replace the cost matrix
with the total energy matrix like (4.2). With this matrix, the algorithm provides
the solution to minimize the total energy. It will be subsequently shown that the
algorithm provides the optimum solution for the only one pairing scheme.

It should also be noted that auction algorithms [84] are also used to solve the
assignment problem. However, in this work, they are not considered and we have
used the Hungarian algorithm only.

**Worst Link First:**

The WLF algorithm is a non-optimal solution to solve the matching problem. The
major advantage of this algorithm is its quadratic complexity in terms of the number
of nodes. WLF has been used in [66] and [30] for partner selection. It is a centralized
algorithm. In [30], the algorithm was based on the links between the nodes and the access point (AP). All the nodes determined their coding gains to the AP and to other nodes and if the links to other nodes were better than their own link to the AP by some threshold, those nodes were declared as their prospective partners. The nodes sent the list of their prospective partners and their coding gain value to the AP. The algorithm was run at the AP such that the node with the worst link (worst coding gain value) was assigned the best node out of its prospective partners as its partner. The nodes reciprocated by acting as partners of one another and the process was continued till either all the nodes were assigned appropriate partners or nodes were left with no prospective partners.

Irving’s Algorithm (Stable Roommate approach):

Stable roommates problem, described by Irving [80], is an interesting problem to find matching roommates from a given set of people who have their own preferences (likes and dislikes). A similar problem also exists that is termed as the stable marriage problem. Stable roommates problem is different from the stable marriage problem in the sense that in stable marriage problem, it is considered that there are two categories i.e. men and women and a man is matched to a women according to their preferences (preference of both man and woman). In the case of stable roommates problem, all the entities are similar and any two could be paired with each other. The solution is called stable because no more preferred partners may be substituted for the already assigned partners. The algorithm works in a distributed way. All the nodes prepare their preference lists and propose or apply to their preferred partners according to their priority. The proposals or application are accepted or rejected by the nodes to which the proposals were made and they also inform about their decisions so that the nodes that made the proposals are aware about the status of their proposals.

The partner selection problem can also be formulated like the roommate problem because all the nodes have a similar status (there are no special relay nodes). The preference lists can be formed by the nodes according to their link qualities when using the other nodes as relays. It is, however, interesting to find the preference of a node to act as a relay. It is natural to think about the preference of a node not to work as a relay for another node that requires a large transmit power. It was found through simulations that such a priority, does not translate to any considerable improvement in the total energy saving or lifetime, because no relay node will prefer to accept a node with the worst channel conditions. A better result is obtained if
4.3 Partner Selection Algorithms

the priority is formed such that the node that can get the maximum benefit due to relaying is given the highest priority. Another problem is that the algorithm only works for even number of nodes. The problem can be circumvented by removing one node if the number of nodes is odd. The criteria to remove the node also affects the overall performance. We remove the node with the best signal quality to the AP.

4.3.2 Proposed Algorithms

We propose modifications to the existing partner selection algorithms and also propose a new distributed algorithm with improved performance in terms of total energy saving and lifetime gain.

**Worst Link First based on the total link quality (WLF Total):**
Unlike [30], in this algorithm, we consider the link qualities of the whole source-relay-destination links to assign the partners. Each node computes the transmit energy for the required outage probability if it uses a particular node as the relay. All the information is conveyed to the central node (AP) where the WLF algorithm is run. The grouping is still reciprocating and the computational complexity of this algorithm is the same as the WLF algorithm. The performance of this scheme is compared in Section 4.4.

**Hungarian with the option to use no cooperation if it is less costly than cooperation (Hungarian+):**
As described earlier, the Hungarian algorithm finds the solution for the one only problem by selecting only one element in each row and column within the energy matrix. In many cases, it is possible that a node consumes less energy for its direct communication as compared to the relayed communication for which it is selected by the Hungarian algorithm. We propose to make this simple check after the result is obtained by the Hungarian algorithm. Thus no node unnecessarily uses relaying when its own communication can be achieved with less energy consumption. The resulting pairing will be one other pairing. The complexity of this additional task is $O(N^2)$, which is less than the complexity of the Hungarian algorithm. Since the two tasks (Hungarian algorithm and the additional check) are being done in a sequence, the overall complexity in terms of the number of nodes will be bounded by the task with the higher complexity i.e. Hungarian algorithm. Thus better performance is achievable without increasing the order of complexity. The performance will be compared in Section 4.4.
Hungarian modified for Lifetime Gain (Hungarian LG):
As previously described, the Hungarian algorithm minimizes the total energy consumption of the network. The reduction in the total energy does not necessarily come with an improved network lifetime. We propose to modify the Hungarian approach in order to improve the network lifetime. We apply the Hungarian algorithm to the energy matrix \(4.2\) and then remove the relay-node pair with the highest energy requirement from further consideration in pairing and repeat the process till no more improvement is realizable or the network can not be completed without the excluded link. It should also be noted that the approach is different from [72] where the exclusion process was performed before applying the Hungarian algorithm. We believe that our approach will, on average, converge faster than the approach presented in [72]. The computational complexity of this approach is \(O(N^5)\). Performance comparison of this scheme is done in Section 4.4.

Distributed Algorithm:
The already discussed Irving’s algorithm is a distributed algorithm that can be used for partner selection. It however, suffers from the following major problems:

- The nodes acting as relay nodes need a priority list before hand to accept or reject the proposals. The formation of such a list requires either some centralized mechanism or more communications are required from other nodes to compile this information.

- The algorithm generates reciprocating pairs. Better lifetime gain values and energy saving may be realized if the restrictions on reciprocating are removed i.e. the other possible pairing schemes provide more flexibility due to the option of more pairing possibilities. Terminating the algorithm before the final elimination stage may help but the algorithm cannot provide the option to have more than one node supported by a single relay.

- The algorithm is designed to work for even number of nodes. The criteria to reject a node in case of odd number of nodes is also debatable.

Our proposed algorithm circumvents the shortcomings of Irving’s algorithm and is designed to be flexible to offer a tradeoff between the network lifetime gain and the total energy saving factor. The algorithm is based on the node saving factor that is defined for a node \(i\) as ratio of the transmit energy for direct communication to the transmit energy for relayed communication when node \(j\) is used as the relay.
Denoting the factor by $\eta_{i,j}$,
\[
\eta_{i,j} = \frac{E_{\text{dir}}^{i}}{E_{\text{rel}}^{i,j}}.
\] (4.10)

The energy for relaying also includes the energy that will be spent by the relay node in relaying.

The proposed algorithm works as follows:

**Phase - I - Estimation Phase**

1. All the nodes determine the channel parameters (mean pathloss and the Rician $K$ factors) to the AP by listening to its broadcast communications. The method proposed in Section 2.2 can be used.
2. Each node broadcasts its calculated parameters according to an already established time division multiple access (TDMA) schedule.
3. Nodes use the broadcast information from other nodes to store their channel parameters to the AP.
4. Nodes also use the received signal strength indicator (RSSI) information of the broadcast packets to calculate the channel parameters to other nodes.
5. Nodes calculate the required transmit power for direct communication as well as the required power when they use other nodes as relays. The calculation is performed using the method proposed in Section 2.3.2.
6. The information calculated in the last step is used to calculate the node saving factors. Each node calculates the node saving factors according to (4.10) when the other nodes are used as relays.
7. The nodes prepare their priority lists in the order of decreasing node saving factors.

**Phase - II - Partner Request and Acknowledgment**

1. Each node sends a request for relaying to its highest priority node. The request includes the value of the node saving factor with that node. The process is also done according to the TDMA schedule.
2. The nodes to which the requests are made store the information consisting of the node address that made the request along with the node saving factor.
3. After the completion of request cycle, the nodes to which requests were made take the decisions by selecting the applied node with the maximum node saving.
factor and announce their decisions. The selected nodes, till the convergence of the algorithm, are termed as the provisionally selected nodes because the decisions may change in the future rounds, if an application is received with a higher saving factor than for the already selected nodes. The decision is announced in the form of a broadcast packet that includes the provisionally accepted node and its node saving factor. The process of requests and decisions is termed as a round.

4. The rejected nodes have to apply to the node that is next in their priority list. Due to the already received decisions, the rejected nodes are also aware of the saving factor of the accepted nodes in the previous step. Hence, if the node to which they intend to apply has already accepted a node with a higher saving factor than their own, the applications are not made. Next node in the priority list is, then, selected and the process is repeated till a node is available that has previously not accepted any node or the accepted node has a saving factor worse than their own. Applications are made and the decisions are again made as it was done in the previous round.

5. The request and decision rounds continue till all the nodes are assigned partners or there may be a fixed number of rounds as will be explained shortly.

Following are some of the important aspects of the proposed algorithm:

The algorithm does not require the relay nodes to have an already available priority list. The priority is created as the requests are made on the basis of the node saving factors that are provided by the applying nodes themselves.

The algorithm is valid both for odd and even number of nodes.

The number of nodes a relay node can support may be chosen to be more than one. If the number of nodes that may be supported by a node is denoted by $k$, during step 3 of phase-II, the nodes can give provisional acknowledgments to $k$ nodes. It will be shown with subsequent results that a smaller $k$ values leads to a better network lifetime gain whereas a high value of $k$ leads to a better transmit energy saving factor. This will be again explained with the help of the simulation results presented in the next section.

It should be noted that even if the channel conditions are time-variant, phase-I of the algorithm is only needed in the start, because afterwards, the overheard regular communication of the nodes and the AP may be used to estimate the channel parameters and calculate optimum transmit power.
The convergence of the algorithm for one supported node per relay node can be explained as follows. In the first round, the node with the maximum node saving factor is definitely assigned the relay node because with its maximum saving factor, all the other nodes may be provisional. It is also possible that some of the nodes that are lower in priority also get their relay nodes with no subsequent better requests and hence the decisions do not change. In the second round, all nodes will be aware about the relay node that has selected the node with the maximum saving factor (due to its broadcast decision message) and hence, apply to other nodes. The node with the second best energy saving factor will be definitely selected in this round if it was not accepted in the previous round since no other node with a higher node saving factor exists to apply to these nodes. Thus with $N$ number of nodes, maximum of $N$ rounds are required for all the nodes to be assigned their partners.

The convergence for $k$ supported nodes per relay node is explained as follows. In the first round, at least $k$ nodes with the highest priority will be assigned the relay nodes to which they have applied. In the second step, the next $k$ nodes are definite to be assigned the relay nodes. Thus $N$ nodes require $\lceil N/k \rceil$ rounds for the assignment to be completed, where $\lceil \cdot \rceil$ denotes the ceiling operation.

In the extreme case, if a relay node is able to support all the $N$ nodes, the assignment will be completed in a single round because all the requests made by the nodes will be accepted by the relay nodes to which the applications were made.

It is also interesting to investigate the effects of lost packets or packets received in error on the performance of the algorithm. A transmitted packet according to the IEEE 802.15.4 standard contains a cyclic redundancy check (CRC) that only allows errors to be detected. Since the packet received in error cannot be corrected at the receiving end, it will be discarded and hence it is treated like a lost packet in the following discussion.

It is possible that packets are lost during the estimation phase. A loss of a few packets does not significantly affect the estimation of the channel parameters and especially the power calculation. Even if only a single packet is received, the channel will be estimated as an additive white Gaussian noise (AWGN) channel with the pathloss estimated from the only received packet. In case of no received packet from
a node, an infinite power requirement may be assumed by the node. If the node from which no packet is received is the AP, it means that the AP is not accessible through direct communication and hence a relay node is definitely required to make the communication to the AP possible. The power calculation is able to handle the case of the direct link requiring infinite power. On the other hand, if the node from which no packet is received is an ordinary node, it means that the particular node may not be used as a relay.

Problem may also arise if the packets are lost during the second phase. It is possible that the request packet sent by a node is lost. In this case, the node to which the request was being made, will have no idea about that request and it will take decision according to the packets that it had received. If the decision is received by the node, it can understand if its request was lost, when the accepted node has a lower saving factor than its own. On the other hand, if the accepted node has a higher saving factor, it cannot be found if the request was lost or not. Nevertheless, in these cases, it can make a fresh request to the same node if the already accepted node has a lower node saving factor or to the next node in the priority list if the already accepted node has a higher node saving factor. Another problem may be the lost or damaged decision announcements by the nodes acting as relays. If the decision packet is not received by a node, it will know that the packet is lost but it will not be aware about the decision. On the other hand, the node that made that decision will not be sure if its decision is received by a certain node or not. Thus if the node was accepted, the relay node cannot accept other nodes in the subsequent rounds. No problem is caused if the node was already rejected. The node that does not receive the acknowledgment will assume that its request was rejected and apply to the next node in its priority list. In these cases, it can be observed that the algorithm will take more rounds to converge unless some handshake mechanism is introduced. It is, however, proposed that rather than increasing the complexity of the algorithm by adding handshaking, more transmit power may be used during the second phase of the algorithm such that the probability of lost packets is significantly reduced. It is also proposed that the number of rounds should also be fixed to $\lceil N/k \rceil$. Thus there will be a very low probability that a node may be left unpaired but pairing of the other nodes will still offer a significant advantage in terms of the energy saving. This approach will not increase the number of rounds and hence the time required for partner selection will remain limited.

The performance of the proposed algorithms is given in the next section.
4.4 Simulation Results

In this section, we compare the performance of all the partner selection algorithms that were described in the previous section. We again consider the problem of multiple resource-constrained nodes transmitting data to the AP. We assume a TDMA schedule such that there are no collisions between the transmitted packets. All the nodes are compatible with the IEEE 802.15.4 standard and use the offset quadrature phase-shift keying (O-QPSK) physical layer (PHY). We consider the problem of even and odd nodes separately as the performance of some of the algorithms (that use reciprocal pairing) is different in the two cases. The nodes estimate the channel parameters i.e. mean pathloss and Rician $K$ factor of the channels using the estimator proposed in Sec. 2.2. The case of small number of nodes (2 to 9) and large number of nodes (more than 9) is also taken up separately because with large number of nodes, the simulation of optimum lifetime gain and total energy algorithms is too time consuming and practically not possible. Hence, for large number of nodes, only the algorithms with polynomial complexity are considered. In order to calculate the transmit power to be used by the partner selection algorithms, we will use the exact power calculation method for small number of nodes and the proposed approximation is used when the number of nodes is large. For all the simulations, 10,000 random placements of nodes were considered.

Two different environment scenarios are considered for comparison:

**Scenario A:** This is the indoor-to-outdoor scenario as given in Sec. 2.1.3, with the ordinary nodes uniformly distributed inside an indoor environment of size $25\,\text{m} \times 25\,\text{m}$ and communicate to an AP that is placed $20\,\text{m}$ away from the outside wall. Due to the outdoor part and the attenuation due to the wall, this scenario is characterized by channels to the AP having higher mean pathloss than the channels between the ordinary nodes. Similarly the channels to the AP have lower Rician $K$ factor values than the channels between the ordinary nodes.

**Scenario B:** This is only the indoor part of the first scenario. All the nodes are placed inside this indoor environment of size $25\,\text{m} \times 25\,\text{m}$ and the AP is located in the center. In scenario B, all the channels have lower mean pathloss values and higher Rician $K$ factors as compared to scenario A. Thus, the channels between the nodes are similar to the channels to the AP.

The performance of the algorithms is determined in terms of the network lifetime gain.
as given by (3.14) and the total energy saving ratio as given by (3.13). Simulations were performed for an outage probability of 0.01 and 0.001. The results are, however, only presented for the outage probability of 0.001 because the derived conclusions are similar for the outage probability of 0.01 except for the decreased values of network lifetime gain and total energy saving ratio.

![Graph showing total energy saving ratio for odd number of nodes (3 - 9), Scenario A](image)

**Fig. 4.2:** Total energy saving ratio for odd number of nodes (3 - 9), Scenario A

Fig. 4.2 shows the total energy saving ratio for odd number of nodes in scenario A. Following observations can be made:

- The total energy saving ratio increases with increasing number of nodes because
with more number of nodes, there are possibilities to group the nodes in a better way and hence more saving is achievable.

- Amongst the compared partner selection algorithms, worst performance is seen for the algorithms that generate reciprocating pairs i.e. WLF, WLF Total, Stable roommate approach, OLG Reciprocating and OTE Reciprocating. The total energy saving ratio curves for these schemes overlap and are shown as the lowest line in the figure. The schemes show the worst performance when compared to the other schemes due to the reason that the number of possible groupings with reciprocating schemes is the least.

- The five schemes for reciprocating pairs as mentioned in the last point show no significant difference in performance amongst them. I.e. WLF based on the channel conditions to the AP or including the channel conditions between the nodes themselves does not change the performance. Same is the case with the optimum schemes. It will be subsequently shown that this observation is only true for scenario A. The reason for this behavior is that the channels to the AP play a significant role in the overall performance of the pairing algorithms. These channels have large pathloss and low $K$ factor values. The role of the indoor channels between the nodes is less significant as these channels have small pathloss and high $K$ factor values.

- The next group of schemes that offer better performance than the reciprocating schemes are those that are based on the only one and one other approaches as previously discussed. These are OLG only one, OLG one other, Hungarian, Hungarian+, Hungarian LG, OTE only one, OTE one other and the proposed distributed scheme with $k = 1$. The curves for these schemes almost overlap each other. Their better performance as compared to the reciprocating schemes is due to the opportunity of better grouping with more possible groups with one other and only one as compared to the reciprocating schemes.

- In this group, the two OLG schemes i.e. OLG only one and OLG one other perform slightly inferior to the other schemes because in these two approaches, the target optimization is the network lifetime gain and not the total energy saving ratio and optimizing one does not optimize the other.

- The different variants of the Hungarian approach also perform similar to each other without much advantage obtained from the modifications.

- The OTE only one and Hungarian exactly overlap over each other because the
Hungarian approach provides the optimum solution with one node assisting one node in order that the total energy of the system is minimized.

- The OTE one other approach performs slightly better than the other approaches in the group because the restriction of not relaying when the node is itself not being helped is removed and hence more pairing options are available.

- After the second group, where nodes could assist a maximum of one other node, there are the schemes where more than one node may be assisted by a relaying node.

- Increasing the number of nodes that could be assisted, increases the energy saving factor for the distributed algorithm.

- The OLG any other approach shows good performance but the improvement with increasing number of nodes becomes less. This is due to the conflicting demands of optimizing the total energy of the network versus the lifetime gain and it becomes evident when the number of nodes is increased.

- The OTE any other approach, being the optimum approach with all possible source-relay combinations available, provides the best results.

Fig. 4.3 gives the network lifetime gain for odd number of nodes in scenario A. Following can be observed:

- Network lifetime gain also increases with increasing number of nodes because the availability of more nodes in the network allows for better pairing.

- Like the energy saving ratio, the reciprocating schemes have an inferior performance amongst the different schemes. The five schemes (WLF, WLF total, Stable roommate, OTE reciprocating and OLG reciprocating) perform almost identically and are seen in the figure as a single overlapping curve. The reason for the worst behavior as explained for Fig. 4.2, is the least number of possible groups as compared to only one, one other and any other pairing.

- Better gain values are obtained by the schemes that are based on the only one and one other approaches due to the possibility of better grouping since the number of possibilities is more than that for reciprocal schemes.

- Contrary to Fig. 4.2, the OLG one other and OLG only one show a slightly better performance than the other schemes in this group, because in this case, the target is to optimize the network lifetime gain.

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Fig. 4.3: Network lifetime gain for odd number of nodes (3 - 9), Scenario A

- Hungarian LG, as originally intended, has a slightly better performance than the other variants based on the same approach.

- An interesting behavior is observed for the distributed algorithm. The scheme with $k = 2$ has a better performance than the scheme with $k = 1$. However, the scheme with $k = 3$ shows a similar performance to $k = 2$ and increasing the value of $k$ further deteriorates the performance as is seen for $k = 5$. For scenario A, $k = 3$ seems to be the best in terms of both lifetime gain and the energy saving ratio. The behavior can be explained as follows. There can always be
some nodes in the network that can offer significant advantage to other nodes in terms of energy saving. When a node is allowed to act as relay for only one other node \((k = 1)\), the node with the best conditions can help the node with the worst conditions. The other nodes, which may not offer the best advantage help other nodes. When \(k = 2\), the best node has to support two other nodes. Hence its own energy consumption is further increased but it can still be beneficial to the network by helping another node that could not, otherwise, be helped in the best way. As \(k\) is further increased, the increasing burden on the nodes helping other nodes becomes more prominent and hence, after a few number of nodes, helping more nodes outweighs the overall advantage. It must also be noted that increasing \(k\) is, still, beneficial for the total energy consumption of the network.

- The OTE any other approach shows the same behavior as was observed with OLG any other in Fig. 4.2. Optimizing the total energy leads to a heavy usage of the node with the best channel conditions to the AP and this decreases its lifetime and therefore the lifetime of the network decreases.

- OLG any other shows the best performance because this is optimized for the network lifetime gain and searches through all the possible combinations of nodes and their cooperation partners.

The total energy saving ratios for even number of nodes in scenario A are shown in Fig. 4.4. The total energy saving ratios for most of the algorithms (except the distributed algorithm with \(k = 2, k = 3, k = 5\), OTE Any Other and OLG Any Other) overlap over each other. The increasing values with increasing number of nodes and the interpretation of the behavior for most of the algorithms are similar to 4.2. However, following differences can be observed:

- With even number of nodes, the reciprocating schemes and the schemes that are based on the only one or the one other approach give an almost similar performance. Thus with even number of nodes, whichever scheme is used (amongst the reciprocating, only one or one other), total energy consumption of the network may be reduced. This different behavior is attributed to the reason that with even number of nodes, all the nodes may be paired whereas for odd number of nodes, the reciprocating schemes always result in at least one unpaired node which is not obtained with only one or one other approach. The unpaired node affects the performance of the reciprocating schemes.
Fig. 4.4: Total energy saving ratio for even number of nodes (2 - 8), Scenario A

The performance of any other approaches and the distributed approach with increasing \( k \) is also similar to Fig. 4.2.

Network lifetime gain values for even number of nodes in scenario A are given in Fig. 4.5. The behavior is similar to Fig. 4.3 with the difference that the reciprocal schemes perform similar to the schemes where a relay node can support a maximum of one node. As explained for Fig. 4.4, this difference owes to the presence of an unpaired node with odd number of nodes which is not the case when the number of nodes is even.
Chapter 4
Partner Selection

Fig. 4.5: Network lifetime gain for even number of nodes (2 - 8), Scenario A

The performance of the partner selection algorithms for large odd number of nodes in scenario A is shown in Fig. 4.6. The optimum algorithms could not be plotted due to their extremely high computational time. The behavior is similar to Fig. 4.2 with the reciprocating schemes having the worst performance followed by one only and one other schemes. The reason, as already explained, is the number of possible groupings upon which the decision is made. The distributed algorithms show different performance according to the number of nodes that could be supported by a relay node as explained in the case of small number of nodes. From this figure,
it can also be observed that for the schemes where a relay node could support a maximum of one node (reciprocating or non-reciprocating), the total energy saving ratio does not significantly increase with the increasing number of nodes and the curves become almost flat for number of nodes greater than 40. This is due to the fact that adding another node to the already available number of nodes, does not increase the grouping possibilities significantly enough to have an appreciable effect on the total energy saving ratio. However, this is not the case when the number of supported nodes is more than 1, because, in this case, the number of grouping options is much increased and the effect is significant enough to be visible.

![Graph showing total energy saving ratio](image-url)

**Fig. 4.6:** Total energy saving ratio for odd number of nodes (> 9), Scenario A
Fig. 4.7 shows the network lifetime gain values for odd number of nodes greater than 10 for scenario A. The difference to Fig. 4.6 reveals that the network lifetime gain values do not flatten out with increasing number of nodes. This is due to the fact that any additional node adds to the increasing possibility of a node with difficult channel conditions that may be helped by relaying. In terms of total energy saving ratio, any additional node helped by relaying still adds to the total energy consumption of the system and hence the ratio does not increase significantly.

**Fig. 4.7**: Network lifetime gain for odd number of nodes (>9), Scenario A

The reciprocating schemes and non-reciprocating schemes with the maximum number
of assisted nodes per relay equal to 1 perform in a similar way as is the case with small number of nodes. The behavior of the distributed algorithm with increasing $k$ can also be interestingly observed. The scheme with $k = 2$ performs significantly better than the scheme with $k = 1$. However, $k = 3$ gives a performance that is slightly inferior to the scheme with $k = 2$. The scheme with $k = 5$ has a much inferior performance and for number of nodes greater than 40, it is even worse than the scheme with $k = 1$. The scheme denoted by $k = \text{All}$ represents the scheme when the relay node can support all the nodes present within the system. It can be observed that this scheme has the worst performance in terms of the network lifetime gain. The reason of this behavior, as explained previously, is that any node acting as a relay saves the energy for the nodes it helps but, as a result, its own energy expenditure increases. With $k = 1$ and $k = 2$, the increase in energy expended by a relay node is not significant in deteriorating the overall network lifetime. A further increase in $k$ makes this extra expenditure by the relay nodes significant enough to compromise the lifetime of the network.

The performance of partner selection schemes, in terms of the network lifetime gain, when the number of nodes is even and greater than or equal to 10 is shown in Fig. 4.8 for scenario A. The performance of the schemes is similar to the case when the number of nodes is small. However, the saturation effect is also visible for the case when the nodes can support only a maximum of one node as was explained in the case of Fig. 4.6.

Fig. 4.9 shows the performance of the algorithms, in terms of the network lifetime gain, for even number of nodes greater than or equal to 10. It can be observed that better performance is observed with increasing number of nodes. All the algorithms where a maximum of one node may be supported perform almost equally. Again it can be seen that the distributed algorithm with $k = 2$ gives the best performance. The performance deteriorates with $k = 3$ showing a slightly worse performance. The performance with $k = \text{All}$ is the worst. The reasons for these observations were already explained.

Interesting differences can be observed with scenario B. Fig 4.10 depicts the performance of the partner selection algorithms when the number of nodes is odd. Some of the important characteristics are as under:

- The reciprocating and the non-reciprocating schemes with number of supported nodes equal to 1 are not grouped as was seen in the case of scenario A (Fig.
4.2) i.e. all the algorithms show a performance that is distinct from each other.

- The stable roommate approach yields the worst performance because the priority was based on the links to the AP whereas the links between the nodes are equally important in this scenario.

- The WLF approach works better than the stable roommate approach. The reason for its worse performance as compared to remaining algorithms is that it is a sub-optimum approach based on reciprocating pairs. It has already been observed that reciprocating pairs have the least grouping options among all
4.4 Simulation Results

Fig. 4.9: Network lifetime gain for even number of nodes (> 8), Scenario A

- A difference can be observed between the WLF approach that is based on the links to the AP and the WLF Total approach that considers the overall relay channel. It can be seen that the latter approach performs better than the former because the channel conditions between the nodes for this scenario are equally important to the channel conditions to the AP.
Fig. 4.10: Total energy saving ratio for odd number of nodes (3-9), Scenario B

- The four variants of the OLG approach also show a performance difference with the reciprocating pairs, only one, one other and any other approaches improving in this given order. This is due to the number of possible grouping options also increasing in the same order.

- The Hungarian+ approach, as designed, performs better than the simple Hungarian approach whereas the Hungarian LG approach is slightly worse in performance because it is not optimized to minimize the overall energy consumption of the network.
4.4 Simulation Results

Like OLG, OTE approaches also perform according to the pairing schemes with OTE any other as the best scheme.

The proposed distributed algorithm gives an increasingly better performance as the number of nodes that could be supported by a node increases.

The distinct behavior of all the partner selection schemes for scenario B is also evident from the network lifetime gain curves shown in Fig. 4.11. The interpretation of the curves is similar to Fig. 4.10 except for the fact that the behavior of OLG algorithm is replaced by OTE and vice versa. Another difference is the superior
performance of the Hungarian LG approach amongst the other algorithms based on the Hungarian algorithm.

In contrast to scenario A, where most of the algorithms show similar performance for even number of nodes, the performance of the algorithms is different from each other for even number of nodes operating under scenario B. Fig. 4.12 gives the performance of the different algorithms in terms of total energy saving ratio. It can again be seen that the stable roommate approach, with the priorities decided from the links to the AP, gives the worst results. Distributed approach with large $k$ gives a performance

Fig. 4.12: Total energy saving ratio for even number of nodes (2 - 8), Scenario B
that is comparable to the optimum scheme. The performance of other algorithms varies as already explained for Fig. 4.10.

![Network lifetime gain for even number of nodes (2 - 8), Scenario B](image)

**Fig. 4.13:** Network lifetime gain for even number of nodes (2 - 8), Scenario B

The results for network lifetime gain given in Fig. 4.13 can also be interpreted like the results for the energy saving factor with the roles of the OTE and OLG algorithms exchanged.

The results for large number of nodes clearly show the difference between the performance of the different partner selection algorithms in scenario B. Fig. 4.14 shows the total energy saving factors for odd number of nodes. The observations are
Fig. 4.14: Total energy saving ratio for odd number of nodes (> 9), Scenario B

as under:

- The stable roommate approach with priorities based on the link qualities to the AP is not a feasible approach due to the significant importance of the links between the nodes.

- WLF approach is better than the stable roommate approach but worse than all other approaches since it is based on a reciprocal pairing and is not optimum.

- The difference between the two WLF approaches is clearly visible. The algorithm that takes the whole relay channel in to account performs better than the
scheme that is based only on the links to the AP, because the channels between the nodes are as important as the channels to the AP.

- The Hungarian-based schemes perform better than the WLF approach because the target pairing in WLF is reciprocal whereas the pairing in the Hungarian approach is non-reciprocal.

- The simple Hungarian and the Hungarian LG algorithms show a similar performance with Hungarian LG slightly worse than the other. Its slightly worse performance is due to the reason that it is designed to give a better

Fig. 4.15: Network lifetime gain for odd number of nodes (> 9), Scenario B
lifetime gain and not the total energy saving ratio.

- The proposed Hungarian+ scheme is much better than the simple Hungarian algorithm. It is even better than the proposed distributed algorithm with $k = 1$. As explained, the Hungarian+ approach converts an only one pairing to one other pairing, thereby increasing the possible grouping options.

- The proposed distributed algorithm gives increasingly better performance with increasing $k$ because the nodes with best channel conditions can support more and more nodes with increasing $k$.

- The distributed algorithm where a relay node could support all other nodes shows the best performance.

Fig. 4.15 reveals the following interesting observations regarding the network lifetime gain in scenario B:

- Like the energy saving ratio, stable roommate approach does not give satisfactory results in terms of the network lifetime gain.

- WLF approach with the whole relay channel in consideration performs better than the WLF approach that is based only on the link quality to the AP.

- Amongst the approaches based on the Hungarian algorithm, Hungarian+ performs the best followed by the Hungarian LG approach. the simple Hungarian approach is the worst amongst these three.

- In scenario B, the distributed approach with $k = 1$ performs the best and increasing $k$ decreases the network lifetime gain. This observation is contrary to the results obtained for scenario A where $k = 2$ could reveal the best values for the network lifetime gain. The reason for this difference is that in scenario A, the links to the AP were more important than the links between the nodes. A node with good channel conditions could help other nodes with a small addition to their own expenditure. Thus, by helping 2 or 3 nodes the network lifetime could be improved. For scenario B, the links to the AP are similar to the links between the nodes. In this case, the additional expenditure for helping a node is comparable to the energy expenditure of the node. Thus helping only one node is beneficial but increasing the number of nodes to be helped, affects the lifetime of the node being used as the relay and as a result, the lifetime of the network is compromised.
Figs. 4.16 and 4.17 show the total energy saving ratio and the network lifetime gain in scenario B when the number of nodes is large and even. The results in terms of the relative performance of the partner selection algorithms are similar to the case when the nodes are odd.

The overall findings for all the simulation results can be summarized as below:

- For a scenario with channels to the AP characterized by high mean pathloss and low Rician $K$ factor values and the channels between the nodes having lower mean pathloss values and higher Rician $K$ factor values, most of the
algorithms that assign one node to a relay node, whether done in a reciprocal manner or not, offer a similar performance in terms of total energy saving ratio and the network lifetime gain when the total number of cooperating nodes is even. In such a case, any algorithm with a low complexity may be used to exploit the advantage due to relaying. For a similar scenario, if the number of nodes is odd, schemes with reciprocating pairings are slightly inferior in performance as compared to the schemes where the pairing is not reciprocal. The reason, as explained, is the mandatory existence of an unpaired node in
reciprocal pairing that cannot be helped by any other node. Such a node can be paired when the number of nodes is even or the pairing used by the algorithm is not reciprocal.

- When the channels to the AP are similar to the channels between the nodes (in terms of the mean pathloss and the Rician $K$ factor), a significant difference in performance is observed amongst the different algorithms. In such cases, the algorithms must consider the whole relay channel in to consideration for the partner selection decisions. The non-reciprocating pairing schemes are better than the reciprocating schemes for both odd and even number of nodes. Selection of an appropriate partner selection algorithm is, therefore, very essential.

- The Hungarian algorithm-based approach gives the optimum solution for minimizing the total energy consumption of the network with each node supporting a maximum of one other node when it is not itself using direct communication. For all the cases, the proposed Hungarian+ approach performs better than the Hungarian approach both in terms of the network lifetime gain and the total energy saving ratio. The reason for the superior performance is the idea of converting the pairing scheme from only one to one other, thereby, increasing the number of possible groupings. The proposed Hungarian LG approach results in a better lifetime gain than the conventional approach because it was designed to improve the lifetime by successively eliminating the nodes consuming the maximum energy from the Hungarian solution.

- The provisions of an appropriate priority list makes it difficult for the stable roommate-based algorithm. The provision of such a list is also difficult to be done in a distributed way and basing the priorities on the quality of the links to the AP results in a poor performance in scenarios like scenario B.

- The proposed distributed algorithm performs better than the existing algorithms. The number of nodes that may be supported by a relay node may be adjusted. With one supported node, the performance is similar to the optimum scheme with one node supported by a relay node in a non-reciprocating way. Total energy saving factor is improved by increasing the number of nodes supported by each node acting as the relay. The same increase in the number of nodes, however, affects the network lifetime gain in a different way. It was observed that for scenario A, the lifetime gain is maximized when each relay
node supports two or three other nodes and a further increase in the number of supported nodes decreases the network lifetime gain. On the other hand, for scenario B, the network lifetime gain was maximum for number of supported nodes equal to one and any increase in it, decreases the network lifetime gain. It can be concluded that with scenarios having more pathloss in the nodes to AP links, a higher number of nodes may be supported by each relay node for a better network lifetime gain and energy saving ratio.

4.5 Summary

The chapter discussed the problem of partner selection in cooperative relaying. When many nodes are available in the network, they can be appropriately paired to assist other nodes in delivering the messages of one another. The chapter described the various ways in which such a pairing is possible. Selecting the best relay combination using exhaustive search with all possible combinations is almost impossible for even a moderate number of nodes. Different lower complexity algorithms already exist in the literature that deal with the problem of partner selection. Some of the algorithms are derived from already available algorithms that exist in entirely different fields. Modifications to the already existing partner selection schemes were suggested and a distributed algorithm was proposed. The performance of all the algorithms was compared using simulations with the help of two example scenarios. It was shown that the proposed algorithms give a better performance in terms of the network lifetime gain and the total energy saving ratio. E.g. for a network consisting of 50 nodes, the WLF Total algorithm can provide an improvement of up to 48% in terms of total energy saving ratio and 132% in terms of the network lifetime gain. The proposed Hungarian+ scheme gives an 18% improvement in total energy saving ratio when compared to the already existing Hungarian algorithm. The proposed Hungarian LG approach results in about 7% improvement in the network lifetime as compared to the simple Hungarian approach. The proposed distributed approach offers an improvement in the total energy saving ratio ranging from 13% to 70% for $k = 1$ to $k = \text{All}$, when compared to the Hungarian algorithm. In terms of the network lifetime gain, the distributed approach provides 9% improvement as compared to the Hungarian algorithm. The maximum absolute values of total energy saving ratio, achievable for these scenarios, is about 700 for even a network consisting of 20 nodes and it is much larger for bigger networks. The maximum absolute value in terms of
the network lifetime gain for a similar network is more than 1500. Thus, significant improvement in the lifetime of the network and reduction in the transmit energy can be realized using cooperative communication and the proposed algorithms can help to achieve these objectives better than the existing algorithms.
Chapter 5

Conclusions

The work presented in the thesis focuses on the problem of saving energy and improving the lifetime of a wireless network consisting of simple low-cost battery-driven nodes. An optimum allocation of transmit power is, therefore, crucial to avoid frequent replacement of batteries. Battery replacement often requires significant effort and cost. The absence of complex hardware demands that the underlying algorithms should be computationally very simple. Relaying helps to reduce the energy consumption of nodes confronted by hostile channel conditions. Accurate calculation of optimum transmit power in relay channels is also computationally demanding and demands simple algorithms that could be implemented on simple hardware. The presence of multiple nodes allows the nodes to cooperate with each other by acting as relays for one another. However, a proper pairing of the nodes is essential to reap the full advantage of relaying. The presented work addresses these stated problems.

5.1 Contributions

During the course of the work, following contributions could be made:

- A MATLAB simulator is developed for IEEE 802.15.4 standard. The simulator allows different types of performance simulations for direct and relayed communications in additive white Gaussian noise (AWGN), Rayleigh and Rician channels. The simulator was first presented and used in [85].
- A novel estimator and its very low-complexity approximation for channel parameter calculation in Rician channels are presented. The approximate
estimator is actually implemented on low-complexity hardware to demonstrate its effectiveness. [86]

- The role of Rician $K$ factor in the coding gain approximation for power calculation in direct links is, for the first time, investigated. It is shown through simulations that the outage probability values reported in the literature for the approximation to be valid are not true for all Rician $K$ factors. A Rician $K$ factor value of 40 needs an outage probability of less than $10^{-15}$ to apply this approximation [61].

- An approach with practical implementation details is presented to calculate transmit power for direct links. The approach uses the mean pathloss and Rician $K$ factor of the channel to find the optimum transmit power. The scheme is actually implemented on simple nodes and practical results are presented [61, 86].

- A novel approximation is proposed to calculate transmit power in relay channels. The approach is very low in complexity and the obtained results are much better than the already existing approximations (e.g. coding gain approach) [61].

- A comprehensive comparison of partner selection algorithms is presented. Two example scenarios are considered that highlight the performance differences between the schemes [83].

- The comparison between the algorithms is conducted using both the network lifetime gain and energy saving ratio. Most of the existing literature considers only one of these parameters [83].

- Modifications to the existing partner selection algorithms are proposed and the performance results indicate that the proposed schemes offer a performance advantage of more than 100% in terms of the network lifetime gain and about 50% in terms of the energy saving ratio [83].

- A novel distributed partner selection algorithm is presented. Simulation results indicate that the approach can be tailored to improve the network lifetime gain or the energy saving ratio. The implementation details of the approach are also presented.

- Most of the existing literature considers no particular standard for performance evaluation. The derived performance parameters are often based on assumptions that are not true in practice. All the presented work conforms to the IEEE
5.2 Future Work

It has been shown that, with the help of cooperative communication, even with 30 nodes, a lifetime gain value of more than 1500 and an energy saving of up to 1000 are realizable in certain scenarios and the proposed algorithms are beneficial in achieving these advantages. These findings and the developed algorithms are very useful for the evolving Internet of Things (IoT). As more and more devices are connected together to share their data, the importance of efficient energy utilization will be further underlined and the discussion given in this thesis can be found very helpful.

The work presented in this thesis focused on the calculation and reduction of transmit energy which is the most significant part of the total energy expenditure in a sensor node. It should also be reiterated that the reduction of transmit energy apart from decreasing the energy expenditure of the nodes, helps to reduce interference with other coexisting networks. With increasing number of devices getting connected with each other, reduction of interference is very essential and the proposed work is helpful in achieving this objective.

An important factor to be considered in future work is the energy efficiency of the transceivers such that the reduction in transmit energy translates in the reduction of the input energy to the transceiver in a similar or at least comparable ratio. Further work is also needed to accurately model the energy consumption of the microcontroller and sensing hardware so that their effect is also included in energy performance of the whole system.
Bibliography


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