A MULTI-HOP ROUTING PROTOCOL IN TAG-TO-TAG NETWORKS OF PASSIVE TAGS

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ABSTRACT

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With the evolution of technology, tag-to-tag communication between passive RFID tags using backscattering, which is accepted as a milestone in RFID technology, has emerged in recent years. Different from the conventional passive RFID systems, tags could communicate with each other with the existence of RF signals in the environment. With this development, passive RFID tags evolved into passive tags because the usage areas could not be limited to the identification or tracking of attached objects. On the other hand, the communication ranges of the passive tags were limited as a consequence of having no internal power sources, such as batteries. Therefore, multi-hop communication was required to connect two passive tags that were not in their communication ranges. In this study, we proposed a novel multi-hop routing protocol with our system design for tag-to-tag networks of passive tags. We created a sectoral circular area design and placed the central controller, which was the RF signal source of the network, at the center of the circular area. Afterward, we divided the circular area into sectors by considering the communication ranges of the central controller and passive tags. To validate and test our solution, we created a simulation environment where passive tags were distributed uniform randomly in the circular area. With the assistance of the central controller, sectors determined by the designed routing algorithms were excited, and multi-hop tag-to-tag communication was achieved. By taking into account the energy requirements of the backscatter communication, our proposed routing protocol has provided an energy-efficient tag-to-tag communication among the passive tags in a multi-hop fashion.

Keywords: Passive Tag, Backscatter, Tag-to-tag Communication, Multi-hop, Routing Protocol

ÖZ

PASİF ETİKETLERDEN OLUŞAN ETİKETTEN-ETİKETE AĞLARDA ÇOK-SEKMELİ YÖNLENDİRME PROTOKOLÜ

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Teknolojinin gelişmesiyle birlikte son yıllarda RFID teknolojisinde bir dönüm noktası olarak kabul edilen geri saçılma kullanılarak pasif RFID etiketleri arasında etiketten etikete iletişim ortaya çıkmıştır. Geleneksel pasif RFID sistemlerinden farklı olarak bu iletişimde etiketler ortamdaki RF sinyallerinin varlığı ile birbirleriyle haberleşebilmektedir. Bu gelişmeyle birlikte pasif RFID etiketler, kullanım alanlarının bağlı oldukları nesnelerin tanımlanması veya takibi ile sınırlandırılamaması nedeniyle pasif etiketlere evrildi. Öte yandan, pasif etiketlerin iletişim menzilleri, piller gibi dahili güç kaynaklarına sahip olmamasının bir sonucu olarak sınırlıydı. Bu nedenle, birbirlerinin iletişim menzillerinde olmayan iki pasif etiketin iletişim kurabilmesi için çok-sekmeli iletişim gerekiyordu. Bu çalışmada, pasif etiketlerin etiketten etikete ağları için sistem tasarımımızla birlikte yeni bir çok-sekmeli yönlendirme protokolü sunduk. Sektörel dairesel alan tasarımı oluşturduk ve ağın RF sinyal kaynağı olan merkezi düzenleyiciyi dairesel alanın merkezine yerleştirdik. Daha sonra merkezi düzenleyicinin ve pasif etiketlerin iletişim menzillerini göz önünde bulundurarak dairesel alanı sektörlere ayırdık. Çözümümüzü doğrulamak ve test etmek için, pasif etiketlerin dairesel alanda tekdüze rastgele dağıtıldığı bir simülasyon ortamı oluşturduk. Merkezi düzenleyicinin yardımıyla, yönlendirme algoritmaları ile belirlenen sektörler uyarılarak çok-sekmeli etiketten etikete haberleşme sağlandı. Geri saçılımla yapılan iletişimlerin enerji gereksinimlerini hesaba katarak, önerilen yönlendirme protokolümüz, pasif etiketler arasında çok sekmeli bir şekilde enerji açısından verimli bir etiketten etikete iletişim sağlamıştır.

Anahtar Kelimeler: Pasif Etiket, Geri Saçılım, Etiketten Etikete İletişim, Çok-sekmeli, Yönlendirme Protokolü

To my family

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ABBREVIATIONS	
RFID	Radio-Frequency Identification
RF	Radio-Frequency
ISO	International Organization for Standardization
EPCglobal	Electronics Product Code Global Incorporated
IEC	International Electrotechnical Commission
GPS	Global Positioning System
FIFO	First In First Out
ID	Identification Number
DSPA	Dijkstra’s Shortest Path Algorithm
RASSA	Routing Algorithm with the Smallest Sectoral Area
RASSD	Routing Algorithm with the Shortest Sectoral Distance

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

While new promising developments are experienced every day in the technology era we live in, at the same time, the devices developed with these innovations are starting to take a very important place in our lives. Every day, a new technological device enters our lives, and thanks to these devices, we can do our daily work easily and quickly.

In the age of technology, new promising developments are experienced at an increasing pace, and the devices developed with these innovations continue to take a very important place ubiquitously and seamlessly in our lives. One of the biggest areas where the mentioned technological developments are frequently experienced is the Internet of Things. With the developments in these areas, we see more and more small computing devices every day. However, each of these devices consumes energy separately, and therefore, how to power each of these devices is a matter of great debate.

Backscattering can provide battery-free and wireless communication, which has come to the fore in recent years [2, 3]. With this technique, which is currently used in many places in our daily life with passive RFID tags, data can be transferred by reflecting the incoming signal on a very small scale (usually only the identification numbers of the devices) wirelessly and without batteries. The main reasons to choose passive RFID tags are that they are batteryless, cheap, and easy to carry. However, passive tags are commonly used in systems with one reader and one or more tags that can communicate with the reader. In such legacy systems, tags can only communicate with their reader and cannot communicate with each other.

RFID tags require an external power source to be activated and communicate with a reader. In contrast to traditional tag and reader systems, if tags can communicate with each other with the existence of an external power source, the overall energy efficiency of the network can be minimized. In other words, in tag-to-tag communication with a proper multi-hop routing protocol, a communication network can be accomplished using passive tags' advantages. The network where passive tags can communicate with each other was introduced in the literature [4, 5]. Afterward, tag-to-tag communication was demonstrated in [6].

Compared to other communication devices, passive tags are more convenient to use and carry. They can be preferred in different scenarios in our daily lives, such as smart homes and smart city applications. Passive tags are very suitable for scenarios where different stationary devices should work cooperatively regarding energy efficiency concerns. They can also be responsible for communication between IoT devices [7]. There are some environments where the temperature should be strictly controlled, such as laboratories or greenhouses. In these circumstances, devices should work cooperatively with the assistance of passive T2T communication. Moreover, they can be used in autonomous traffic light management systems where the devices should directly communicate with each other using passive T2T communication.

Demonstrating T2T communication is just the starting step of a T2T network shown in Fig. 3.3. The communication range of a passive tag is very small, leading us to a more critical question. The question is whether two passive tags can communicate with each other even if they are not in their communication range. In other words, if a multi-hop routing protocol supports tag-to-tag communication, a complete network of passive tags that can communicate with each other can be demonstrated.

In order to realize a multi-hop tag-to-tag communication, it is required to excite the passive tags properly with the external RF source. However, it is not easy to determine which passive tag or tags should be excited or when they should be excited. Because of the energy concerns, passive tags should be excited, in other words, activated, for a limited time. Moreover, the external RF source should be controllable, and it should also plan and manage the communication between the two passive tags. The reason is that passive tags have very limited computation power, and they need the assistance of an external regulator. Therefore, instead of only an external RF source, there should be a central controller responsible for all of the passive tags in its communication range. The central controller should also create the routing path between two passive tags and assist the tags in the path to route the message by exciting them.

1.2 Proposed Solution

Considering the described problems about passive tag-to-tag communication, we propose a multi-hop tag-to-tag routing protocol with stationary passive tags and a central controller by dividing the circular area into sectors. Details of our protocol design can be found in the following.

- In our protocol design, we propose a sector-based design in the circular area by dividing the circular area into sectors and placing the controller in the center.
- To create the sectors in the circular area, we determined two variables that are beamwidth and level width. These values can be given to the system manually, or they can be determined by the system automatically.
- Without knowing the exact location of the stationary passive tags, we can activate the required tags by exciting the belonging sectors.
- To create the routing path between the sender and receiver passive tags, the central controller creates the routing path and excites the required sectors. In this thesis, two routing path determination algorithms are proposed to find the path between the passive tags. In both algorithms, the sectors that should be excited in the routing path are determined by knowing the sender and receiver passive tags' belonging sectors.
  - In the first algorithm, the sectoral shortest path is determined between the sender and receivers' sectors by applying DSPA. Without considering the size of the sectors in the sectoral routing path to excite and whether there are enough passive tags in the routing path that create a connected path,

  the minimum number of sectors to excite between the sectors of the sender and receiver passive tags.
  - In the second algorithm, the most energy-efficient path is determined without knowing whether there are enough passive tags in the routing path that makes the path connected. The path is determined by considering the areas of the sectors to excite. The reason is that a bigger sector area means that more power is required to excite the sector. Three routing path options are determined by the system from the sector of the sender to the receiver. Afterward, the most energy-efficient path, whose total area sum is the minimum, is chosen among the three options.

- In the excitation step of the sectors in the determined sectoral routing path with the proposed routing algorithms, the sectors are excited in a pairwise manner, and under the control and assistance of the central controller, the message is hopped between the passive tags until the receiver passive tag.

- To test and validate our proposed routing protocol, we designed a simulation environment and placed our central controller, which is also the RF source, at the center and passive tags in the circular plane uniform randomly. Afterward, we simulate our proposed routing protocol between the passive tags in different scenarios considering the effect of different parameters, such as passive tag count, the communication range ratio, and the sector count.

1.3 Contributions and Novelties

The main purpose of realizing the multi-hop tag-to-tag communication among the passive tags is to create an energy-efficient network according to the typical communication networks by using the batteryless environment advantage of the passive tags. For this purpose, the contributions of this thesis are listed in the following.

- We present a novel multi-hop routing protocol for passive tag-to-tag communication. As distinct from the studies in the literature, division of the circular area into the sectors in our design and exciting a specific sector or sectors when required improves energy efficiency significantly.

- We propose a sector-based design in the circular area for our routing protocol. In this design, the stationary passive tags are distributed uniform randomly, and the central controller, which is also the RF source, is placed in the center.
- With the proposed routing protocol, we present two routing path determination algorithms that are uniquely designed for multi-hop passive tag-to-tag communication.
- As the application of the proposed routing algorithms, the central controller excites required sectors by following a uniquely designed excitation algorithm for our multi-hop routing protocol.
- By using the energy-efficient communication ability of the passive tags, we realize the multi-hop tag-to-tag communication among passive tags that are not in their communication range. According to ordinary communications between two devices, energy efficiency is increased remarkably.
- We focus on the routing algorithm design in comparison to the studies in the literature, and we create a simulation environment to test and validate our protocol. In the simulation environment, by distributing the stationary passive tags uniform randomly in each test case, we analyze our routing protocol in different conditions.

1.4 The Outline of the Thesis

The rest of the thesis is structured as follows. The related studies in the background information about our study are presented in Chapter 2. We refer to the problem as Multi-hop Routing Problem in Tag-to-tag Networks of Passive Tags, which is explained in Chapter 3. The created routing protocol, which is referred to as Multi-Hop Tag-to-Tag Routing Protocol with Stationary Passive Tags in Sectoral Circular Area, is proposed in Chapter 4. We present the results of numerical evaluations of the simulations and discussions in Chapter 5 and conclude the study in Chapter 6.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Related Work

The routing problem for tag-to-tag backscatter networks has been studied in the literature previously. The most important studies about the multi-hop tag-to-tag protocol design for the passive tags in the literature were accomplished by Liu et al. [8, 9, 10]. Previously the same authors published their first studies about routing [9, 10] in 2017, and these are the first steps in developing a complete design. Afterward, they proposed a complete design [8] while concentrating on a routing protocol for multi-hop tag-to-tag communication using passive tags. In the study, they were also interested in large-scale networks and concentrated on designing their own 'Network of Tags' model. They categorized different types of passive tags while creating routing protocols according to the ability to measure received power and attenuate their transmit power. They explained their algorithm step-by-step, and some possible real-life examples of tag-to-tag communication were shared with the readers. This is the most similar study to our study in the literature, considering the problem definition and solution approach. While Liu et al. divided the area of the reader's communication range into the levels, we divided the circular area into optimum-sized sectors, where our design is more energy-efficient because we tried to find the optimum-sized total excitation area in our solution. During the communication between the passive tags, the total excitation area is directly related to the excitation power provided by the reader or central controller, and finding optimum-sized sectors minimizes the energy requirements of the communications. Additionally, in their design, the reader controls all of the transmissions between the passive tags, and it determines the positions of the passive tags. On the other hand, we accepted that the central controller does not know the exact positions of the passive tags and assists the passive tags to communicate with each other in a multi-hop fashion instead of controlling the communication between them. In another study, Majid et al. [11] focused on realizing the multi-hop tag-to-tag backscatter communication. They also created their tag architecture and a prototype of their design. Afterward, they proved that the multi-hop ability extends the communication range significantly. They focused on the passive tag design that is capable of multi-hop tag-to-tag communication between the passive tags, while we created a complete system design with a multi-hop tag-to-tag routing protocol using the passive tags that have multi-hop communication capability.

In the literature, Liu et al. [12] proposed a multi-hop tag-to-tag network based on turbo backscattering operation. The reader determines the routing path in their system design and broadcasts the RFID tags. Then, tags on the routing path were activated for the transmission. They proved the efficiency of their routing algorithm by showing the test results, which include the bit error rate, transmission delay, and power consumption measurements. Another comprehensive research was conducted by Ryoo et al. [13] in 2018. They created their own tag architecture and showed their solution for the technical problems in tag-to-tag communication. Moreover, they proved their study by developing a prototype for their tag architecture. As another study focused on creating a routing protocol for the devices that uses backscattering to communicate with each other was conducted by Zhou et al. [14]. In this study, they proposed a routing protocol design for the wireless sensor networks where the backscattering is enabled. Additionally, they analyzed both distributed and centralized solutions for the routing protocol and presented the results. A multi-hop backscatter system that works with commodity WiFi devices is proposed by Zhao et al. [15] named as X-Tandem. Different from the other multi-hop tag-to-tag backscatter approaches, they designed a system where the passive tags are excited with commodity Wi-Fi and communicate with the backscatter reader through the other passive tags. However, they focused on the communication of the passive tags with the reader instead of tag-to-tag communication. They created a prototype for their proposed study and demonstrated a two-hop implementation. Considering the large-scale backscatter networks and the number of concurrent communications in these networks, Hessar et al. [16] proposed a distributed coding mechanism for the backscatter networks. They created the novel

NetScatter network protocol that is capable of performing more concurrent transmissions according to the studies in the literature.

Enhancing the backscattering technology, Liu et al. [17] introduced a novel technique which is ambient backscattering, for the first time in the literature with a prototype tag design. With this emerging technology, passive tags can use the already existing ambient signals without requiring a specific power source. Moreover, using the ambient signal, they can communicate with each other. In total, passive tags can communicate with each other without any necessity for an external power source in a batteryless fashion. By developing the tag design created by Liu et al. [17], Parks et al. [18] proposed their tag and multi-antenna cancellation design with a novel coding mechanism that enables long-range concurrent tag-to-tag communications. With their improvements, tags could communicate with other tags over tens of meters. Notably, the proposed long-range concurrent tag-to-tag communication was applicable for both RFID and ambient backscatter systems.

Devices capable of backscattering or ambient backscattering require the signals to receive and transmit the backscattered signals to the environment by processing their own data. However, the source of the incoming signals to the devices is another research topic in the literature. Different types of devices that use different signals to backscatter are designed in the literature. Using ambient Wi-Fi signal as the excitation signal for the very low power backscatter IoT sensors, Bharadia et al. [19] proposed a system design by verifying with prototypes. Using a single plugged-in RF signal provider, Kellogg et al. [20] introduced the Passive Wi-Fi architecture to the literature where the 802.11b transmissions can be realized by backscatter communications. By preferring to use FM radio signals as the source for backscatter communications, Wang et al. [21] turned everyday objects into FM radio stations and creates connected cities since FM radio signals exist in cities around the world. With a novel codeword translation technique, FreeRider [22] could use the signals of multiple commodity radios, such as 802.11g/n WiFi, ZigBee, and Bluetooth, as RF source for backscattering. By improving the system design proposed in FreeRider, Chen et al. [23] presented a robust BLE (RBLE) backscatter system to the literature. They implemented a prototype for their design and realized uplink ranges up to 25 and 56 meters, indoor and outdoor environments, respectively. From another perspective on the backscatter networks, Lu et al. [24] combined ambient backscatter communications and wireless-powered communications and created hybrid transmitter devices that can switch between the communication types flexibly when required. WiSensor [25], a passive wireless sensor platform where the wireless sensor nodes use ambient Wi-Fi signals to backscatter and modulate the sensor data onto the Wi-Fi channels, is presented and a prototype is established by Feng et al.

In backscattered and ambient backscattered networks, the communication range is very limited since the power of the backscattered signal is reduced according to the incoming signal. To overcome the communication range limitation, in the literature, there are many studies that focused on the range of backscatter communication. With LoRa [26] and PLora [27] designs, ranges of the backscatter and ambient backscatter communications were enhanced significantly, respectively. In both studies, the proposed designs are demonstrated with prototypes and tested in various outdoor and indoor environments. Additionally, to increase the range of the backscatter communication, there are different approaches that enhance the backscatter communications by some technical improvements in the literature, such as an energy-efficient demodulator design [28] and an ultra-low-power reflection amplifier with a phase-shift modulator [29].

To overcome the security concerns of backscatter communications, there are studies of backscattered networks on the basis of these concerns in the literature. Since the most important layer for backscatter communications is the physical layer, the studies in the literature concentrated on the vulnerabilities in the physical layer. Saad et al. [30] and Han et al. [31] analyzed the backscatter communications and ambient backscatter communications, respectively. Afterward, they used the method of artificial noise injection to prevent eavesdropping. Additionally, Song et al. [32] presented a sub-optimal relay selection method with artificial noise injection in backscatter networks. Li et al. [33] also studied ambient backscatter communications, and they propose a security-enhancing transmission protocol against eavesdropping in their study.

Backscattering and tag-to-tag communication provide an energy-efficient way of communication, and therefore, these development are intended to use in the IoT and 6g.

In [34], Nawaz et al. analyzed the non-coherent communication and backscatter communication with their application areas in 6g by presenting a comprehensive literature research. As a new communication paradigm for passive IoT, Long et al. [35] proposed a symbiotic radio where a backscatter device is parasitic in the primary transmission. Moreover, the symbiotic approach was used in another study [36] by presenting a symbiotic system of cellular and IoT networks, referred to as backscatter-NOMA (Non-orthogonal multiple access), which incorporates cellular NOMA and ambient backscattering. As a novel approach by augmenting the IoT systems with the assistance of backscattering technology, Pérez-Penichet et al. [7] used passive sensor tags to improve the sensing capabilities of IoT deployments without the need to modify the existing deployment. A comprehensive research for the green IoT is conducted by Yang et al. [37]. They proposed a cooperative ambient backscattering communication by technically detailed research where the cooperative receiver recovers the information from both the ambient backscatter device and RF source. Another extensive research was performed by Ji et al. [38], where they proposed multi-hop communication protocols for the large-scale tag/sensor nodes of IoT. Additionally, they used ambient backscattering with energy harvesting under Wi-Fi architecture and called this method as BackFi. Using the recently developed reconfigurable intelligent surfaces technology, which shares the same reflective principle with ambient backscatter communication, Liang et al. [39] presented an overview of three types of backscatter communication systems assisted by reconfigurable intelligent surfaces for the passive IoT. In addition to the applications and improvements of backscatter communication in IoT, some real-life usage examples were discussed in the literature. One of them is BARNET [40], which is a network that provides the identification of tagged objects and an activity recognition system by using passive tags. Another one is a body area sensor network (bodyNET) [41], which helps us to monitor human body physiological signals with stretchable passive tags. By using the stretchability advantage of the passive tags, they presented their on-skin sensor tags to read the signals from the human body.

2.2 Preliminaries

Technical details about RFID devices, tag-to-tag communication, and routing protocols that were used to define and complete the study presented in this thesis are described in this section. The thesis is based on the preliminary information below.

2.2.1 RFID

Jeremy Landt, who is a scientist from Los Alamos National Laboratory, defines RFID technology as "RFID is a term coined for short-range radio technology used to communicate mainly digital information between a stationary location and a movable object or between movable objects." [42]. Basically, RFID technology is used for wireless communication in short ranges by using electromagnetic fields to transmit digital data. Nowadays, a common RFID system consists of two components, a reader and a tag. The reader includes a transmitter and a radio receiver. While the transmitter is used for producing, the radio receiver is used for receiving the radio waves with antennas. The tag is a transponder itself, which emits a different signal in response to an interrogating signal. The technique which is used to transmit a modulated signal from the received signal is called backscattering. In reader-to-tag communication, tags do not have to be in the line of sight of the reader.

The first studies which are related to RFID technology were developed in the 1960s [43, 44, 45]. The first patent which can be accepted as the ancestor of the RFID devices was published by Cardullo et al. [46] in 1973. The first passive tag, which can operate in the range of tens of meters, was presented by Koelle et al. [47] in 1975. Although there are many scientists who work on the development of RFID technology, Charles Walton is the patent owner of the first RFID device in 1983 [48].

In typical RFID systems, tags can communicate only with the reader wirelessly. On the other hand, there exist novel studies in the literature that changes the common RFID systems, such as ambient backscattering or tag-to-tag communication. Types, standardization, and technical details of the RFID devices are explained in this section.

2.2.1.1 Types of RFID Systems

The first RFID systems in history were developed to use low-frequency bands which are between 119-135 kHz, and it was not regulated by any international standard provider. Afterward, scientists used a high-frequency band (13.56 MHz) which was also unregulated. However, using high-frequency improved the data rate and maximum communication range, and with these improvements, RFID systems are started to be used in daily lives commonly. With the usage of ultra-high frequency in RFID systems, the data rates are enhanced, and the maximum communication range is increased by up to 6 meters, according to some manufacturers [49]. Even though it is not commonly used, there is another type of RFID system, which is the microwave RFID system. With these systems, data rates of RFID tags are increased; however, because of the high frequency (2.45GHz), the communication ranges cannot be improved as expected. The chosen frequency bands and typical read ranges of RFID systems can be seen in Table 2.1. Additionally, these improvements make RFID a commercial product, and frequency standards are regulated internationally. The main standard provider organizations for RFID systems are ISO, EPCglobal, and IEC.

Frequency	Band	Typical Read Range
Low-Frequency	119 - 135 kHz	<0.5 m
High-Frequency	13.56 MHz	∼1 m
Ultra-High Frequency	860 - 960 MHz	∼4-5 m
Microwave Frequency	2.45 GHz	∼1 m

Table 2.1: Frequency & Read Range Comparison in RFID Systems [1]

Depending on the type of RFID system, usage areas of RFID systems vary from the agricultural areas to the defense industry. As can be understood from the name, it was used generally to detect and uniquely identify humans, animals, or objects. Because they are small and cheap devices, they can be attached to objects. If the attached object is movable, the movement of the object can also be tracked and monitored by the reader. However, because of the power source restrictions, tracing or monitoring can be limited in a small area.

2.2.1.2 Types of RFID Tags

There are three types of RFID devices in the literature, which are passive, active, and semi-passive tags. They have different capabilities, communication ranges, and usage areas. Although they have different capabilities, RFID tags generally have very small read-only or read-write memory in their circuitry, and they hold their ID with other system-related information. The main factor which affects the communication ranges of the RFID tags is whether they have an internal power source. However, the surrounding environment and interference have an important effect on the communication ranges of the RFID tags.

Passive tags do not have any power source and which means they are batteryless devices. They also do not have a transmitter; instead, they use the reader's electromagnetic fields in their internal circuitry to send the information back to the reader. Therefore, passive tags are the cheaper RFID tags. The message which was sent from the RFID tags generally includes only the unique ID of the tags, and in some cases, it may include the manufacturer or other relevant information with the ID.

Active tags have their internal power source and a transmitter. Thus, their capability is higher than the passive tags'. Because they do not use the readers' electromagnetic fields, they can send a signal by themselves to the reader, and their communication range is higher than the passive tags' communication ranges. They also use their internal power source in their circuitry.

Semi-passive tags have their internal power source, like active tags. However, they do not have a transmitter like passive tags. Therefore, they use backscattering to send their signals to the reader and use the power source for their internal circuitry. In other words, while the communication is powered by the reader, the circuitry is powered by their internal power source in the semi-passive tags.

2.2.2 Tag-to-Tag Communication

As can be understood from the name of the RFID, the main purpose of RFID systems is to detect, track or identify the objects, animals, or humans to which RFID tags are attached. The reason is that RFID tags can only communicate with their readers in ordinary RFID systems, and in this case, they are not capable of accomplishing more tasks.

In the study published in 2012, it was proved that tags can communicate with each other [6]. This novel study actually changes the capabilities of the tags broadly. When tags can communicate with each other, tags do not have to be responsible for only identifying, tracking, or detecting tasks. On the other hand, there are many technological devices that can communicate with each other. Therefore, as the next step, we ask the question of why we need to use the tags to communicate. The answer is the main and the most important advantage of the tags. If the passive tags are used in the communication, there is no need to use the batteries anymore. Another advantage is the cost of producing a tag is inexpensive, and tags are cheap products with respect to other products that can be used in communication networks. Moreover, tags are small electrical devices that can be attached to many objects easily, or they can be used as an accessory. Therefore, for green energy and energy-efficient communication, realizing tag-to-tag communication is very important.

In our proposed routing protocol, instead of focusing on the architecture of the passive tags, we concentrate on presenting a complete system design that realizes multi-hop tag-to-tag communication. The architecture of the employed passive tags in our study is determined by following the studies in the literature. The chosen and proven passive tag architecture is shown in Fig. 2.1. The communication range of the passive tags is another problem that is considered in the literature. As stated by Stanaćević et al. [2], the range of the communication between a passive tag and the exciter relies on the excitation power that is provided to the passive tag. Additionally, they showed that the transferred data rate and communication range is inversely proportional to each other. However, with the improvements in the components of the passive tags or the techniques that are used in the transmissions, the communication range of the passive tags can be improved. In one of the most impactful studies in the literature,

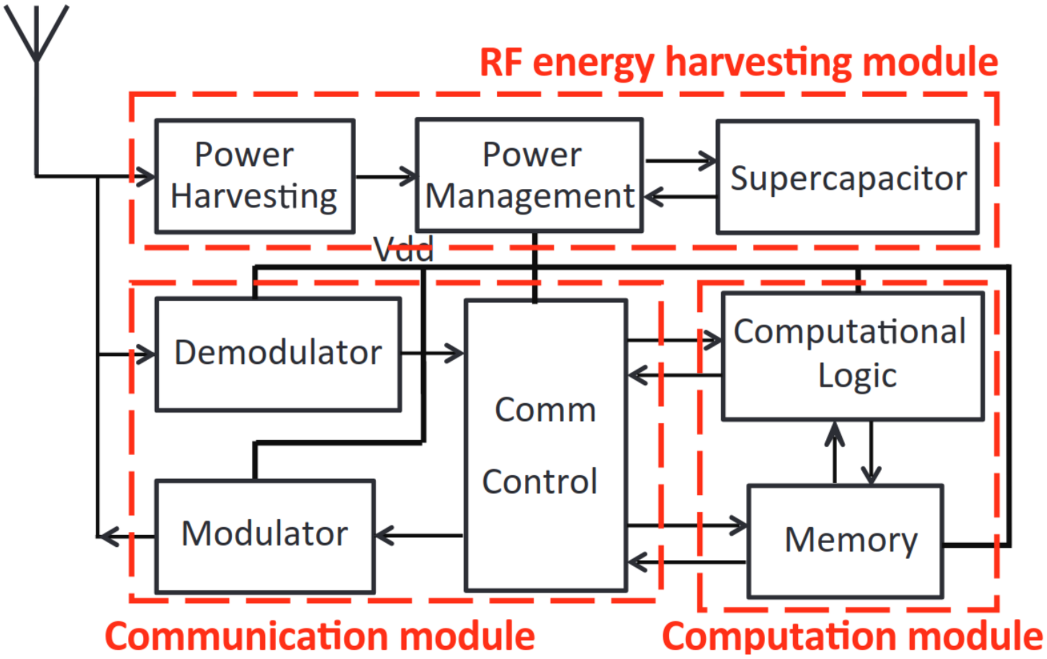

Figure 2.1: The architecture of the passive tags used in our protocol is presented [2].

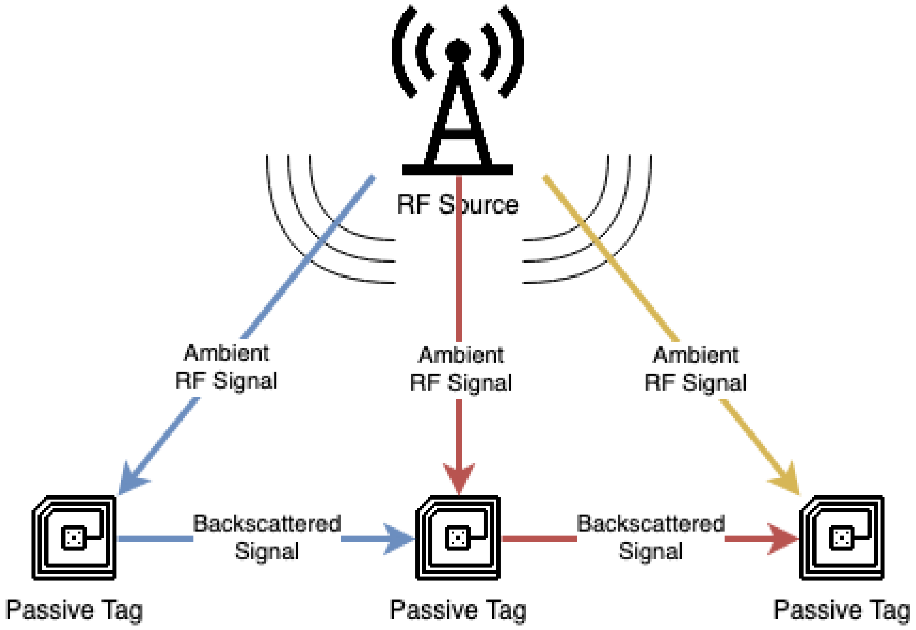

Figure 2.2: Tag-to-tag communication with ambient backscattering is illustrated.

Parks et al. [18] increased the communication range of the backscatter communication as mentioned previously by a multi-antenna cancellation design and a novel coding mechanism. Additionally, they have proposed that the communication range is increased up to 10 meters in their study with the decrease in the bit rates of the transmissions.

After realizing tag-to-tag communication, scientists have also presented another novel study that removes the dependency of the readers on the passive tags [17]. In ordinary RFID systems, RFID tags are activated and energized by the readers, as mentioned before. However, with the novel ambient backscattering technique, passive tags can be activated and energized with ambient RF signals, such as those broadcasted by the TV towers. Therefore, passive tags can run and send messages independently from the readers. With tag-to-tag communication and ambient backscattering, passive tags can communicate with each other as common communication devices in an energy-efficient way which is illustrated in Fig. 2.2.

2.2.3 Routing Protocol

Two devices can contact each other if they are in their communication range, and the resources used by the devices limit the communication range. As mentioned before, when we use UHF passive RFID tags, they can communicate with their reader if they are not more than 4-5 m far away. The same condition is valid for the devices that we use in our daily lives. On the other hand, two devices have to be connected even if they are not in their communication range. This problem is solved by routing, which is finding a path from the source to the destination in a network for the message through one or more devices. While the routing is interested in finding the path, forwarding is focused on transporting the packets on the determined routing path. The Internet is the best example that can be shown for routing.

To route the packet successfully from the destination to the sender, devices on the routing path should agree on a protocol. With a protocol that is agreed on, the routed packet can be meaningful to other devices. In addition, there must be extra information with the data in the packets, and the information should be in the previously determined protocol format. Devices that agree on the same protocol can communicate with each other by routing through other devices, even if they are not in their communication range.

There are many routing protocols proposed in the literature for different types of networks, such as wireless sensor networks. These protocols will not be explained in detail in this chapter. However, routing protocols can be categorized from different perspectives. For example, they can be designed for mobile networks, or the networks have stationary devices. Moreover, the designed network can be managed by a central controller, or each node in the network can decide the routing path by itself without a central controller.

CHAPTER 3

MULTI-HOP ROUTING PROBLEM IN TAG-TO-TAG NETWORKS OF PASSIVE TAGS

After the capability of passive tags was enhanced to be able to communicate between tags, the passive tags can be a part of our daily lives as other communication devices in the near future. However, there are still some problems to overcome in tag-to-tag networks of passive tags. The passive tags' communication range is relatively short with respect to the other communication devices because of their batteryless environment. Therefore, it is essential to create a well-designed routing protocol that has multi-hop capability in tag-to-tag networks. In this chapter,

- the multi-hop tag-to-tag problem,
- the constraints and limitations that should be considered to create a routing protocol,
- why the existing routing protocols cannot be applied,

are explained in detail.

The batteryless environment of the passive tags has some disadvantages besides many advantages. As shown in Fig. 3.1, multi-hop tag-to-tag communication with only an external RF source can be realized by meeting some requirements. The energy efficiency of the network is improved with respect to the common communication networks because only the RF source needs to be connected to power in the system. When passive tags need to communicate, they should be energized to be activated by the RF source. Therefore, the system should be designed so that passive tags should be energized only when it is required.

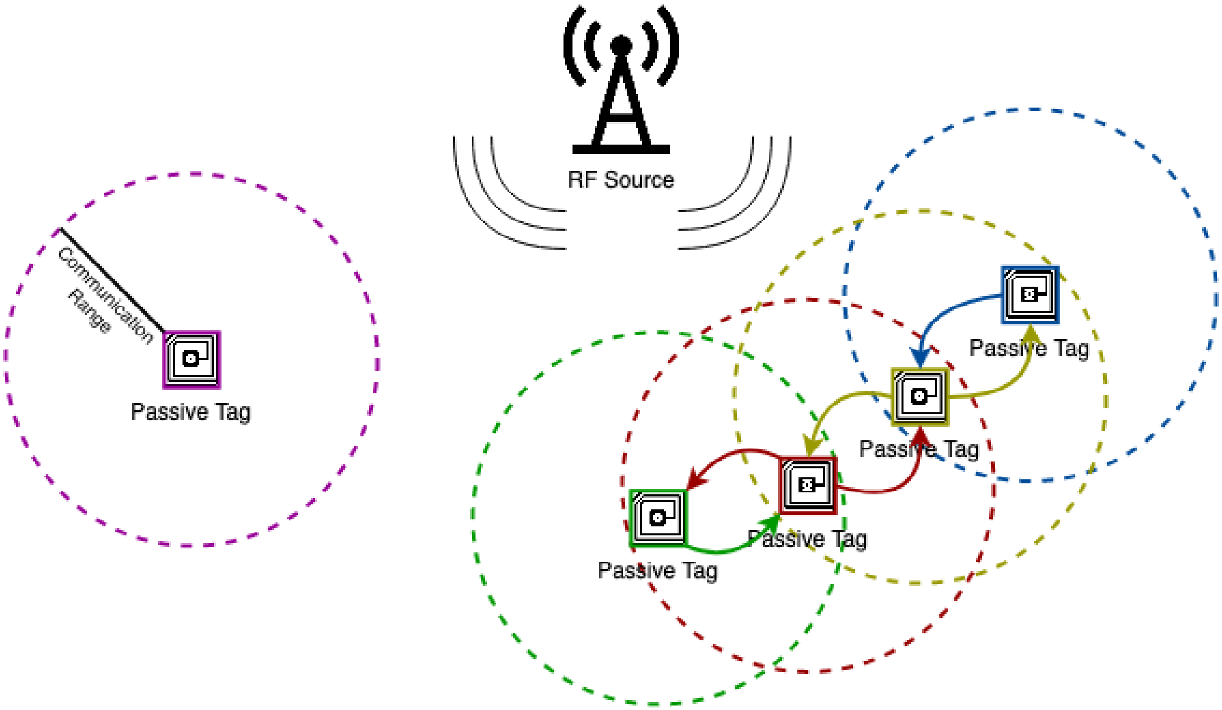

Figure 3.1: Multi-hop tag-to-tag communication between passive tags is illustrated.

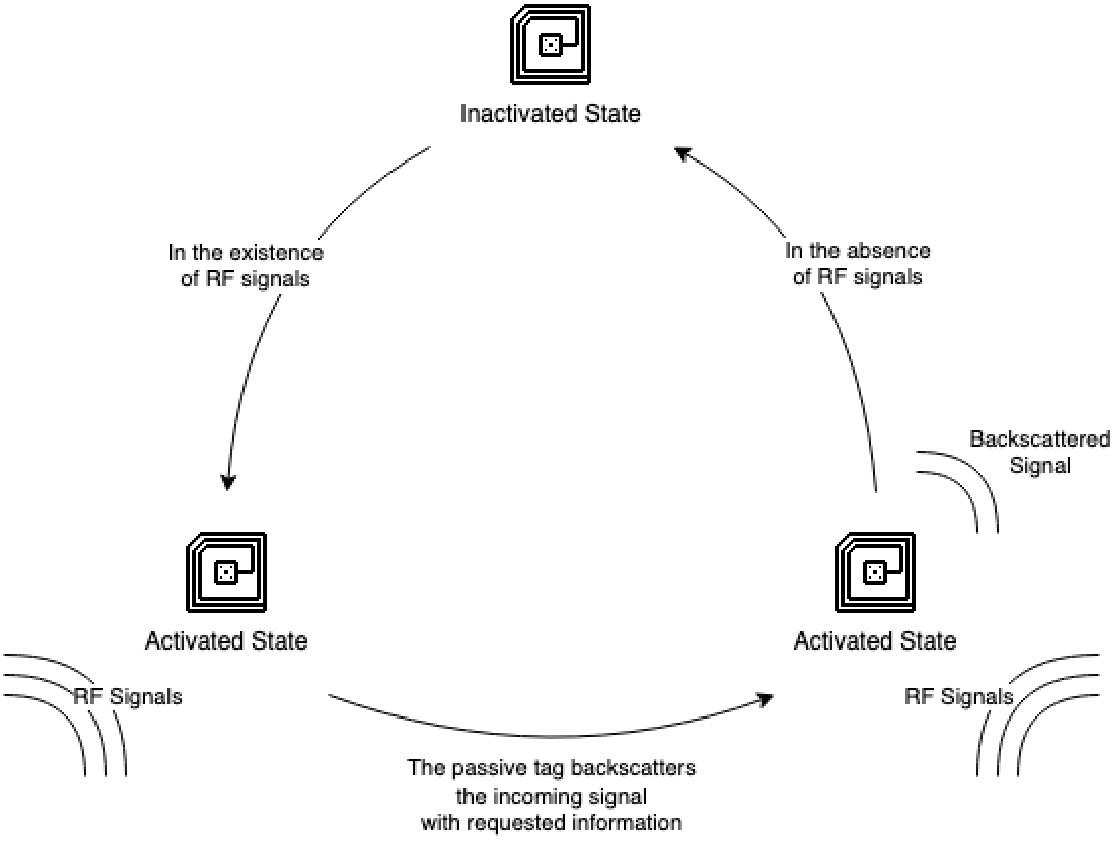

Figure 3.2: The working cycle of the passive tags is clarified.

The working cycle of the passive tags is represented in Fig. 3.2. Without the existence of external RF signals, passive tags are in the inactivated state, and they are not ready to communicate. When external RF signals are supplied, the RF signals activate the internal circuitry of the passive tags. With a previously designed routing protocol, if the incoming signals carry information, this information can be read by the passive tags. Then, the passive tags backscatter the incoming RF signals with the requested information. Because the incoming RF signals excite the passive tags, these signals can be named excitation signals. When the excitation signals are absent, the passive tags turn back to the inactivated state again. Then, they wait for the new excitation signals to be activated again when it is required.

Considering the energy efficiency limitations, passive tags have limited power for their internal circuitry. Even though there are sensor RFID tags presented in the literature, these types of tags have their own chip design to read and transmit the sensor data. On the other hand, the design of the passive tags that can communicate with each other can have limited components connected to them. As mentioned before, the main reason is that they are batteryless devices, and they cannot provide energy to many types of components. If the connected component's energy requirement is remarkable, the component cannot take place in the passive tags' design. For example, tags cannot have GPS chips in their circuitry. This indicates that the exact coordinates of the passive tags' cannot be determined by the RF source or the passive tag itself. Therefore, while designing the routing protocol, it should be considered that the passive tags' exact coordinates should be unexplored in the entire system.

As another limitation due to power constraints, passive tags have limited processing capability. Although the computational capabilities of the passive tags are enhanced by the studies in the literature, the energy that is harvested from the RF source is still limited for many computational tasks. On the other hand, in many of the routing algorithms proposed in the literature, the nodes in the network have tasks that require significant power to route the packet from the sender to the receiver. However, passive tags are not capable of performing these types of computational operations, such as creating a routing path or deciding which node should be the next on a routing path. They can backscatter a signal and receive a backscattered signal due to the nature of passive tags, as expected. Moreover, they can also perform some lightweight computational operations, such as reading the incoming message or comparing a value from the incoming message with a constant value. Therefore, while developing the routing protocol, the responsibility of a tag in the system that has multi-hop tag-to-tag communication capability must be as limited as possible.

Due to their origin in conventional RFID tags, passive tags have their own memory in the internal circuitry. However, the size of the memory cannot be in megabytes, they can have kilobytes sized memory. In addition, they can perform read and write operations on their restricted memory. Thus, the stored data in the passive tags' memory is restricted, and the storage capacity should be used efficiently in the routing algorithm.

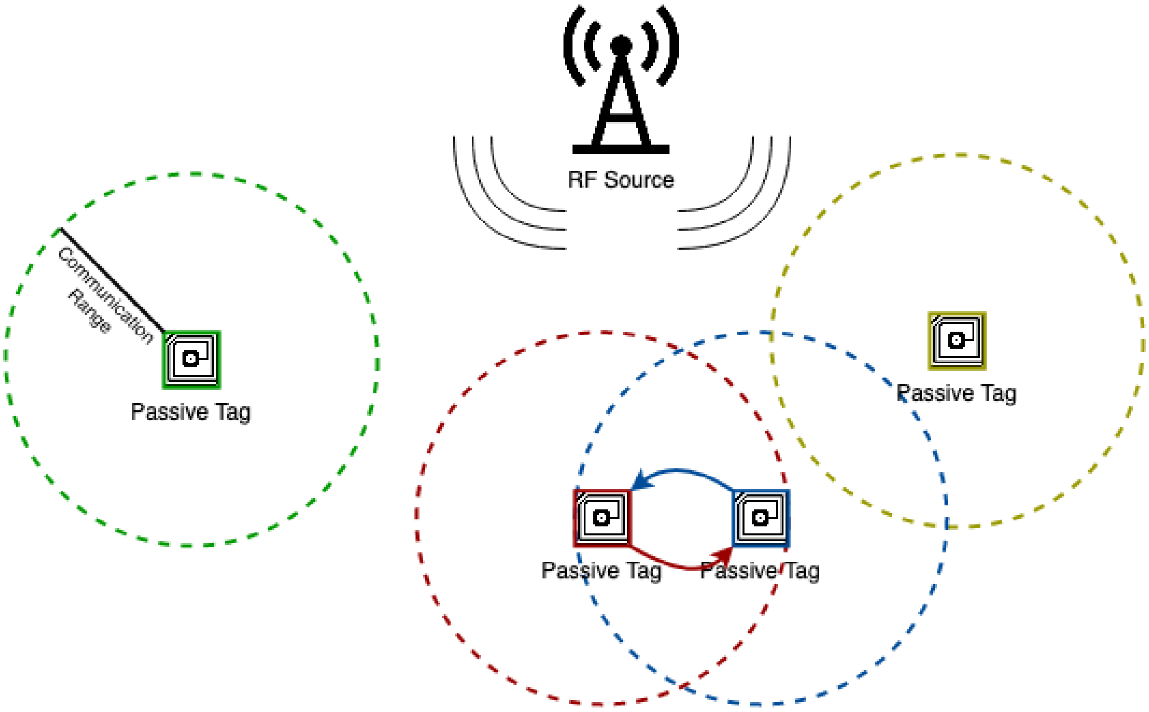

Figure 3.3: Tag-to-tag communication between passive tags is illustrated.

The main purpose of designing a routing protocol for a communication network is to increase the reachability of the nodes in the network. With respect to the typical devices that are used in communication networks, passive tags have a shorter communication range. They can backscatter the incoming signal in only a limited range; therefore, they can communicate only with the other tags that their backscattered signal is reached, as shown in Fig. 3.3. Thus, a well-designed routing protocol is required for passive tag communication networks more than other types of networks.

This is actually the main motivation to realize multi-hop communication among the passive tags. Without a routing protocol, tags can communicate only with the other tags in their relatively short range, which is one of the most important obstacles to making passive tags commercial products.

Passive tags cannot detect their exact coordinates or the coordinates of the neighbor tags, as mentioned previously. Therefore, passive tags can only backscatter the incoming signals by placing a message into them without knowing the receivers of the signal. In other words, they send their packets blindly by backscattering the incoming signal from the RF source. As an advantage, in conventional RFID technology, RFID tags do not require the line of sight communication. Passive tags retain the same principle, and sender passive tags do not have to determine the direction of the receiver passive tags according to themselves. Simply, passive tags propagate the backscattered signal in their communication range, as can be seen in Fig. 3.3.

In the literature, there are two approaches to excite the passive tags. The first one is to use the ambient backscattering technique, and the second one is to use a predetermined RF source, which is permanent and steady, to excite the passive tags. In both of the approaches, passive tag-to-tag communication is achievable. In the first technique, which is ambient backscattering, instead of using the RF signals that were propagated from a predetermined RF source, the ambient RF signals are preferred. Ambient RF signals are also propagated by the RF sources, such as TV towers, as in the second technique. However, unlike the second technique, the main purpose of these signals is not to excite passive tags, and these signals are around us continuously, although we do not realize them. The ambient backscattering technique was proved by Liu et al. [17] in 2013, and the passive tags design, which was presented in this study, supports tag-to-tag communication. Therefore, while designing the routing protocol, passive tags that use ambient RF signals to communicate with other passive tags can be chosen. In the second approach, tag-to-tag communication can be realized by the passive tags, which are excited by predetermined RF sources. By a predetermined RF source, it is implied a stationary RF source whose main task is to excite the passive tags within its range. Passive tag-to-tag communication with a steady RF source in the environment was proved in the literature earlier than ambient backscattering by Nikitin et al. [6] in 2012. Different from the approach that uses ambient backscattering, this approach is less energy-efficient because the on-purpose RF source is a supplementary device that requires power continuously. Additionally, the second approach is more restrictive because only the passive tags, which are in the communication range of the RF source, can be activated. On the other hand, in the ambient backscattering, if there is any ambient RF signal in the environment, passive tags are activated and ready to communicate. However, ambient RF sources are not as reliable as permanent and steady RF sources. As explained before, the main task of predetermined RF sources is to excite the passive tags in their range when it is required. On the other hand, RF signals might not exist in any circumstances in ambient backscattering, or the power of the ambient RF signals might not be enough as always. Therefore, ambient RF sources cannot be accepted as stable RF signal providers for the passive tags.

Another concern in the multi-hop tag-to-tag routing problems is whether there should be a central controller to manage packet routing from the sender to the receiver or not. In other words, the main question is whether the chosen routing algorithm should be centralized or not. To find an answer to this question, we should consider the computational capability of the passive tags. If passive tags conduct the routing by themselves, there should not be a need for a centralized routing algorithm. If a centralized routing algorithm is chosen for the multi-hop tag-to-tag communication, the central controller should have some capabilities to manage the system. First of all, it should determine the routing path and the approximate locations of the passive tags. The main consideration while determining the routing path should be the energy efficiency of the communication. After deciding the routing path, the central controller should assist the passive tags while they send their messages in a multi-hop way. If a centralized routing algorithm is chosen, another question which is whether the central controller should also be the RF source or the passive tags should be excited by ambient RF signals, should be considered. Therefore, the solution for the multi-hop passive tag-to-tag communication can be categorized into three design alternatives, as shown in Fig. 3.4.

- The option where the ambient RF source is chosen and the central controller is not used.

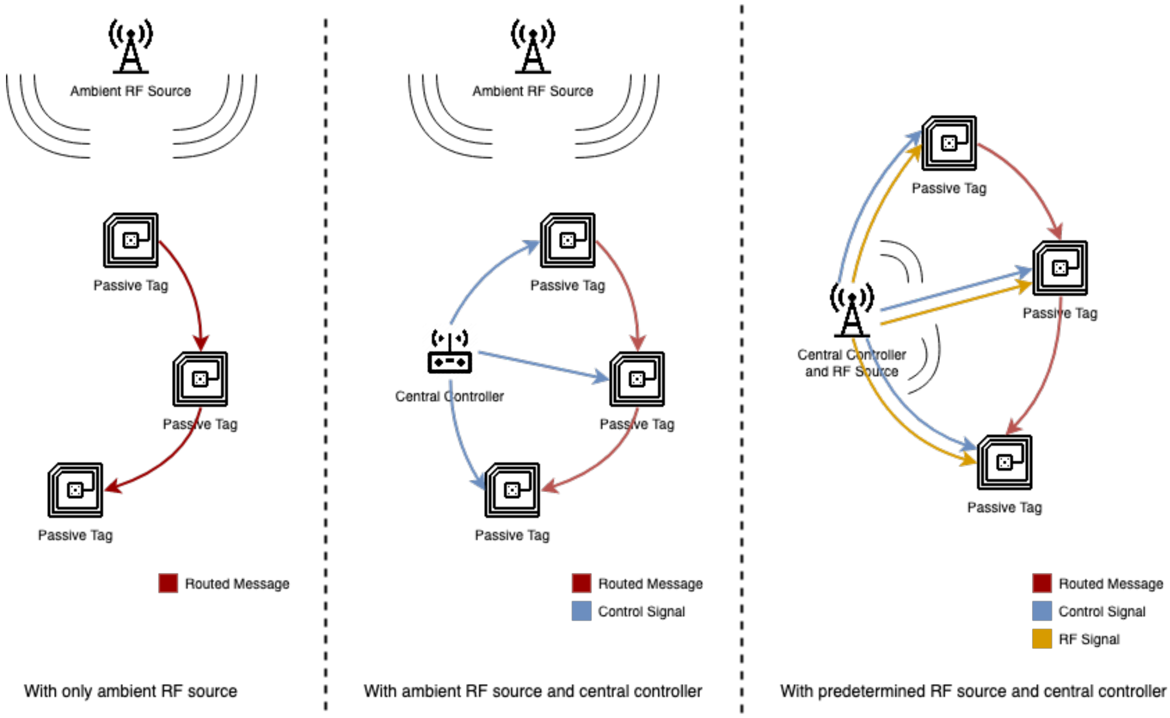

Figure 3.4: Three design alternatives for multi-hop passive tag-to-tag communication are described.

- The option where the ambient RF source is used with the existence of the central controller.
- The option where the central controller is at the same time the RF source of the system.

In the first option, the ambient RF sources are chosen to excite the passive tags for tag-to-tag communication. Because there is no central controller in this design, passive tags should determine the routing path or where to forward the packets by themselves. The main problem in this design is that the computational capabilities of the passive tags are very limited. Additionally, the ambient RF sources are not reliable as predetermined RF sources, as mentioned before, and the absence of the RF signals may cause interruptions in the routing path. Therefore, a routing algorithm that is based on flooding or random walk techniques can be preferred, or a lightweight routing algorithm can be developed.

In the second option, the ambient RF sources are chosen to excite the passive tags for tag-to-tag communication, as in the first option. Different from the first option, the routing path is determined by the central controller instead of the passive tags. However, the same problem, which is about the unreliability of the ambient RF sources, is also valid in this option. In the case of the absence of RF signals, the routing path might be incomplete. Therefore, the central controller should take into account the absence of RF signals. On the other hand, the cluster head cannot run with the ambient RF sources collaboratively because of the nature of the ambient RF sources. Thus, a routing protocol can be developed so that the cluster head should regulate the routing path according to the existence or the absence of the ambient RF signals.

In the third option, instead of using ambient RF signals, passive tags are excited by a predetermined RF source, which is also the central controller of the network. By assigning the RF source responsibility for the passive tags to the central controller, the central controller can regulate the RF signals by itself instead of a collaborative run with the ambient RF source. In other words, the central controller should create the routing path and provide the RF signals to the passive tags at the same time. Moreover, it can energize the passive tags by following the routing path only when it is needed because the central controller knows which of the passive tags should be excited and creates the routing path, and therefore it can excite only the required passive tags when it is needed. Unlike using ambient RF sources, in this approach, the activation of the passive tags can be regulated by the central controller, and it is a reliable RF source. As the negative side of this design choice, first of all, the borders of a cluster should be determined by the communication range of the central node. Another one is that the central controller cannot know the exact locations of the passive tags, as mentioned previously. Therefore, an energy-efficient algorithm, where the approximate locations of the passive tags are known, can be developed, and under the authority of the central controller, passive tags can communicate with each other by routing the packets.

Due to the explained limitations in the routing protocol design, especially restrictions from the passive tags, the routing protocols in the literature cannot be applied for multi-hop tag-to-tag networks of passive tags. In many of the existing routing protocols, nodes need to have a significant computational capability. These algorithms cannot be applied because of the limitations of the passive tags. In some other routing protocols, networks are divided into subnetworks by assigning a node as a cluster head. In these cases, cluster heads manage the subnetworks by knowing the nodes under their responsibility. These algorithms may be applied; however, the cluster head should be a node that has improved capabilities. On the other hand, the cluster head cannot know the passive tags that are under its responsibility. Finally, a well-designed and energy-efficient routing protocol is required to be developed for the tag-to-tag networks of passive tags, which support multi-hop communication.

CHAPTER 4

MULTI-HOP TAG-TO-TAG ROUTING PROTOCOL WITH STATIONARY PASSIVE TAGS IN SECTORAL CIRCULAR AREA

In this chapter, we present our novel protocol design in detail with implementation and design decisions. By considering the problem definition in Chapter 3, we created a multi-hop tag-to-tag routing protocol for networks of passive tags. The main purpose of designing a routing protocol for networks of passive tags is to improve device-to-device communication's energy efficiency by exploiting the passive tags' batteryless environment. With a proper and applicable multi-hop routing protocol, passive tags can be used in daily communication tasks, and today, it is very critical for our world.

In our system design, we chose passive tags that do not have an internal power source. In other words, they are batteryless devices, and a passive tag can send a message to another passive tag by using backscattering. Tag-to-tag communication was proven in the literature previously [5], [6], and the passive tags that we use in our system are capable of communicating with each other as described in Fig. 3.3.

By taking into consideration the positive and negative sides of the design alternatives described in Chapter 3, we prefer to use a central controller, which is the RF source of the system at the same time. Although choosing the central controller having RF source capability requires an external setup and power, it gives us full control over the system to apply the routing protocol in a reliable manner. The reasons are explained in detail by comparing our choice with the other alternatives in the following.

- Ambient RF signals are not dependable for the entire system. By using the ambient RF signals, the passive tags might not be activated when it is required, or non-required passive tags might be activated in the system, which creates additional and unwanted routing paths.

- Specifying the borders of the circular area with the central controller might be seen as a negative aspect of our choice. However, it is actually an advantage to control the communication in the circular area of the central controller. The passive tags that are outside of the circular area can send signals to the passive tags that are inside with the existence of the ambient RF signals. By determining the borders of the circular area, the passive tags outside the circular area cannot communicate with the passive tags inside the circular area because they are not activated by any central controller.
- Considering the internal processing capability of the passive tags, they cannot create a routing path by using the algorithms explained in the literature without a central controller. Therefore, a central controller is required to apply the routing protocol for the communication between the passive tags.

The main objective of designing a multi-hop routing protocol is to communicate the passive tags that are outside of their communication range. It is crucial to realize the multi-hop transmission for the network of passive tags to use these devices commercially for device-to-device communications.

One of the main design questions of the routing protocol is whether the passive tags that are employed in our routing protocol should be mobile or stationary. We prefer to use the stationary passive tags by considering some design concerns. As the passive tags have no internal power source, they do have any component in their internal circuitry to determine their exact location, such as a GPS module, as mentioned previously. Thus, the designed algorithm should operate under the circumstances of having no knowledge about the exact locations of the passive tags. Although the exact location of the tags cannot be known, we can determine the approximate location of the tags with some techniques, such as determining whether they are in a limited area. Additionally, choosing the mobile passive tags implies that their location can change non-deterministically. Therefore, by not knowing the exact location of the passive tags and determining their approximate location of them in an error-prone way, if we choose the mobile passive tags in our protocol design, it means that we have no knowledge about the locations of the passive tags completely. In total, without having any knowledge about the locations of the passive tags, the routing path cannot be determined in our protocol design. In addition, realizing the multi-hop tag-to-tag communication is a recently focused research area. The routing protocol design for the networks of stationary passive tags can be accepted as a starting step, and the mobile passive tag-to-tag networks can be analyzed as the next phase in this research area.

4.1 Sectoral Circular Area Design

In this section, our sectoral circular area design that is created with our novel multi-hop tag-to-tag routing protocol for networks of passive tags is explained in detail with the main motivation to prefer a circular shape design instead of other possible alternatives, such as rectangular or square-shaped designs.

In our routing protocol, the central controller assists the multi-hop tag-to-tag communication by exciting the required sectors, which are the subparts of the area. Dividing the circular area into beams and levels is more applicable and realistic by considering the signals propagated by the central controller's antenna. By controlling the power of the central controller, the signals propagated by the central controller can reach a certain distance. This creates a circular shape where the central controller is placed in the center, and the maximum distance of the central controller according to the power of propagated signals is the radius of the coverage area circle. Therefore, by changing the power of the signals, the circular area can be divided into levels practically and realistically. By propagating the signals at certain angular portions, we can easily signalize the determined beams of the circular area. Considering the maximum reachable signal distance of the central controller, we can determine the maximum communication range of the central controller in a realistic way. In the case of more than one central controller, they can create their own clusters bordered by the maximum communication distance of the central controllers.

The developed sectoral circular area design and the visual explanations of the technical terms can be seen in Fig. 4.1. We divided the circular area into a grid-like structure

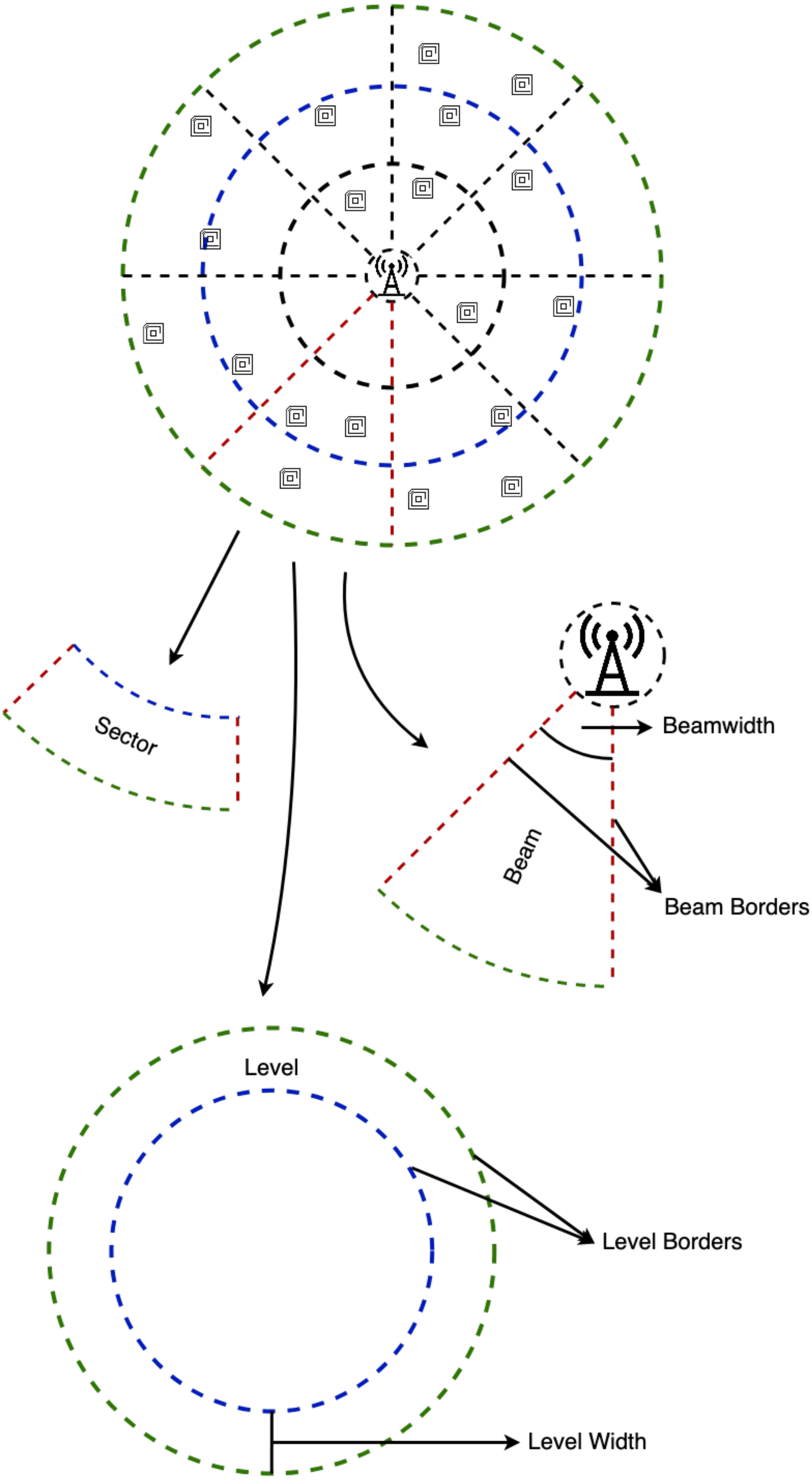

Figure 4.1: The proposed sectoral circular area design is explained in detail.

consisting of levels and beams. Our method of dividing the circular area into levels and beams serves several purposes. In addition to allowing us to maintain a rough estimate of the tag's position without the need for precise location information, the structure also enables us to easily assist the passive tags to communicate with each other within the communication range of the central controller. While the beamwidth is defined as the angle of a beam, we enumerated the beams in the clockwise direction starting from the top right, as can be shown in Fig. 4.2. Likewise, levels can be determined with the direct distance through the central controller, and the level width is the interval between the two consecutive levels. We enumerated the levels, and the number of levels increases as you move away from the central controller, which can be seen in Fig. 4.3. Each intersection area between the beams and levels is called a sector. We use this sectoral structure to assign a passive tag to a specific sector because we cannot specify the exact location of a passive tag in the communication range of the central controller. Instead of determining the exact location of a passive tag, we can decide on the sector the passive tag belongs to. Overall, the use of a sectoral structure greatly improves our ability to manage the communications of the passive tags within the network.

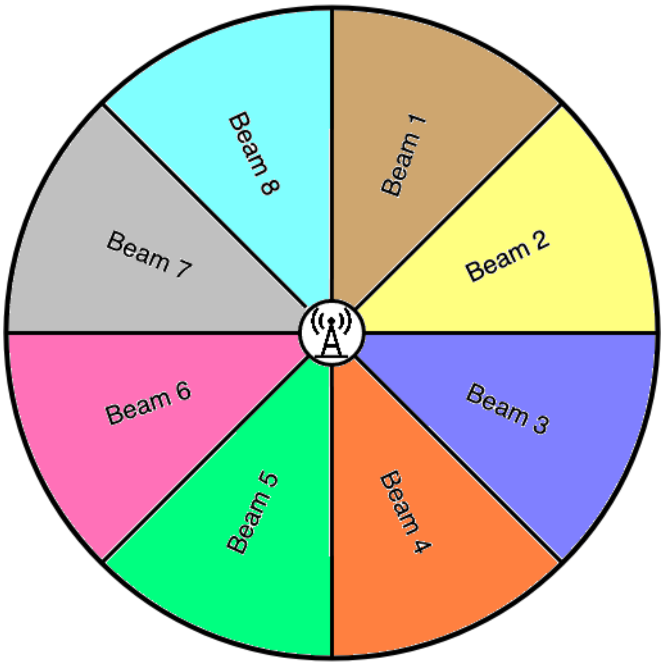

Figure 4.2: The example enumeration of the beams in the circular design is presented.

In order to distinguish a sector from a different one, we use the level and beam in-

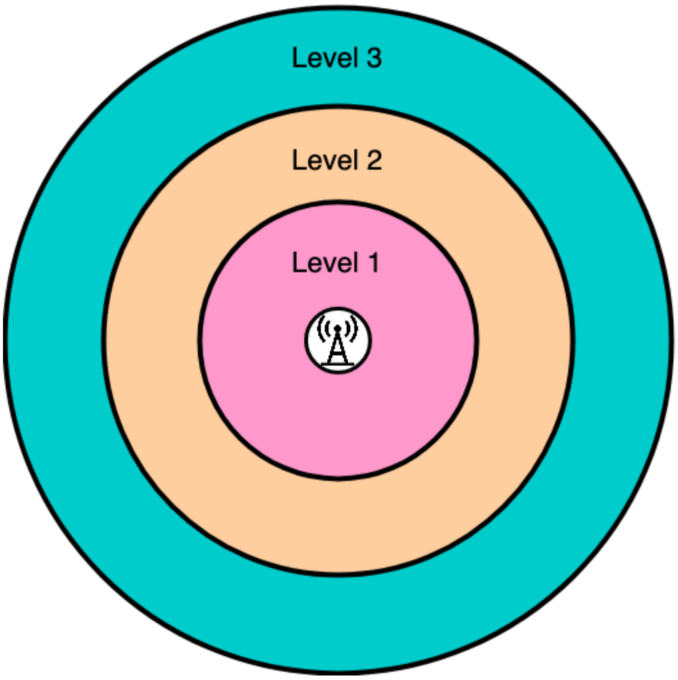

Figure 4.3: The example enumeration of the levels in the circular design is presented.

formation of the sector. Since each intersection of a different beam and level creates a sector, we can uniquely identify a sector with its beam and level number. This identification is actually very similar to the location determination of a point in the two-dimensional coordinate plane. In a two-dimensional coordinate plane, while a point can be identified by its x and y coordinates, in our circular design, a sector can be identified by its beam and level numbers. Considering the example shown in Fig. 4.1, there are three levels and eight beams, and in this case, we can uniquely identify twenty-four sectors by their beam and level numbers. Therefore, each sector has its own unique ID, which is determined by the beam and level number of the sector. In detail, we concatenated these values in the order of level number and beam number. It has many advantages in creating the routing path between the sender and receiver sectors. By knowing only the ID of the sector, we can also find out which level and beam intersection the sector is. Additionally, the sender and receiver sectors can be specified by the sender and receiver passive tags' belonging sectors.

Diving the circular area into sectors and determining the sector of a passive tag by the central controller have important advantages in our system design. If a passive tag is to be excited, instead of the entire area, we can only excite the tag's belonging sector and, therefore, activate the passive tag. We can excite the intended sector area by controlling the direction of the central controller's antenna and the transmit power. On the other hand, when the central controller excites a sector, all passive tags in the sector area are excited and ready to communicate.

In our system design, we prefer using binary values instead of decimals. As mentioned previously, each sector has its unique ID, determined by the beam and level number of the sector. We store these values in base-2 format instead of base-10 format; in other words, we represent these values in binary format. We decided to convert these numbers to base-2 format because while creating a routing path or comparing two ID values, having numbers in base-2 format facilitates our job significantly. Moreover, passive tags are also identified by their unique ID values, which were given in the producing step by the manufacturer. We design in a way that these values are also stored in binary format. This design choice simplifies the computation steps inside the passive tags.

The sector count of our system design depends on two variables which are beamwidth and level width value, as can be seen in Fig. 4.1. The determination of these values is one of the most important steps for our routing protocol. The reason is that they directly affect the success rate of tag-to-tag communication. Because we applied a flooding-based routing algorithm inside the sectors, which will be explained in the next section, the sector size and the passive tag count in a sector are influential parameters while routing a packet from one sector to another sector. These values should be chosen optimally to get the best tag-to-tag communication success rate, which is our design's main trade-off. We have considered the following concerns to find the optimal beamwidth and level width values.

- If the sector count is more than the optimal value, the sector size and the passive tag count per sector are reduced, with the increased possibility of having a sector that does not consist of any passive tag. The advantage of this alternative is that the number of unnecessary communications in a sector is decreased because the flooding-based algorithm is applied inside the sectors. On the other hand, the routing path is created with consecutive sectors, and a packet cannot be routed by a sector if the sector does not consist of any passive tag. Therefore, having smaller-sized sectors increases the possibility of disconnectivity in a determined routing path by increasing the possibility of having a sector that does not consist of any passive tag. There is actually another advantage of increasing the sector count, which is about the internal connectivity of a sector in the routing path. With the smaller-sized sectors, the possibility of connectivity between the passive tags in a sector is increased. Considering the main purpose of the routing protocol is to create a connected path between the sender and receiver passive tags, the internal connectivity of a sector has an important effect on the total routing path connectivity.

- If the sector count is less than the optimal value, the sector size and passive tag count per sector area are increased. In this case, the internal sector connectivity, which has an important effect on the connectivity of the total routing path, is decreased. In other words, the possibility of having a disconnected routing path is increased because the internal connectivity of a sector is decreased. By creating bigger-sized sectors, we have more unnecessary communications in a sector because the flooding-based algorithm is applied inside the sectors. On the other hand, with the same number of passive tags in the system, having a sector that does not consist of any passive tag is decreased significantly, which directly reduces the possibility of creating a disconnected path. Additionally, the number of consecutive sectors for a routing path that should be passed is decreased because we have bigger sectors, which decreases the possibility of a disconnected routing path. Considering the energy efficiency of the overall routing path, although the sector count that should be excited in the routing path is less, the sector sizes are bigger, and exciting a bigger-sized sector requires more power with respect to a smaller-sized sector.

Deciding the optimal sector size in our routing protocol design is the most challenging part of our study. By considering the trade-off explained previously, we specified two formulas to determine our systems' beamwidth and level width values. The reason that makes this decision step the most challenging part of our study is that the central controller cannot know the passive tag count in its communication range. The central controller can only utilize the communication range of passive tags and its own communication range as parameters. By taking into consideration the trade-off,

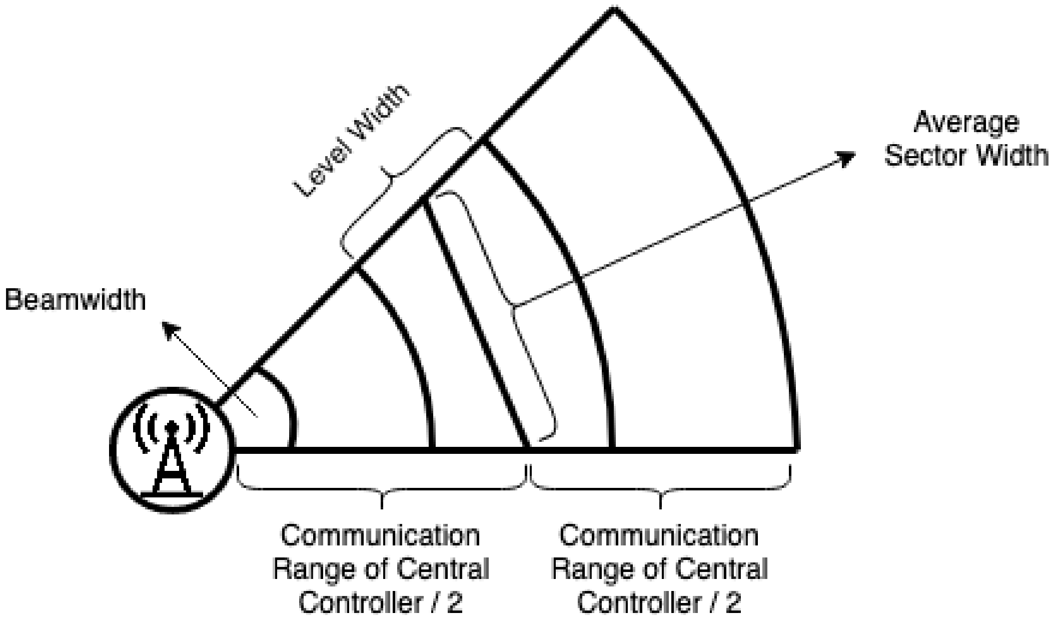

Figure 4.4: The level width and average sector width is described.

we try to find an optimal value between the communication range of a passive tag and the central controller, and the founded optimal value should be assigned to level width (w_l) and average sector width (w_s) as shown in Fig. 4.4. Therefore, we have used the following formulas to calculate the beamwidth degree (w_b) and level width (w_l) value by using the communication ranges of the passive tags (r_t) and the central controller (r_c).

In the first step, we determine that the level width (w_l) and the average sector width (w_s) should be equal, and the value assigned to them can be calculated with the following formula.

$$w_l = w_s = \log_2(r_t \times r_c)$$

The level width (w_l) can be found directly with the shown formula; however, the beamwidth value is the angle in degrees and can be found by applying the cosine theorem in the triangle as shown in Fig. 4.5.

After the application of the cosine theorem, we can find the beamwidth degree; however, the beamwidth should be divided by 360 degrees without any reminder because the area of each sector on the same level should be the same. Therefore, a temporary

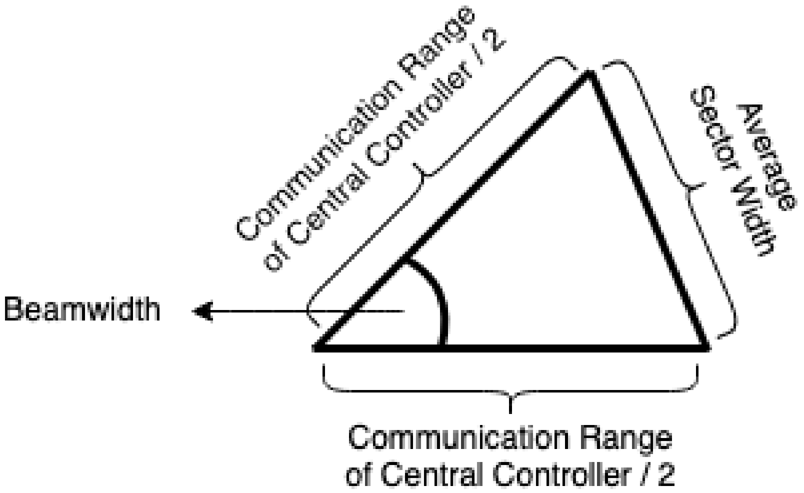

Figure 4.5: The cosine theorem is applied in the triangle.

beamwidth (w_{tb}) is chosen as degrees at first. Then, the sector count per level (c_s) of the system, which should be an integer value, is calculated with $c_s = \frac{360}{w_{tb}}$ by rounding up the result after division. Because the founded sector count per level (c_s) is an integer, after dividing it by 360, we can find the final beamwidth degree with $w_b = \frac{360}{c_s}$. The level count of the system can be found with $c_l = \frac{r_c}{w_l}$ by rounding up the result after division directly, and all of the levels do not have to be in the same level width. Our system is designed in a way that the level width of the last level can be smaller than the determined level width (w_l). Additionally, all of the rounding operations in the calculations are protected against precision loss while developing our system design.

In total, the beamwidth degree (w_b) and level width (w_l) value can be calculated with the direct relation of the communication range of the central controller and passive tags. Afterward, using the calculated beamwidth degree (w_b) and level width value (w_l), level count (c_l) and sector count per level (c_s) values can be specified. Finally, the total sector count of the system can be calculated by multiplying the level count (c_l) and sector count per level (c_s) values, and we can construct the circular design in Fig. 4.1.

4.2 Routing Path Determination Algorithms

With the sectoral circular area design, we have defined the background structure of our protocol design. By utilizing the sectoral circular area with a central controller that is the RF source of the system at the same time, we created our novel multi-hop tag-to-tag routing protocol for the network of passive tags. With the routing protocol, we created two sectoral routing path determination algorithms that are RASSA and RASSD. We prefer to define it as the sectoral routing path since the central controller does not know the exact locations of the passive tag; instead, it determines the sectors on the routing path to excite. Although the working principles and design characteristics are different, the main objectives of these algorithms are to determine a sectoral routing path between the sectors of the sender and receiver passive tags by utilizing the same sectoral circular area design described in the previous section. In this section, we explain the design constraints and assumptions first. Secondly, we define the fundamental configurations that are used in the sectoral routing algorithms. Finally, we present the sectoral routing path determination algorithms, and to apply the path found by the algorithms, we propose an excitation algorithm of sectors in the path.

4.2.1 Design Constraints and Assumptions

Independent of the simulation environment we designed, we considered some constraints and assumptions while designing the proposed routing protocol. These are defined by considering the studies in the literature in order to create a realistic and applicable multi-hop tag-to-tag routing protocol. We created the entire system design by considering the constraints and assumptions explained in this section. Some of the constraints described in the following were explained previously in this chapter. These are mentioned in this section without explaining them in detail. Other constraints and assumptions, which were not mentioned previously, are described in detail.

As a design choice, the location of the passive tags is fixed, and they are stationary. Additionally, the central controller cannot know their exact positions in the sectoral circular area because passive tags cannot consist of any module that helps to determine their exact locations. Instead of determining their exact locations, the central controller can specify the sectors of some passive tags in which the passive tags are deployed. By exciting the specified sectors one by one and waiting for the response from these sectors, the belonging passive tags of these sectors can be determined. However, this method can be applied only if the central controller is in the excited passive tags' communication range. Therefore, the belonging sectors of the passive tags, which are in the limited range, can only be determined by the central controller. This method can be improved to determine the belonging sectors of the passive tags, which cannot communicate with the central controller directly. However, it can never be guaranteed that the sectors of all passive tags in the sectoral circular area will be detected by the central controller. Without knowing the exact locations or the deployed sectors of the passive tags, the total passive tag count in the sectoral circular area cannot be determined by the central controller. In total, the location of the stationary passive tags in the sectoral circular area is fixed; instead of the exact locations, the deployed sectors of some passive tags can be resolved by the central controller, and therefore, the initial passive tag count of the system cannot be determined.

In our sectoral circular area design, the central controller is always positioned at the center of the system, and the entire circular design with the sectors is created by taking the central controller as a reference point. The central controller knows all of the beams, levels, sectors, and their borders. If a sector is needed to be excited, the central controller can excite the specific sector area. By exciting the sector area, all of the passive tags deployed in the sector are excited and ready to communicate by backscattering the incoming excitation signal. Additionally, the central controller has another functionality, as it can send a message directly to a specific sector. In other words, the central controller can send a message to the passive tags in a specific sector besides exciting them.

Our main assumption is that the central controller can know the sender and receiver tag's sectors instead of their exact location in the routing path; however, it cannot know any other passive tag and their sectors. In addition to the sector information of the sender and receiver passive tag, the central controller also knows unique tag IDs of the sender and receiver passive tags. Therefore, the central controller can only determine the sectors to excite in a routing path without knowing the transmission will be completed from the sender tag to the receiver tag.

While deciding the routing path between two passive tags, our main principle is that the smallest area we excite the smallest energy we use. As we can see from Fig. 4.1, when the level increases, both the sector areas and the deployed passive tag count in this sector increase if we distribute the passive tags uniform randomly. If the number of passive tags increases, the hop count of communicating across the sector increases. Then, we should excite the sector for a longer period of time in the routing path. For example, comparing two sectors in the routing path, if the first sector's area is smaller and it has less passive tag according to the second sector, then there must be less transmission in the first sector with respect to the second sector in the routing path. Therefore, we can excite the first sector in a shorter period of time with respect to the second sector. Because of that, the total sum of the areas that we excite in the routing path must be the smallest in order to use the least energy.

While two passive tags are communicating directly, both of the passive tags should be excited by the RF source, and they should be in their communication range. With the existence of the excitation signals, passive tags can broadcast a message in the circular area whose radius is the communication range of the passive tags. In one-way communication, the sender passive tag sends the message by backscattering the incoming signal, and the receiver tag reads the incoming message successfully if there are excitation signals in the environment. In this case, while the sender passive tag requires the excitation signals for backscattering, the receiver tag requires the excitation signals to activate its internal circuitry and read the incoming message. After a passive tag in our system receives a message that was sent by another tag, the received packet can be opened and edited. The data in the received packet can be extracted and compared with some expected information, such as the unique passive tag id. Furthermore, it can be sent to another tag again with the existence of excitation signals produced by the central controller. In total, passive tags can use the excitation signals for two purposes, which are activating the internal circuitry or broadcasting a message by backscattering in their communication range.

4.2.2 Fundamental Configurations

To create a complete routing protocol for the networks of passive tags, we designed the required fundamental configurations for multi-hop tag-to-tag communication. Although the main focus in the routing protocol designs is on the creation of an efficient routing path, there are many regulations, configurations, and setups in the background to arrange proper communications between the nodes in the system. These configurations and regulations define the shared language used in the system so that every activity in the system can be performed in an expected and error-free way. Moreover, they specify the system limitations and abilities of every different component in the system. The agreed rules and regulations are valid and necessary to be used in the entire system which conducts the proposed routing protocol.

Considering the requirements of the routing path determination algorithms, two operating states for the passive tags are defined. In other words, if the passive tag is activated by the existing excitation signals, it can be in one of the two states, as shown in Fig. 4.6. The states of the passive tags are arranged by the central controller to make them route the messages properly, and these are explained in the following.

- Receive-Only State: In this state, the passive tag does not broadcast any signal and uses the excitation signals to receive incoming messages. If an incoming message is received by the passive tag, it adds the message to its message queue and does not process the incoming message. The message queue size is directly related to the internal memory size of the passive tags, which is determined by the manufacturer. When the queue becomes full, the incoming messages are added to the queue by removing the oldest messages in the queue. Additionally, to prevent receiving duplicate messages, passive tags check the message queue by comparing the incoming message ID with the IDs of the messages that are stored in the queue.

- Receive-Execute State: In this state, the passive tags are responsible for the same operations in the Receive-Only state. In addition to the operations in the Receive-Only state, passive tags fetch the message from the message queue first. To reach the messages that are received in the Receive-Only state, they

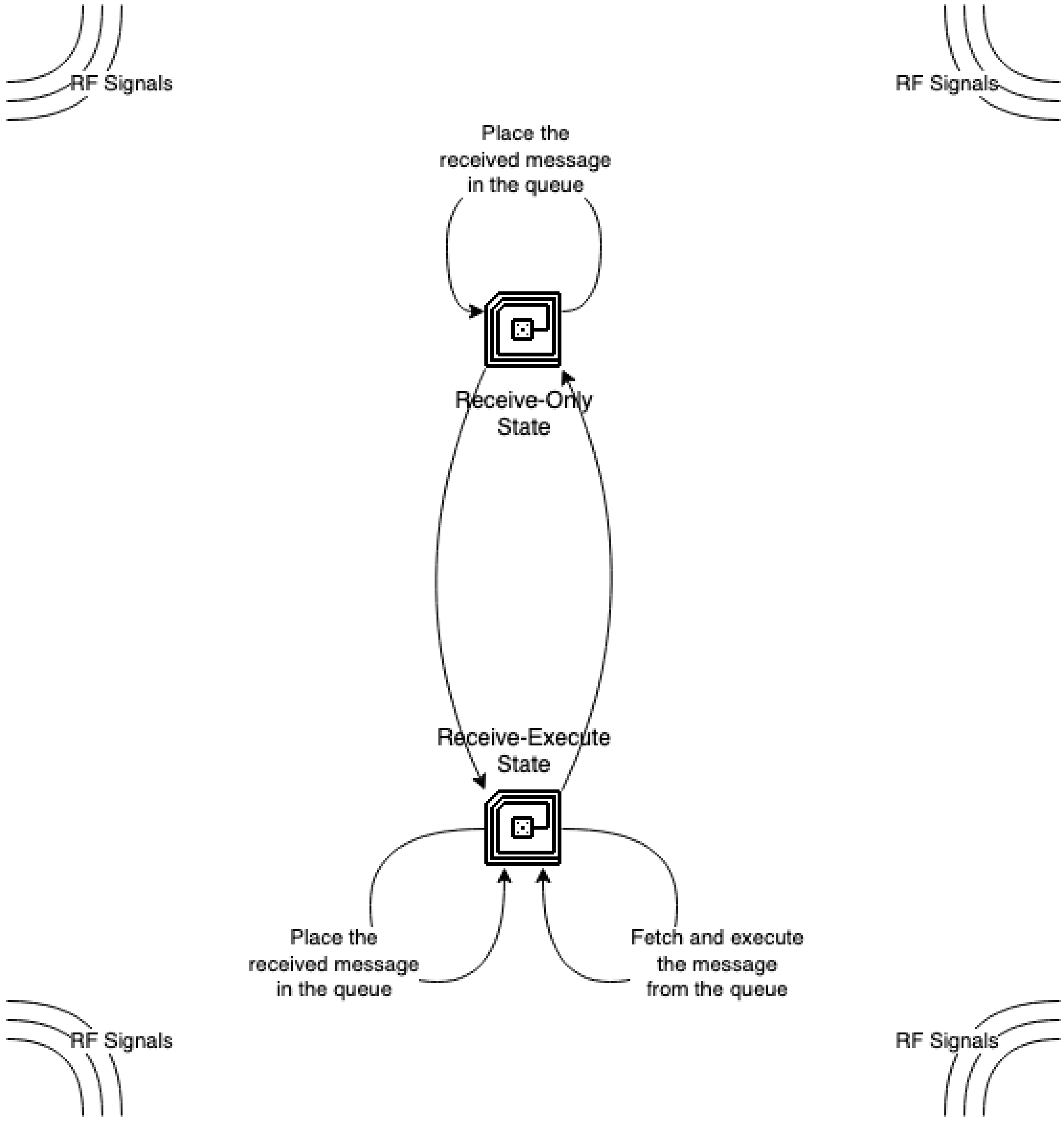

Figure 4.6: The operating states of the activated passive tags with the existence of the RF signals are described in detail.

read the messages from the message queue by obeying the FIFO property. Afterward, the incoming message is opened and executed by the receiver passive tag considering the message type. In the execution step, if the destination of the message is not the receiver passive tag, the message is broadcasted to the neighbor passive tags. Otherwise, the message is reached the destination passive tag, and the message routing operation is completed successfully. As in the Receive-Only State, another duplicate message prevention mechanism is applied in this state. In the Receive-Only state, it is prevented from placing the same message in the message queue. On the other hand, in this state, previously executed message IDs are stored in another queue in the limited internal memory. The main purpose of this queue is that if the same message is executed by the same passive tag, the last received message is ignored. Similarly, when the queue becomes full, the executed message IDs are added to the queue by removing the oldest message IDs in the queue.

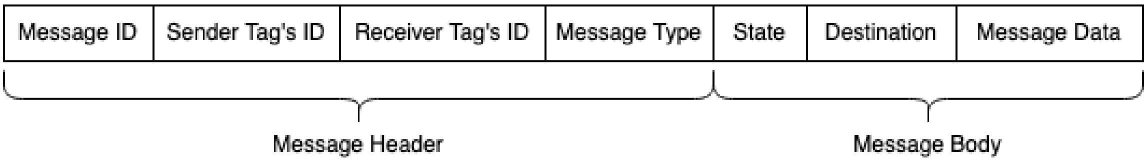

Figure 4.7: The structure of a message transmitted in the routing protocol is clarified.

The structure of a message which is transmitted between the passive tags is described in Fig. 4.7. This structure is the agreed message format by each component in the entire system that applies our routing protocol. As can be seen from Fig. 4.7, we divided the message into two parts, which are the message header and the message body. Each part of the message structure has its own fields, and in the following, these are explained in a detailed manner.

- Message ID: This is the unique message ID in the entire system. The uniqueness of this message ID is preserved by the central controller. Each message ID for the messages routed in the entire system is provided by the central controller, and passive tags do not modify the IDs of the messages while forwarding them. In the first step of the routing, the message ID is sent to the sender passive tag, and the passive tag initiates the routing by attaching the provided message ID to the message. Because it is not required to change the message ID in the system, each message's ID remains unique. The uniqueness of the message IDs is essential to prevent routing duplicate messages because passive tags compare the messages by their ID while inserting their queues or executing the messages.

- Sender Tag's ID: The ID of the sender passive tag that initiates the routing is stored in this field. In the routing path, more than one tag-to-tag transmission occurs in a multi-hop fashion. In each tag-to-tag transmission, Sender Tag's ID field remains unchanged, and it is determined by the first passive tag that starts the communication. For example, if the routing path of a message that is sent from the sender passive tag to the receiver passive tag is 1 - 2 - 3 - 4, the Sender Tag's ID field of the message is 1 during the entire communication.
- Receiver Tag's ID: As similar with the Sender Tag's ID field, the Receiver Tag's ID field is the unique ID of the message receiver passive tag. Likewise, this field does not change during multi-hop tag-to-tag communication. The receiver passive tag of the communication is also determined by the first passive tag, and the ID of the receiver tag is not modified by the other passive tags during the tag-to-tag transmissions. Considering the same example given for the Sender Tag's ID field, if the routing path of a message is 1 - 2 - 3 - 4, the Receiver Tag's ID field of the message is 4 during the entire communication.
- Message Type: This field defines the type and identifies the purpose of the transmitted message. There are three message types defined in our protocol, which are "Send", "Forward" and "Change State". While "Send" and "Forward" messages have the same priority, "Change State" messages are the highest priority messages. Additionally, by looking at the message type of a message, it can be identified whether the message is sent from the central controller or the passive tag. While "Send" and "Change State" messages can be sent by only the central controller, "Forward" messages can be sent by only the passive tags. In our system design, the central controller and passive tags do not know the IDs of each other. However, by checking the message type, the sender of the message can be identified easily. The message types defined in our routing

protocol are detailed in the following.

- “Send”: To initiate the multi-hop communication by the sender passive tag, this message is sent from the central controller to the sender tag’s sector. The Receiver Tag’s ID field of this message is the ID of the sender passive tag in the excited sector. The Destination field of the messages is utilized by the central controller for this type of message. The central controller transmits the ID of the receiver passive tag for the communication that will be started with the Destination field, and the Destination field is used only if the message type is “Send”. After receiving the “Send” message, the sender passive tag broadcasts the message to their neighbors by changing the fields of the messages. First of all, the Message ID field of the incoming message is preserved, the Message Type of the message is replaced with “Forward”, and the Receiver Tag’s ID field of the message is changed with the passive tag ID stored in the Destination field. After adding the message to be transmitted to the Message Data field and replacing the Sender Tag’s ID field with its own unique ID, the message is prepared to be routed.
- “Forward”: This is the message type defined for the communication between the passive tags. After the sender passive tag starts the communication by broadcasting the message first, the message is forwarded by the passive tags until it reaches the receiver passive tag, whose ID is stored in the Receiver Tag’s ID field. While forwarding the message by the passive tags in the routing path, all of the information in the message is not modified. Passive tags compare their ID with the ID in the Receiver Tag’s ID field before forwarding the message, and if the IDs are matched, it indicates that the message is reached the destination. In this case, the receiver passive tag can read the message in the Message Data field.
- “Change State”: To change the states of the passive tags in a specific sector, this message type can be sent by the central controller to all of the passive tags in the sector. Other fields, except the State field, are not considered by the passive tags that receive the “Change State” message. When a passive tag receives a “Change State” message, it sets its state as

the state type stored in the State field of the received message.

- State: This field stores the information about which state the passive tags in a sector should be changed to. It is used only for messages whose type is "Change State". The central controller sets this field to one of the states that a passive tag can be in, and passive tags that receive "Change State" messages modify their states as specified in this field.
- Destination: As similar with the State field, the Destination field is used only for the messages whose type is "Send". This field is created to store the destination passive tag ID of the communication that will be initiated by the passive tag that receives the "Send" message. The passive tag that receives the "Send" message starts the communication by setting the Receiver Tag's ID field as specified in the destination field of the incoming message.
- Message Data: The information transmitted with a multi-hop tag-to-tag approach is stored in the Message Data field, and it is the required field for only the "Forward" messages. When the message is transmitted until the end of the routing path, the last passive tag of the entire communication receives the incoming message and reads the data in the Message Data field to fetch the information that is sent from the first passive tag of the communication, which means the message is transmitted between the passive tags in multi-hop tag-to-tag fashion successfully.

4.2.3 Sectoral Routing Path Determination Algorithms

The sector determination process is the central part of our presented study. The reason is that the major novelty of our design is presented in this part of the study. The primary purpose of the algorithms is to determine a path between the sender and receiver passive tags. However, considering the limitations and restrictions of the passive tags, it is required to create a new and novel routing protocol for communications among the passive tags. A multi-hop tag-to-tag routing protocol for the networks of passive tags is one of the major obstacles to passive tags becoming commercial products. After an applicable routing protocol in the literature for the networks of passive tags is proposed, the energy efficiency of ordinary communication in our daily lives will be enhanced significantly. In this section, two unique algorithms for sectoral routing path determination are presented and explained in detail.

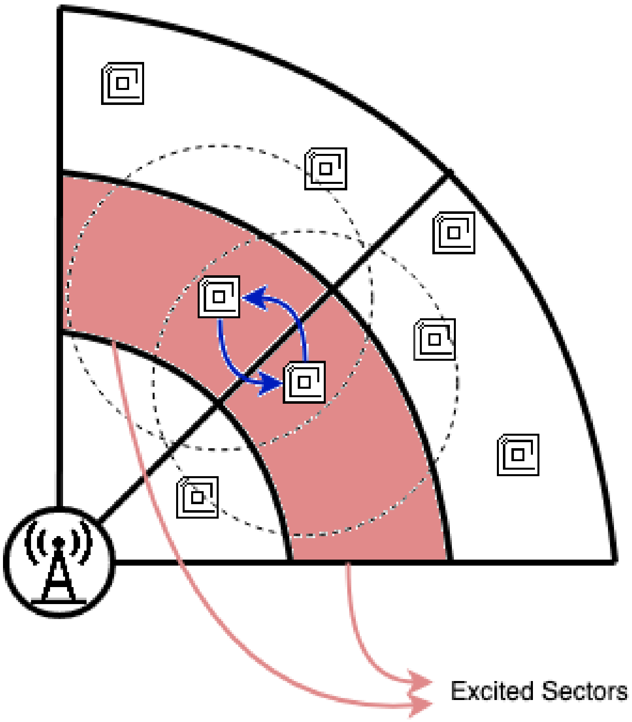

Figure 4.8: The communication between the passive tags in the excited consecutive sectors is illustrated.

The presented algorithms in this section are designed by following every regulation and restriction that was introduced in the previous sections. The main objective of the presented algorithms is to create a sectoral routing path between the sectors of the sender and receiver passive tags. Instead of using the “routing path” phrase solely, we prefer to use the “sectoral routing path”. By the sectoral routing path, it is denoted that instead of passive tags, the sectors are marked as nodes in the routing path determination algorithms. On the other hand, while the path is determined with the sectors, the message is transmitted between the passive tags in the entire system instead of the sectors. Therefore, the main principle of our study is that the sectors are excited with our realistic and proper strategy so that the passive tags can forward the message from the sender to the receiver passive tag. In our approach, the consecutive sectors of the sectoral routing path are excited pairwise, and without controlling the passive tags, the message is forwarded from one sector to another as shown in Fig.

4.8. In detail, by controlling the states of the passive tags in the specified sectors and exciting consecutive sectors at the same time, the passive tags in one sector can forward the message to the passive tags in the other sector if there is at least one pair of passive tags in different sectors where the passive tags can communicate with each other. Consequently, with the assistance of the central controller, the message can be forwarded via tag-to-tag communication until it reaches to the destination by exciting the consecutive sectors in a pairwise method.

By exciting a sector, all of the passive tags in the sector are activated, and they are ready to communicate with each other. For intra-sector communications, a flooding-based routing algorithm is chosen to apply. By applying the common flooding algorithm in our system, when a message is received by a passive tag, and it should be forwarded, the receiver passive tag broadcasts the message to all of its neighbors, regardless of which neighbor(s) the message should be forwarded to in order for the message to reach the destination. In other words, while the message is transmitted from one tag to another as one of the hops in the routing path, the passive tag sends the message to all of its neighbors by backscattering instead of sending the message to a specific tag. As mentioned, instead of directly applying the common flooding algorithm, we create a flooding-based routing algorithm with some significant expansions. Different from the standard flooding algorithm, each passive tag has two queues to store the incoming messages or the IDs of the incoming messages so that they can check whether the incoming message has been received or executed before. This approach prevents duplicate message transmissions between the passive tags and reduces the total transmission count in a sector significantly. Therefore, we can call our flooding-based routing algorithm the controlled flooding algorithm.

While designing the routing protocol, energy efficiency is one of the primary considerations. As explained previously, to improve the energy efficiency of the multi-hop tag-to-tag communication, the entire circular area is divided into sectors. Additionally, the size of the sector areas is determined by the beamwidth and level width values, which are directly related to the communication ranges of passive tags and the central controller. As the controlled flooding algorithm is implemented within sectors, increasing sector size causes more intra-sector communication and increases interference inside the sectors. To increase the successful communication rate and decrease the intra-sector communications, we determine the optimal beamwidth and level width values and divide the circular area in a well-planned way.

The excitation time of each sector is directly related to the area size of the sector, as demonstrated previously. Without considering the beamwidth and level width values, area ratios of the sectors relative to each other can be calculated by the circular area. In other words, the area size of the sectors can be calculated with respect to each other. The sectors on the same level have the same size, and when the level increases, the sector sizes also increase. Therefore, we can specify the area of a sector at a level relative to the area of another sector at a different level. Considering the relation between the sector areas and excitation times, the excitation time of a sector can also be determined according to another sector that is at a different level. For example, if the area size of the sectors in the first level is A, then the second level sectors' area size is $3 \times A$. Since the excitation time for each sector is directly related to the area size of the sector, if the first sector is excited T seconds, the second sector should be excited $3 \times T$ seconds.

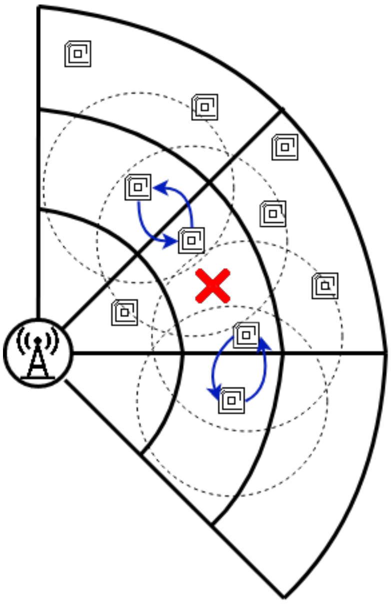

Figure 4.9: First possible fail circumstance of a multi-hop tag-to-tag communication in the sectoral circular area is illustrated.

After the determination of the routing path between the sender and receiver passive tags' sectors, sectors are excited in a pairwise manner to make the passive tags of the

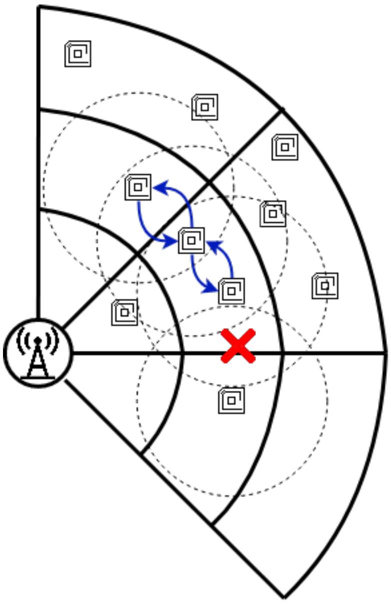

Figure 4.10: Second possible fail circumstance of a multi-hop tag-to-tag communication in the sectoral circular area is illustrated.

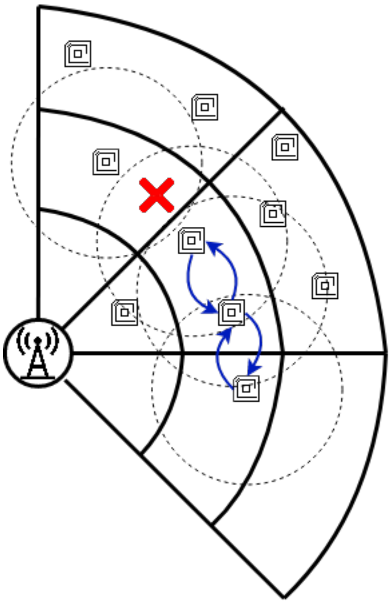

Figure 4.11: Third possible fail circumstance of a multi-hop tag-to-tag communication in the sectoral circular area is illustrated.

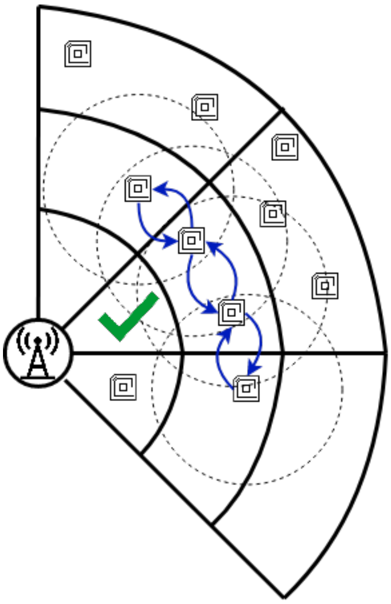

Figure 4.12: A successful multi-hop tag-to-tag communication in the sectoral circular area is illustrated.

sectors forward the message to the destination. In this step, the founded routing path does not guarantee successful communication between the passive tags in a multi-hop fashion. To perform a successful communication from the sender to the receiver passive tag, the main condition that must be satisfied is that there should be a path between the sender passive tag to the receiver passive tag through the passive tags in the sectors of the determined sectoral routing path. Therefore,

- there should be at least one pair of passive tags that are in their communication ranges in each consecutive sector pair of the routing path, and
- the passive tag that is the first receiver of the message in the sector and the passive tag that sends the message to the passive tag(s) in the next sector of the sectoral routing path should be connected with a path in each sector of the sectoral routing path.

While the example failure circumstances of multi-hop tag-to-tag communication are illustrated in Fig. 4.9, 4.10 and 4.11, the example for a successful communication is shown in Fig. 4.12. On the other hand, the average sector width in Fig. 4.4 can be determined so that it is guaranteed that passive tags in consecutive sectors can communicate with each other. However, in that case, the sector size becomes too small, and the sector count to pass from the sender passive tag to the receiver passive tag is increased. The number of sectors that have no passive tags is increased, and it also increases the possibility of creating disconnected paths from the sender to the receiver passive tag. To achieve a better successful communication rate in our design, we specify the optimal beamwidth and level width values. Therefore, the determined sectoral routing path does not guarantee a connected path between the sender and receiver passive tags.

4.2.3.1 Routing Algorithm with the Shortest Sectoral Distance (RASSD)

Without having no knowledge about the exact locations of the passive tags, we divide the circular area into sectors according to the central controller. As the main assumption of our system design, the central controller has the information in which sectors the sender and receiver passive tags are. While the message is transmitted to the receiver passive tag by hoping between the tags with tag-to-tag communication, the routing path includes only the sectors that should be excited in a pairwise manner. Since the central controller cannot directly manage the passive tags in the determined sectoral routing path, it controls the passive tags indirectly through the sectors by exciting them. Therefore, while determining the sectoral routing path, each sector in the sectoral circular area is marked as a unique node, and the path between these nodes is specified as the sectoral routing path.

After marking the sectors as different nodes in the circular area, the neighbor sectors horizontally or vertically can be connected with each other. In total, we have a graph containing sectors as nodes and the neighborhoods between the sectors as edges. The neighbor sectors are determined with the horizontally or vertically consecutive sectors. The reason is that each neighborhood between two sectors is represented with an edge in the graph, and each edge in the graph shows the connectivity between the sectors. If the passive tags in one sector can communicate with the passive tags in another sector, these sectors can be connected with an edge in the graph. However, the exact locations of the passive tags are not known, and these types of connections cannot be directly inferred from the passive tags in the system. On the other hand, the beamwidth and level width values of the circular design are calculated with the communication ranges of the central controller and passive tags, and by considering the effect of the beamwidth and level width values on the average sector size, the average sector size of the circular design is indirectly related with the communication ranges of the central controller and passive tags. As a result, the possibility of the passive tags' connectivity in the consecutive sectors is relatively acceptable according to the other sector pairs. Thus, the edges between the nodes in the described graph are determined so that there should be an edge between each of the horizontally or vertically consecutive sectors.

By applying a shortest path algorithm, such as DSPA, on the created graph, the sectoral routing path between the passive tags can be determined easily. In this case, the created graph of sectors is generated easily by the central controller, and it is constructed independent of the coordinates of the passive tags and the passive tag count of the circular area. There are two conditions that are followed to create the graph of sectors.

- Every sector in the sectoral circular area corresponds to a node in the graph of sectors.
- Every neighborhood, which is between the horizontally or vertically consecutive sectors in the sectoral circular area, is represented as an edge in the graph of sectors.

In the graph of sectors, there can be many routing paths found between the nodes that correspond to the sender and receiver passive tag's sectors. To find the shortest path between the specified nodes, a shortest path algorithm should be applied, and we choose DSPA by giving the same weight to each edge as one. DSPA returns the shortest path to all other nodes from the source node, and we take the shortest path where the destination node is the sector of the receiver passive tag. Since there is no difference in distance between the neighbor sectors of a sector and we do not guide the algorithm to find a particular path, we prefer to set each edge weight to one. There might be more than one result sectoral shortest path between the sender and receiver passive tag's sectors because the edge weight between the nodes in the graph of sectors is equal. Our routing algorithm chooses one of the paths that are found by

DSPA, and different example paths between the same sender and receiver passive tag sectors are shown in Fig. 4.13, 4.14 and 4.15.

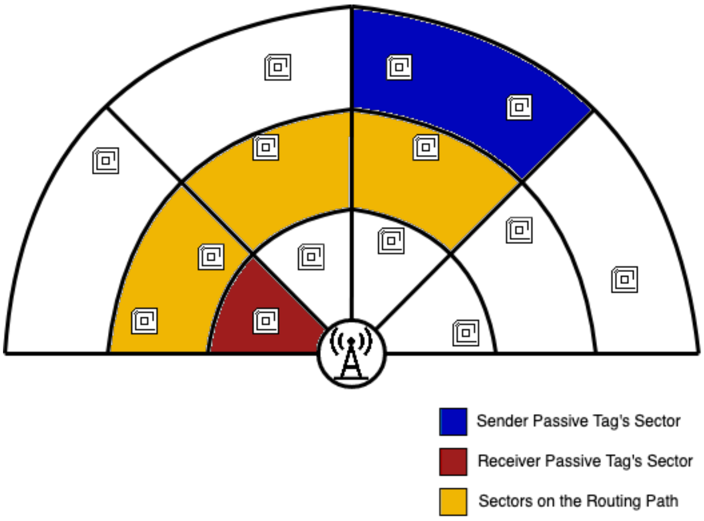

Figure 4.13: First example of the sectoral path founded by RASSD is illustrated.

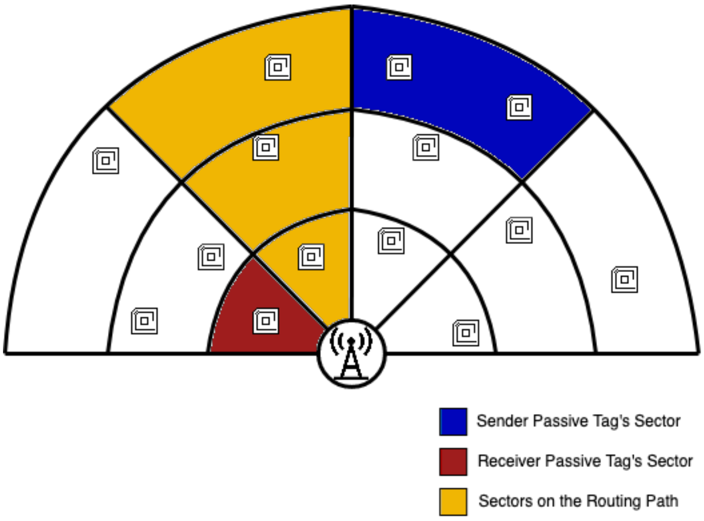

Figure 4.14: Second example of the sectoral path founded by RASSD is illustrated.

The proposed RASSD algorithm is clarified in Algorithm 1. The steps of the algorithm are explained in the following.

- Every sector of the circular design and its corresponding node are added to the S_{all} array and $G_{sectors}$ graph, respectively.
- Every two sector pair in S_{all} is checked whether they are consecutive sectors

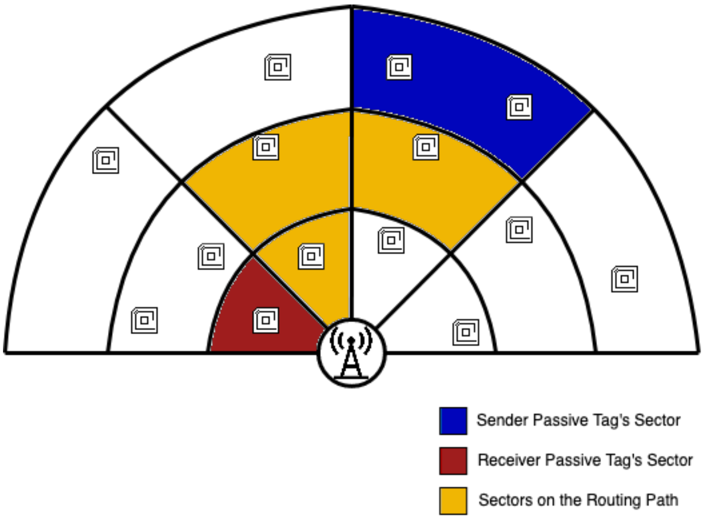

Figure 4.15: Third example of the sectoral path founded by RASSD is illustrated.

or not, and if they are consecutive sectors, an edge between the sectors' corresponding nodes in $G_{sectors}$ is added.

- The corresponding nodes of the sender and receiver passive tags' sectors are found.
- DSPA is applied where the source node is the corresponding node of the sender passive tag's sector.
- The shortest path while the destination node is the corresponding node of the receiver passive tag's sector is fetched.
- For each node of the shortest path, the corresponding sector is found and added to the result sectoral routing path.

Algorithm 1: Routing Algorithm with the Shortest Sectoral Distance (RASSD)

```
Input: $SS_{ID}$: sender passive tag's sector ID, $RS_{ID}$: receiver passive tag's sector ID, $B_{count}$: Beam Count, $L_{count}$: Level Count
Output: $S_{excite}$: determined sectors to excite
$S_{all} \leftarrow []$
$G_{sectors} \leftarrow$ empty graph
for $b \leftarrow 0$ to $B_{count}$ do
    for $l \leftarrow 0$ to $L_{count}$ do
        append the sector whose ID is $b + l \times B_{count}$ to $S_{all}$
        $N \leftarrow$ create node whose ID is $b + l \times B_{count}$
        add $N$ to $G_{sectors}$
    end for
end for
$S_{all_{length}} \leftarrow length(S_{all})$
for $s_1 \leftarrow 0$ to $S_{all_{length}}$ do
    for $s_2 \leftarrow s_1$ to $S_{all_{length}}$ do
        if $S_{all}[s_1]$ and $S_{all}[s_2]$ are consecutive sector pair horizontally or vertically then
            $N_1 \leftarrow$ find corresponding node of $S_{all}[s_1]$
            $N_2 \leftarrow$ find corresponding node of $S_{all}[s_2]$
            add edge whose weight is one between $N_1$ and $N_2$
        end if
    end for
end for
$N_{SS} \leftarrow$ find corresponding node of $SS_{ID}$
$N_{RS} \leftarrow$ find corresponding node of $RS_{ID}$
$D \leftarrow$ Apply DSPA on $G_{sectors}$ where the source node is $N_{SS}$
$G_{sectors_{excite}} \leftarrow$ Get the sectoral path whose destination is $N_{RS}$ from $D$
$S_{excite} \leftarrow []$
$G_{excite_{length}} \leftarrow length(G_{sectors_{excite}})$
for $i \leftarrow 0$ to $G_{excite_{length}}$ do
    $S_i \leftarrow$ find corresponding sector of $G_{sectors_{excite}}[i]$
    append $S_i$ to $S_{excite}$
end for
```

4.2.3.2 Routing Algorithm with the Smallest Sectoral Area (RASSA)

In our sectoral circular area design, the size of the sectors in different levels is not the same, and the sector size increases with the level number. Since a level is divided into equal-sized parts, the size of the sectors in the same level is equal to each other. The size of a sector is directly related to the power to excite the passive tags in the sector. The power that is required to excite a bigger sector is more than a smaller sector. The reason is that a bigger sized sector requires more time for the intra-sector communications between the passive tags with the controlled flooding algorithm. Additionally, between the sender and receiver passive tags' sectors, more than one sectoral path can be found, and the sectors on the founded path are excited in a pairwise way so that the message is forwarded to the destination. As a result, if the sum of the sector areas in the path between the sender and receiver passive tags' sectors is smaller, the total energy required to excite all of the sectors in the routing path is also smaller according to the path whose sum of the sector areas is bigger. Therefore, choosing a path whose sum of the sector areas is smaller improves the energy efficiency of the communication between the passive tags. In this routing algorithm, the algorithm's purpose is to determine the sectoral routing path whose sum of the sector sizes is smaller in different path options.

In RASSA, we specified three main choices that can be followed while determining the routing path from the sender to the receiver passive tag's sector, and the routing path calculation of these choices is presented in the Algorithm 3.

- The sectoral path through the level of the sender passive tag's sector (Fig. 4.16): The message sent from the sender passive tag's sector is forwarded in consecutive sectors that are at the same level in the clockwise or counterclockwise direction without changing the level until it reaches the sector, which is in the same beam as the receiver passive tag's sector. Then, the message is forwarded to the sectors upward or downward in the beam of the receiver passive tag's sector until reaching it.

- The sectoral path through the level of the receiver passive tag's sector (Fig. 4.17): The message sent from the sender passive tag is forwarded in consecu-

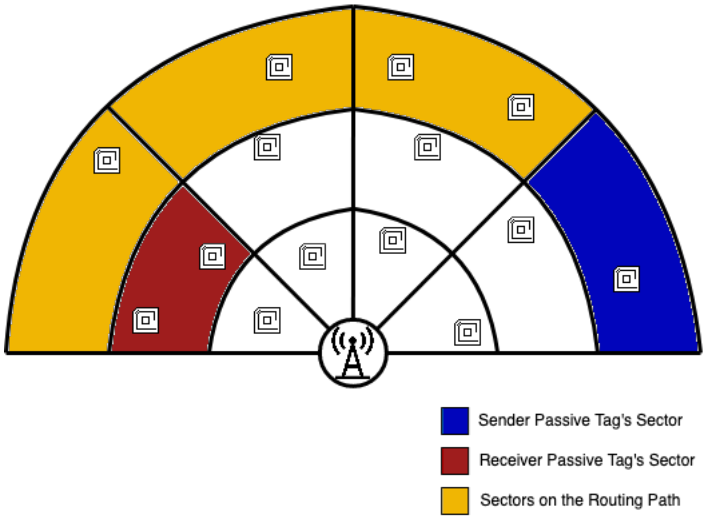

Figure 4.16: An example of the sectoral path through the level of the sender passive tag's sector is described.

tive sectors that are in the same beam upward or downward until it reaches the sector which is in the same level as the receiver passive tag's sector. Then, the message is forwarded in consecutive sectors in the clockwise or counterclockwise direction until the receiver passive tag's sector.

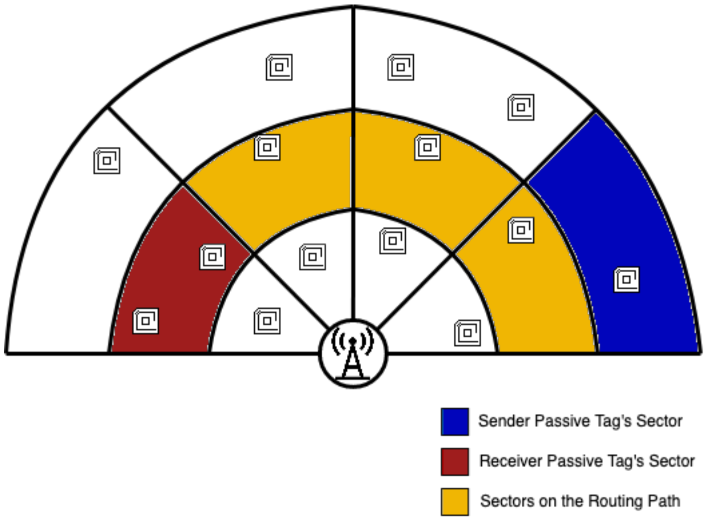

Figure 4.17: An example of the sectoral path through the level of the receiver passive tag's sector is described.

- The sectoral path through the first level (Fig. 4.18): The message sent from the sender passive tag is forwarded to the first level, which is closest to the central controller, without changing the beam at first. Then, the message is forwarded in consecutive sectors in the clockwise or counterclockwise direction without changing the level until it reaches the sector, which is in the same beam as the receiver passive tag's sector. Then, the message is forwarded to the sectors in the beam of the receiver passive tag's sector until reaching it.

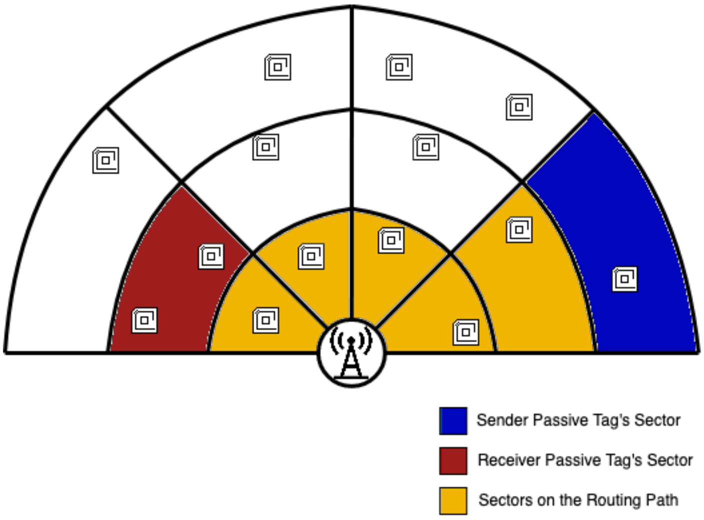

Figure 4.18: An example of the sectoral path through the first level is described.

While forwarding the message in consecutive sectors in the clockwise or counterclockwise direction, our algorithm finds the shortest direction and chooses that direction in the routing path determination algorithm. For example, if there are three sectors that should be passed in the clockwise direction and five sectors in the counterclockwise direction, RASSA chooses the clockwise direction to reach the destination.

For all these cases above, the proposed routing algorithm calculates the total sum of the sector areas that should be excited. Then, it determines the best routing path in which the total sum of the sector areas to excite is the smallest. After choosing the routing path that requires minimal sector area excitation, the central controller assists the passive tags to forward the message to the receiver passive tag by exciting the sectors in a pairwise manner.

The proposed RASSA algorithm is clarified in Algorithm 2. The steps of the algorithm are explained in the following.

Algorithm 2: Routing Algorithm with the Smallest Sectoral Area (RASSA)

```
Input: $SS_{ID}$: sender tag's sector ID, $RS_{ID}$: receiver tag's sector ID
Output: $S_{excite}$: determined sectors to excite
$S_{first\_level} \leftarrow Find\_Sectoral\_Path(''first\_level'')$ $SL_{first\_level} \leftarrow$ length($S_{first\_level}$)
$S_{sender\_level} \leftarrow Find\_Sectoral\_Path(''sender\_level'')$ $SL_{sender\_level} \leftarrow$ length($S_{sender\_level}$)
$S_{receiver\_level} \leftarrow Find\_Sectoral\_Path(''receiver\_level'')$ $SL_{receiver\_level} \leftarrow$ length($S_{receiver\_level}$)
$AreaSum_{first\_level} \leftarrow 0$
for $i \leftarrow 0$ to $SL_{first\_level}$ do
    $AreaSum_{first\_level} += S_{first\_level}[i]$
end for
$AreaSum_{sender\_level} \leftarrow 0$
for $i \leftarrow 0$ to $SL_{sender\_level}$ do
    $AreaSum_{sender\_level} += S_{sender\_level}[i]$
end for
$AreaSum_{receiver\_level} \leftarrow 0$
for $i \leftarrow 0$ to $SL_{receiver\_level}$ do
    $AreaSum_{receiver\_level} += S_{receiver\_level}[i]$
end for
$AreaSum_{min} \leftarrow$ min($AreaSum_{first\_level}$, $AreaSum_{sender\_level}$, $AreaSum_{receiver\_level}$)
if $AreaSum_{min} == AreaSum_{first\_level}$ then
    $S_{excite} \leftarrow S_{first\_level}$
else if $AreaSum_{min} == AreaSum_{sender\_level}$ then
    $S_{excite} \leftarrow S_{sender\_level}$
else if $AreaSum_{min} == AreaSum_{receiver\_level}$ then
    $S_{excite} \leftarrow S_{receiver\_level}$
end if
```

Algorithm 3: Find_Sectoral_Path() Algorithm

```
Input: $SS_{ID}$: sender tag's sector ID, $RS_{ID}$: receiver tag's sector ID, $T$: calculation choice, $B_{count}$: Beam Count
Output: $S_{path}$: determined sectors on the path
$S_{path} \leftarrow []$
$SS_{level} \leftarrow$ the level of $SS_{ID}$, $SS_{beam} \leftarrow$ the beam of $SS_{ID}$
$RS_{level} \leftarrow$ the level of $RS_{ID}$, $RS_{beam} \leftarrow$ the beam of $RS_{ID}$
if $T ==$ "$first\_level$" then
    for $l \leftarrow SS_{level}$ to $0$ do
        append the sector whose ID is $SS_{beam} + l \times B_{count}$ to $S_{path}$
    end for
    for $b \leftarrow SS_{beam}$ to $RS_{beam}$ do
        append the sector whose ID is $b$ to $S_{path}$
    end for
    for $l \leftarrow 1$ to $RS_{level} + 1$ do
        append the sector whose ID is $RS_{beam} + l \times B_{count}$ to $S_{path}$
    end for
else if $T ==$ "$sender\_level$" then
    for $b \leftarrow SS_{beam}$ to $RS_{beam}$ do
        append the sector whose ID is $b + SS_{level} \times B_{count}$ to $S_{path}$
    end for
    for $l \leftarrow SS_{level}$ to $RS_{level}$ do
        append the sector whose ID is $RS_{beam} + l \times B_{count}$ to $S_{path}$
    end for
    append the sector whose ID is $RS_{beam} + RS_{level} \times B_{count}$ to $S_{path}$
else if $T ==$ "$receiver\_level$" then
    for $l \leftarrow SS_{level}$ to $RS_{level}$ do
        append the sector whose ID is $SS_{beam} + l \times B_{count}$ to $S_{path}$
    end for
    for $b \leftarrow SS_{beam}$ to $RS_{beam}$ do
        append the sector whose ID is $b + RS_{level} \times B_{count}$ to $S_{path}$
    end for
    append the sector whose ID is $RS_{beam} + RS_{level} \times B_{count}$ to $S_{path}$
end if
```

- The sectoral routing paths through the first level, through the level of the sender tag's sector, and through the level of the receiver tag's sector are calculated by using the "Find_Sectoral_Path" function presented in Algorithm 3.
- Total sum of the sector areas is calculated for each of the three approaches.
- Then, the minimum of the calculated sums is found, and the routing path whose total sum of the sector areas is minimum is returned.

4.3 Excitation Algorithm of Sectors in the Routing Path

Creating the sectoral circular area by finding the optimal sector size and determining the sectoral routing path between the sender and receiver passive tags' sectors are the main and significant parts of the study. Performing the multi-hop tag-to-tag communication on the determined routing path is the next step and the application of the protocol that we propose. The central controller manages the performing step, and the passive tags forward the message to the receiver passive tag under the authority of the central controller. Passive tags do not realize where they are forwarding a message because there is no information shared with them. They cannot choose the next tag to forward the message, instead, they can only broadcast the incoming message to all of their neighbor passive tags that are in their communication range. Only the received message carries the information about the communication, and by checking whether they are the receiver of the message or not, they decide to broadcast the incoming message. Therefore, they cannot direct the message in a specific path, and the routing direction of the communication is not supervised by the passive tags on the path. The central controller handles all of the communication and determines the direction of the message, while passive tags forward the message to each other. Therefore, without giving any responsibility to the passive tags about giving direction to the message in the routing path, the central controller manages the communication by exciting the sectors and setting the states of the passive properly.

The main condition that should be satisfied while routing the message is that if a message is forwarded from one passive tag to another, both of the passive tags should be excited. However, after the message is forwarded by one passive tag to another, if the receiver passive tag forwards the message also, there should be the third passive tag, which is the next receiver of the message. The reason is that if the message is not received by the third passive tag, it is disappeared, and this creates a disconnectivity in the routing path. Because this is valid for the next passive tags in the routing path, all of the passive tags and their deployed sectors should be excited in the routing path. Since all of the sectors in the routing path should be excited at the same time for communication, this is not an energy-efficient way of communicating. Actually, it is the reason why we specify the different states of the passive tags. By setting the passive tags in one sector as the sender and the other passive tags in the consecutive sector as the receiver, passive tags in one sector can send a message to the passive tags in another sector, and the receiver passive tags do not forward the message to other consecutive sectors. Instead of forwarding, the receiver passive tags store the incoming message and wait for the signal that changes their state as sender to forward the message to the passive tag in another consecutive sector. With this methodology, the message is hopped between the sectors one-by-one until the receiver passive tag's sector. Additionally, for each sector, the excitation time is calculated according to its sector size, and while exciting pairwise sectors as the sender and receiver, they are not excited separately in different periods of time. Instead, the maximum excitation time of the pairwise sectors is chosen, and both of the sectors are excited in the chosen time period to prevent disconnectivity.

As highlighted previously, we define two state types for the passive tags, which are "Receive-Only" and "Receive-Execute" states. In the "Receive-Only" state, the passive tags are excited; however, they do not transmit any message to the other passive tags; instead, they receive and store the incoming messages without reading the message. In the "Receive-Execute" state, passive tags receive and forward the incoming messages at the same time. Additionally, if the received message is reached the destination, the receiver passive tag should be in the "Receive-Execute" state because, in the "Receive-Only" state, passive tags do not open and read the incoming messages. Therefore, by using the excitation power and setting the states of the passive tags in the sectors of the sectoral routing path properly, passive tags can be assisted in forwarding the message to the destination passive tag. The steps of the message transmission, which is presented in Algorithm 4 in the sectoral routing path, are explained step-by-step in the following and in Fig. 4.19.

- While triggering the message to be transmitted by the sender passive tag, the central controller knows the path that should be followed.
- At first, the passive tags in the sector of the sender and next sector in the sectoral routing path are excited, and their states are set to “Receive-Execute” and “Receive-Only”, respectively.
- Excitation signals are applied to both sectors until the end of the excitation period. The excitation period is determined by the maximum excitation time of the sectors calculated according to their sizes.
- In this period, the sender passive tag is triggered to send its message.
- The excitation signals are removed from both sectors.
- The sector whose passive tags’ state is “Receive-Only” is excited again, and the state of the passive tags is changed to the “Receive-Execute”. The next sector is excited by setting the states of its passive tags to “Receive-Only”.
- Until reaching the receiver passive tag’s sector, the sectors in the routing path are excited and set their states “Receive-Execute” and “Receive-Only” in a pairwise manner.
- When the sector of the receiver passive tag is reached, the state of its and the previous sector’s passive tags is set to “Receive-Only” and “Receive-Execute”, respectively.
- The excitation signal is removed from the previous sector, and the state of the passive tags in the sector of the receiver is set to “Receive-Execute”. Because it is the last sector in the sectoral routing path, there is no sector to excite next. After setting their state to “Receive-Execute”, the message is reached the destination and read by the receiver passive tag.

In this algorithm, a message can only be read in the “Receive-Execute” state. However, whether the message is received by the passive tag in the “Receive-Only” state

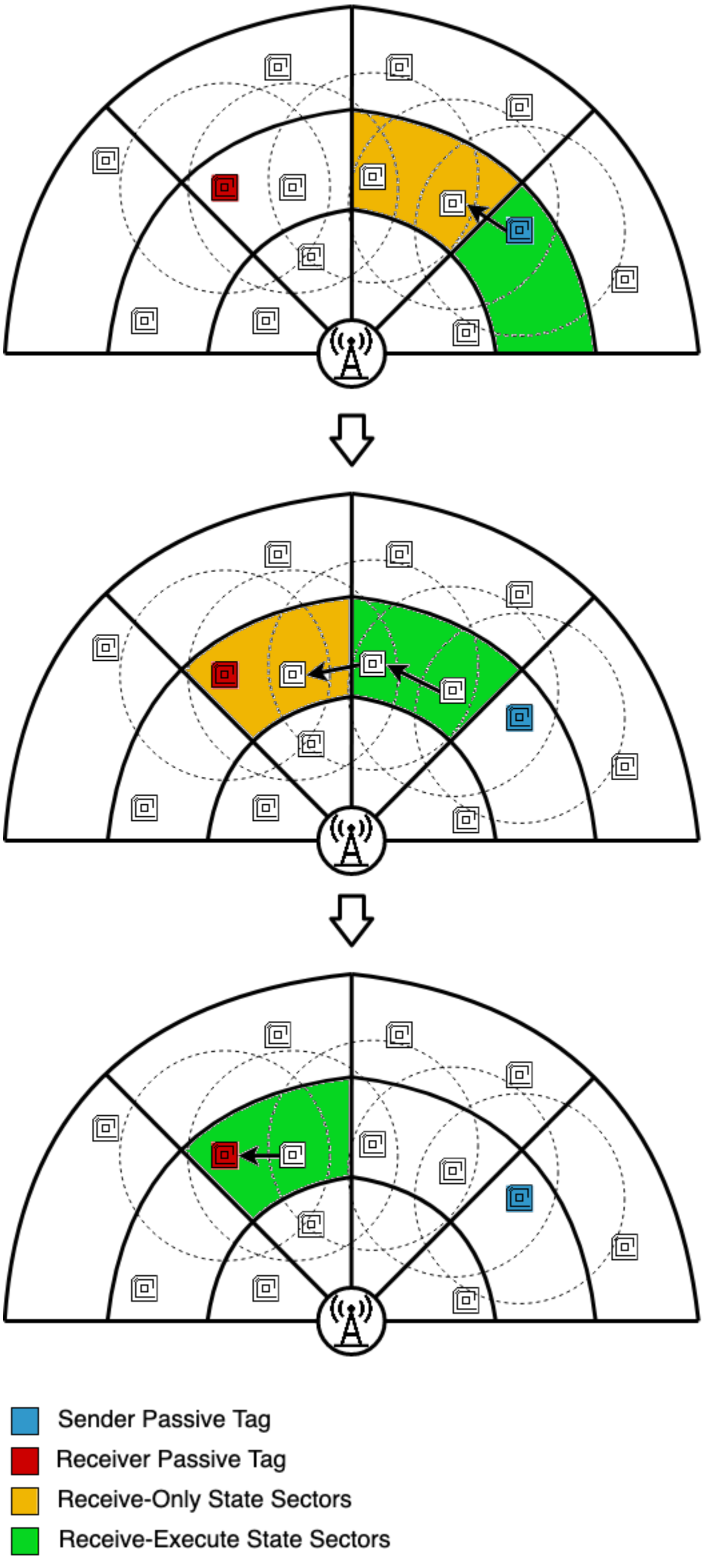

Figure 4.19: An example step-by-step application of the excitation algorithm is presented.

Algorithm 4: Excitation Algorithm of Sectors in the Routing Path

```
Input: $S_{excite}$: determined sectors to excite, $S_{excite\_time}$: excitation times of sectors
    according to their size, $ST_{ID}$: ID of the sender passive tag, $RT_{ID}$: ID of the
    sender passive tag
$S_{length} \leftarrow length(S_{excite})$
for $i \leftarrow 0$ to $S_{length}$ do
    if $(i == S_{length} - 1)$ then
        Excite $S_{excite}[i]$
        Create a message $M$
        $M_{type} \leftarrow$ "$ChangeState$", $M_{state} \leftarrow$ "$Receive - Execute$"
        Send $M$ to $S_{excite}[i]$
        $E_{time} \leftarrow S_{excite\_time}[i]$
        Wait until $E_{time}$ ends
        Remove Excitation Signal from $S_{excite}[i]$
    else
        Excite $S_{excite}[i]$
        Excite $S_{excite}[i+1]$
        Create a message $M$
        $M_{type} \leftarrow$ "$ChangeState$", $M_{state} \leftarrow$ "$Receive$"
        Send $M$ to $S_{excite}[i+1]$
        $M_{state} \leftarrow$ "$Receive - Execute$"
        Send $M$ to $S_{excite}[i]$
        if $(i == 0)$ then
            $M_{receiverID} \leftarrow ST_{ID}$, $M_{type} \leftarrow$ "$Send$", $M_{destination} \leftarrow RT_{ID}$
            Send $M$ to $S_{excite}[i]$
        end if
        $E_{time} \leftarrow max(S_{excite\_time}[i], S_{excite\_time}[i+1])$
        Wait until $E_{time}$ ends
        Remove Excitation Signal from $S_{excite}[i]$
        Remove Excitation Signal from $S_{excite}[i+1]$
    end if
end for
```

or the “Receive-Execute” state cannot be determined. The options are explained in the following.

- The message can be received in the “Receive-Only” state, added to the message queue, and read in the “Receive-Execute” state. This implies that the receiver passive tag is one of the first receivers of the message in its deployed sector from the previous sector in the sectoral routing path.
- The message can be received in the “Receive-Execute” state, added to the message queue, and read in the same state after reading the previous messages in the queue. This implies that the message is received from the other passive tags in the same sector by the controlled flooding algorithm.

To transfer a message from one sector to another sector, both sectors should be excited first. Afterward, in the excited sectors, there should be at least one pair of passive tags that are not in the same sector and are in their communication ranges of each other as shown in 4.8. Therefore, if there is a disconnectivity between the passive tags in the routing path, the communication cannot be completed successfully.

As highlighted before, passive tags have the least responsibility in our system design since they do not have an internal power source and are powered by the central controller. The central controller manages the communications between the passive tags, and the tasks assigned to the passive tags in our proposed multi-hop tag-to-tag routing protocol are minimized as much as possible. Passive tags are activated with the existence of the excitation signals, and they do not have any responsibility for routing path determination or excitation planning. Until they receive a message, they do not have any jobs, and when a message is received, the “Passive Tag Receive Message Algorithm” presented in Algorithm 5 is executed.

- When a message is received by a passive tag, the message type is extracted at first.
- If the received message’s type is “Change State”, they extract the state information in the message and modify their state with the read information from this field. Additionally, the default state of the passive tags is “Receive-Only”.

- If the type of the received message is not “Change State”, then the message queue is checked whether the same message has been received before by comparing the message IDs.
- If the message has not been received before, it is added to the message queue.
- The common part of “Receive-Only” and “Receive-Execute” states is until adding the message to the message queue after checking if it is received before.
- If the passive tag’s state is “Receive-Only”, there is no task left. Otherwise, to execute the messages in the queue Passive_Tag_Execute function presented in Algorithm 6 is called.
- In the Passive_Tag_Execute function, the following operations are executed.
  - All of the messages stored in the message queue are executed one by one.
  - By comparing the message IDs, it is checked whether the incoming message is executed previously.
  - If it is not executed previously, the message ID is added to the previously executed message ID queue.
  - The message type is extracted from the message.
  - If the message type is “Send” and the receiver ID of the message is matched with the ID of the passive tag, it implies that this message is sent from the central controller to start the communication between the passive tags. Therefore, by forwarding the incoming message, multi-hop tag-to-tag communication should be started. However, before forwarding, some fields of the message are changed first. The sender and receiver IDs of the message are replaced with its own passive tag ID and the ID stored in the destination field of the message, respectively. Moreover, the message type is set to “Forward” and the data to be transmitted to the receiver passive tag is placed in the message data field. Then, the message is forwarded by broadcasting to all of its neighbors.
  - If the message type is “Forward” and the receiver ID of the message is matched with the ID of the passive tag, it implies that the receiver passive

tag is the destination of the message, and the message has reached the destination. In this case, the message data can be opened and read by the receiver passive tag. Otherwise, the message has not reached the destination and should be forwarded to neighbor passive tags without changing any field.

As mentioned previously, there are two queues in a passive tag for different purposes. The first one is the message queue, where the received messages are stored to be executed when the passive tag is in the "Receive-Execute" state. The second one is the previously executed message ID queue, and it stores the IDs of the messages that are not only received but executed by the passive tag.

Algorithm 5: Passive Tag Receive Message Algorithm

```
Input: $M$: received message, $MQ$: message queue, $T_{state}$: tag state
$M_{type} \leftarrow$ Extract message type from $M$
if ($M_{type} == "ChangeState"$) then
    $M_{state} \leftarrow$ Extract state from $M$
    $T_{state} \leftarrow M_{state}$
else
    $M_{ID} \leftarrow$ Extract message ID from $M$
    $MQ_{length} \leftarrow length(MQ)$
    $temp \leftarrow 0$
    for $i \leftarrow 0$ to $MQ_{length}$ do
        $MQ_{ID} \leftarrow$ Extract message ID from $MQ[i]$
        if ($M_{ID} == MQ_{ID}$) then
            $temp \leftarrow 1$
        end if
    end for
    if ($temp == 0$) then
        Enqueue $M$ to $MQ$
        if ($T_{state} == "Receive - Execute"$) then
            $Passive\_Tag\_Execute()$
        end if
    end if
end if
```

Algorithm 6: Passive_Tag_Execute() Algorithm

```
Input: $T_{ID}$: tag ID, $PM$: previously executed messages ID queue, $MQ$: message queue
$MQ_{length} \leftarrow length(MQ)$
while ($MQ\_length > 0$) do
    $M \leftarrow$ Dequeue message from $MQ$
    $M_{ID} \leftarrow$ Extract message ID from $M$
    $PM_{length} \leftarrow length(PM)$
    $temp \leftarrow 0$
    for $i \leftarrow 0$ to $PM_{length}$ do
        if ($M_{ID} == PM[i]$) then
            $temp \leftarrow 1$
        end if
    end for
    if ($temp == 0$) then
        Enqueue $M$ to $PM$
        $M_{type} \leftarrow$ Extract message type from $M$
        if ($M_{type} == “Send''$) then
            $M_{receiverID} \leftarrow$ Extract receiver ID from $M$
            if $M_{receiverID} == M_{ID}$ then
                $M_{senderID} \leftarrow T_{ID}$
                $M_{receiverID} \leftarrow M_{destination}$
                $M_{type} \leftarrow Forward$
                $M_{messageData} \leftarrow$ Information to send receiver tag
                Broadcast $M$
            end if
        else if ($M_{type} == “Forward''$) then
            $M_{receiverID} \leftarrow$ Extract receiver ID from $M$
            if $M_{receiverID} == M_{ID}$ then
                $M_{messageData} \leftarrow$ Extract message data from $M$ to read
            end if
        end if
    end if
end while
```

CHAPTER 5

EVALUATION AND EXPERIMENTS

In this section, we demonstrate the experimental results of our routing protocol with detailed analyses and discussions. To simulate and test our presented multi-hop tag-to-tag routing protocol with different parameters, we created a simulation environment which is uniquely designed for our study by using Python programming language. Then, we implemented our protocol in this environment and conduct different types of experiments to examine the influencing and non-influencing factors on our system performance.

5.1 Simulation Environment Setup

To create our simulation environment, we preferred to use Python programming language (version 3.10) because of the flexibility of the syntax, library support, and easy implementation of the selected algorithm. Besides the internal library support of the Python programming language, three main external libraries are used, which are Matplotlib, NetworkX, and NumPy.

- Matplotlib: It is used to draw and visually check the created graphs.
- NetworkX: It is used for multiple purposes in our simulation environment design. At first, the central controller and each passive tag in the system are created as a graph node in the NetworkX library. Additionally, to apply DSPA in RASSD, a library function of NetworkX is used.
- NumPy: To prevent precision loss and perform the mathematical operations in an errorless way, the NumPy library is preferred.

At the beginning of the simulation process, the passive tags are uniform randomly distributed in a circular area. An example distribution of the passive tags used in the simulation environment is shown in Fig. 5.1, where the node whose ID is 0 is the central controller. Since our routing algorithm is designed for the fixed passive tags, it is assumed that the passive tags are stationary and their locations are not changed during the simulations. For the internal functions of the passive tags, a thread-based approach is used, and the excited passive tags are run in parallel. Their operations are performed in their threads to create a realistic simulation environment.

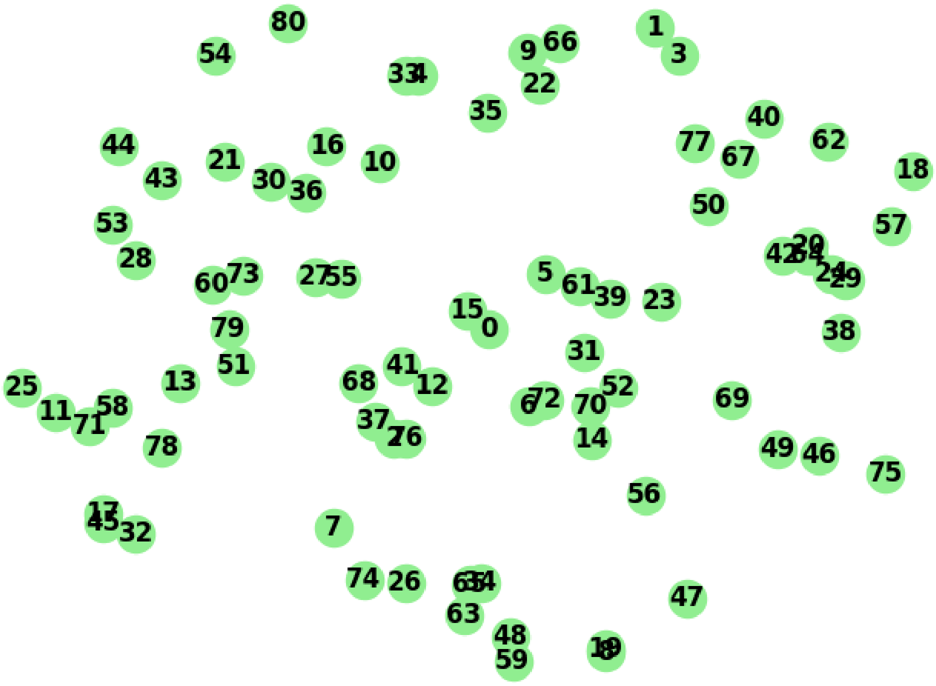

Figure 5.1: An example distribution of passive tags in the simulation environment is presented.

In our system design, we prefer to use base-2 or binary format while setting IDs for each sector. In the simulation environment, we follow this principle and designed our simulator that works in binary format. In addition, while many of the system parameters can be determined automatically, some of the parameters should be provided to the system. The reason is these input parameters are determined independently of our system design, such as the communication range of the passive tags. These parameters are taken as input by our system, and all input parameters of our simulation environment are listed in the following.

- Communication range of passive tags
- Communication range of the central controller
- Message queue size of passive tags
- Size of the previously executed message ID queue of passive tags
- Base excitation signal time of the central controller

The values of these parameters are determined independently of our system. Therefore, we take them as input parameters because these should be defined by the manufacturer of the passive tags or the central controller. In this study, instead of specifying the technical design of the central controller or passive tags, we create a novel system and protocol design for the networks of passive tags. Therefore, we do not determine or provide any technical detail about them. Except for the base excitation signal time of the central controller, other input parameters are directly related to the technical design of the central controller or passive tags, and these should be specified in the producing step of the devices. As a reason why we take them as input parameters, we want to create a flexible system for every circumstance and provide a well-designed system that can operate with devices having different capabilities. For the base excitation signal time of the central controller, the central controller should excite a sector for a longer time period if its area is bigger than others, as already stated. In the simulation environment, a base excitation signal time is given to the simulation environment as a parameter, and sectors were excited in the multiples of this time. In addition to these parameters, we design our system to take the beamwidth and level width values manually instead of determining them according to the communication ranges of the central controller and passive tags.

The important steps of our simulation design to reach the experimental results are as follows:

- For each result, we run the simulation 1000 times and took the average of the calculated values.

- In each test case, we created the unique graph (an example graph is shown in Fig. 5.1) repeatedly and distributed the passive tags uniform randomly.

- For each test case, we selected the sender and receiver passive tags randomly in the graph without any condition.

- The mentioned base excitation signal time is chosen as 1 second for each test case. For example, the sector in the first level was excited for 1 second, and for the sector in the second level, it is 3 seconds because the area of the sector in the second level is three times bigger than the sector in the first level.

- For each routing path determination algorithm, we run our tests separately with the same parameters, and their results are compared.

In the simulation scenarios, the message sender tag is triggered by the central controller externally to send its message, and with the assistance of excitation signals that come from the central controller, the message is transmitted to the receiver tag by hopping on the passive tags. As explained step-by-step previously, the sectoral routing path is created by the central controller; however, it is not guaranteed that the message will reach the receiver tag. The message sent from the sender tag might be lost in the sectoral routing path that was created by the central controller. The reason is that the created path determines only the sectors that will be passed; however, the message will be hopped on the passive tags. Therefore, the created path by the central controller might be disconnected, and the delivery ratio is one of the main concerns in our simulation cases.

In addition to the delivery ratio, the latency of a message and the number of hops in the transmissions between the sender and receiver passive tags are the other concerns. We preferred to use the passive tags in our system design because we wanted to benefit from the energy advantages of the passive tags. The average latency of a message is a useful indicator of the energy efficiency of our protocol design because the time passed in the transmission for a message shows the time of the excitation by the central controller. The average number of hops in the routing paths gives information about the efficiency of the created paths by the routing path determination algorithms. While the average number of hops is directly related to the routing path, to check the transmission count in each sector of the routing path, the average number of concurrent transmissions is a good indicator. Moreover, because we apply the controlled flooding algorithm in sectors, the average number of concurrent transmissions gives information about the efficiency of the controlled flooding algorithm. In total, these are the output parameters that indicate the working efficiency of the system, and we want to create a realistic system design where the latency, number of hops, and number of concurrent transmissions of the communications between the passive tags are within acceptable limits.

We determine the system-specific input and output parameters for our design as different from the common metrics that show the information about the system. The reason is that in this study, we present a complete system design for the routing protocol. If we test our system with the common input and output parameters, such as bit error rate, the result does not give an idea about how our system is well-designed and completes the tasks successfully. Therefore, we should test our system with the parameters specific to our system design to measure how our proposed design performs the multi-hop tag-to-tag communications successfully. Our system-specific input and output parameters are listed in the following.

The input parameters of the simulation cases are listed below.

- The number of passive tags in the system,
- The communication range ratio (the central controller's communication range / a passive tag's communication range),
- The number of sectors in the sectoral circular area.

Instead of taking the communication ranges of the central controller and a passive tag as separate parameters, we prefer to use their ratio because their effect on the results is similar. Therefore, to see the importance of the parameter on the result without the effect of the other parameter, we use the communication range ratio of the central controller and a passive tag. Although the number of sectors in the system is indirectly related to the communication ranges of the central controller and a passive tag, we want to see the effect of the number of sectors on the result directly, and we accept it as an input parameter separately.

The output parameters of the simulation cases are listed below.

- Delivery ratio (%)
- Average latency (s)
- Average number of hops
- Average number of concurrent transmissions

In the output parameters, while the delivery ratio is the percentage of the successfully delivered transmissions over the total transmissions, the average latency is the average time difference between the message sending and receiving time by the passive tags. The average number of hops shows how many passive tags are passed on average from the sender passive tag to the receiver passive tag in a message transmission. The average number of concurrent transmissions is the number of how many times the same message is reached the receiver passive tag on average.

5.2 Simulation Results

In this section, we present our simulation results separately by considering the different input and output parameters. The following simulations are run on a machine whose specifications are listed in the following.

- Processor: Intel Core i5-4590 (3.30 GHz × 4)
- Operating System: Ubuntu 20.04.5 LTS
- Operating System Type: 64-bit
- Memory: 7.7 GB

To see the effect of the number of passive tags and communication range ratio on our system design, we have observed their effects on all of the output parameters by applying both of our proposed algorithms. While the number of passive tags can be seen in the x-axes, communication range ratios are presented in the legend of the figures. While the communication range of the central controller is Rc, a passive tag's communication range is Rt in the figures, and their ratio is represented as Rc/Rt. Additionally, the number of sectors parameter remains unchanged in all of the test cases where the effect of the number of passive tags and communication range ratio are measured. All of the measurements in this chapter are accomplished under the 10% packet loss probability.

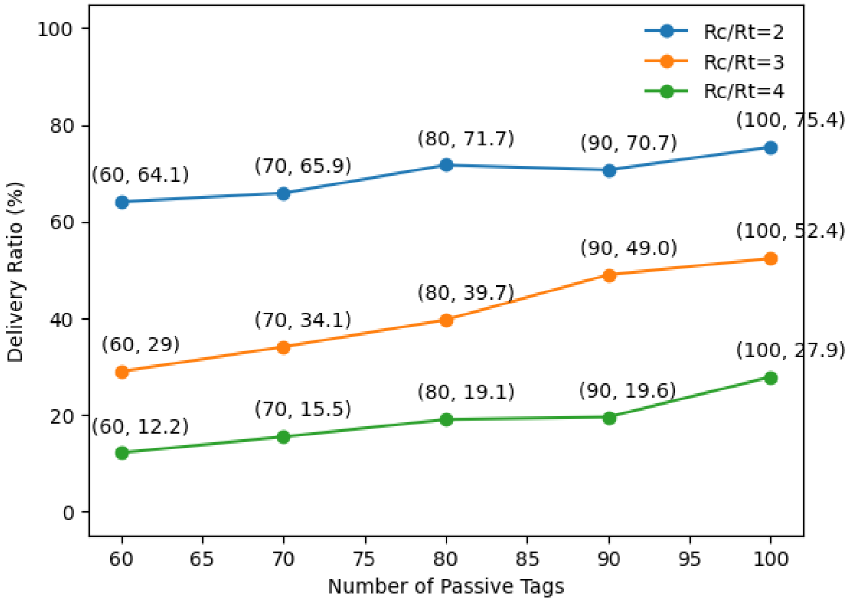

Figure 5.2: The effects of the number of passive tags and communication range ratio on the delivery ratio applying RASSD are presented.

The delivery ratio is one of the main concerns of our routing protocol design. In Fig. 5.2 and 5.3, the effects of the number of passive tags and communication range ratio on the delivery ratio are presented by applying RASSD and RASSA, respectively. We can see that raising the number of passive tags increases the delivery ratio, as expected for both of the routing algorithms. The reason is that there are more passive tags per area to forward the messages, and more passive tags mean more possible routing paths between the sender and receiver passive tags. In addition, we can see the effect of the communication range ratios on the results. When the range declines, the same number of passive tags are placed in a smaller location where the number of sectors is stable. For the same reason as the increase in the number of passive tags, the

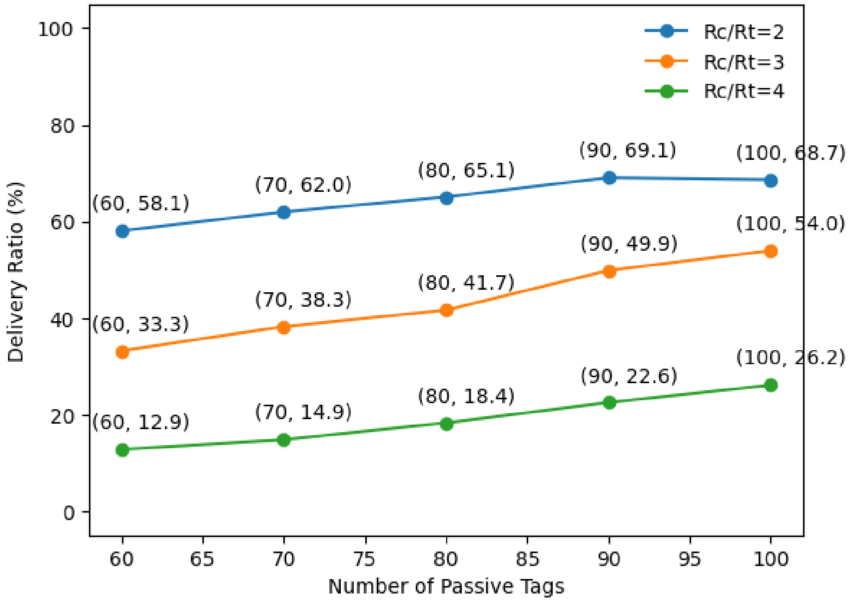

Figure 5.3: The effects of the number of passive tags and communication range ratio on the delivery ratio applying RASSA are presented.

more passive tags in a sector area, the more possible routing paths, and it increases the delivery ratio.

To calculate the average latency values for our tests, we started the time when the message was sent by the sender passive tag and stopped the time it was received by the receiver passive tag. As there are concurrent communications between the sender and receiver passive tags, the message might be received by the receiver passive tag more than once. In this case, we consider the first message that reaches the destination. As presented in Fig. 5.4 and 5.5, the average latency values rise with the increasing number of passive tags and fall with the increasing ratio of the communication ranges with a 95% confidence interval. It should be mentioned that if two messages whose sender and receiver passive tags are the same reach the destination by following the same sectoral path, the difference between their latency is reasoned from the number of hops in the last sector in their path. The required times for the messages to reach the last sector are the same since the central controller excites the pairwise sectors on the path one by one, and although the message is received by a passive tag in the next sector before the excitation of the sector ends, it waits for the change in the states of

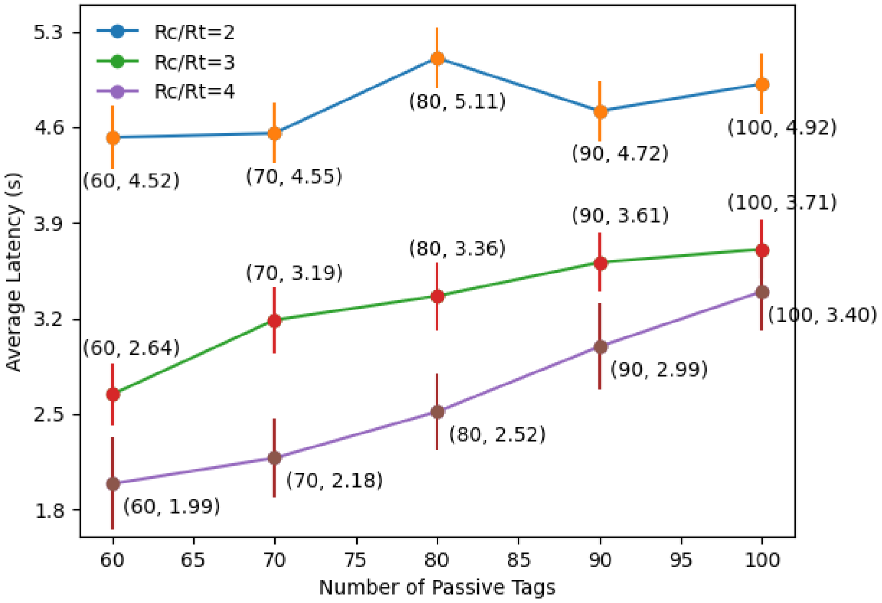

Figure 5.4: The effects of the number of passive tags and communication range ratio on the average latency with a 95% confidence interval applying RASSD are presented.

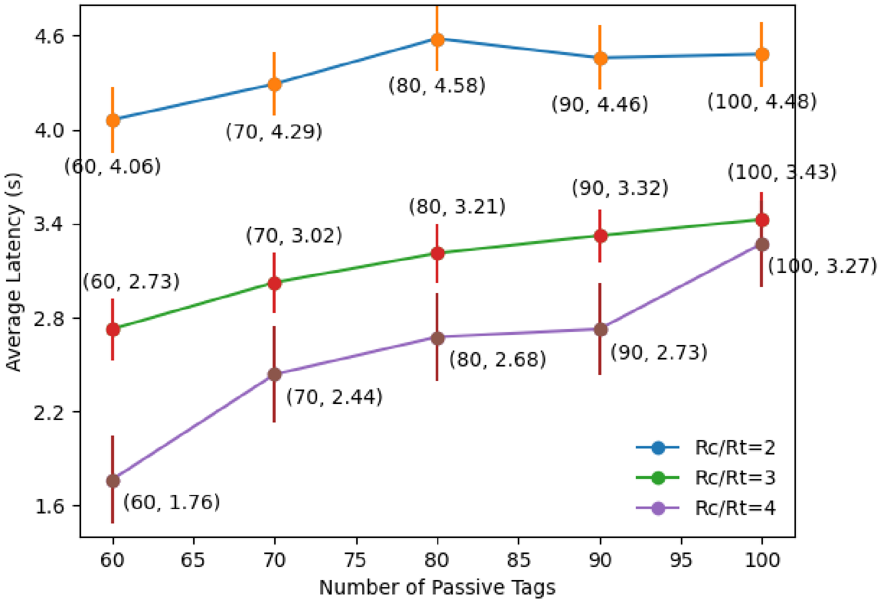

Figure 5.5: The effects of the number of passive tags and communication range ratio on the average latency with a 95% confidence interval applying RASSA are presented.

the passive tags of the received sector. Therefore, it can be accepted that the times passed until the messages reach the last sector are the same, and the reason for the differences in the figures is the number of passive tags in the last sector. Because of the controlled flooding algorithm in the sectors, if the number of passive tags per sector area increases, the flooding in the sectors multiplies, and the time to reach the receiver passive tag in the last sector extends by requiring more hops between the passive tags. Because the increase in the number of passive tags or the decrease in the communication range ratio multiplies the flooding in the sectors by raising the number of passive tags per sector area. In total, more flooding in sectors results in increased average latency on our system.

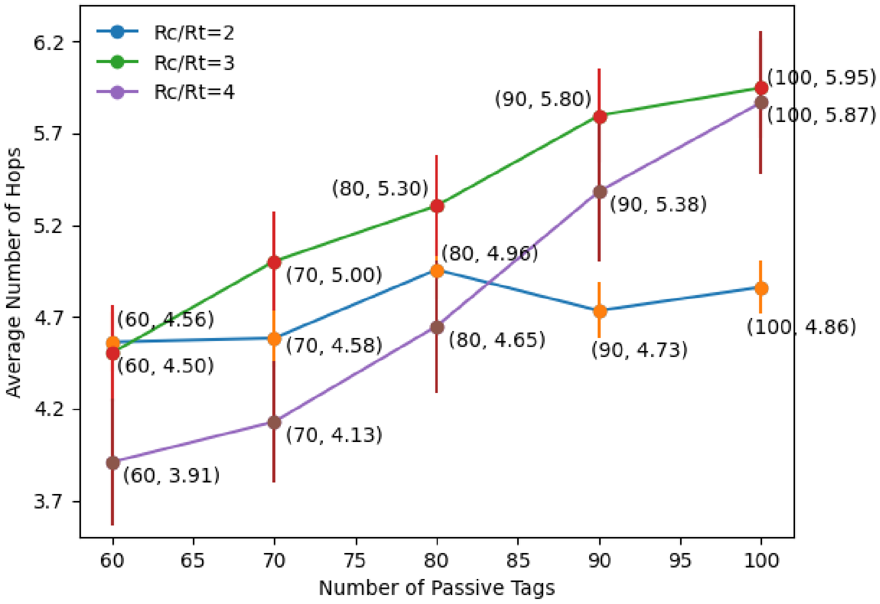

Figure 5.6: The effects of the number of passive tags and communication range ratio on the average number of hops with a 95% confidence interval applying RASSD are presented.

In Fig. 5.6 and 5.7, the change of the average number of hops according to the number of passive tags and communication range ratio can be seen with a 95% confidence interval. As in the calculation of the average latency values, the first message in the concurrently received messages is considered. As shown in the figures, there is no direct effect of the communication range ratios on the average number of hops.

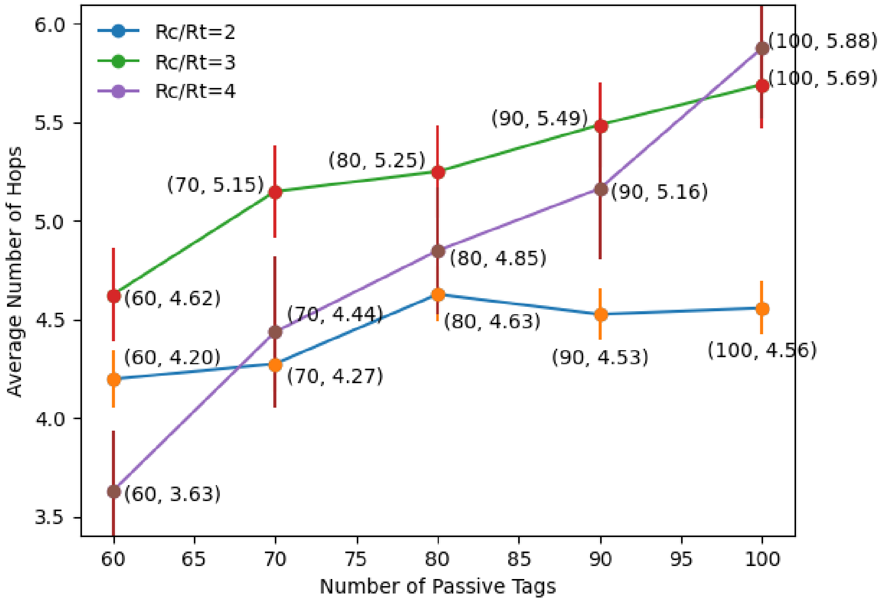

Figure 5.7: The effects of the number of passive tags and communication range ratio on the average number of hops with a 95% confidence interval applying RASSA are presented.

The reason is that while calculating the average number of hops, we consider the successfully delivered transmissions between the sender and receiver passive tags, and for each test case, we choose them randomly. Where the communication range ratio increases, the possibility of a successfully delivered transmission between the passive tags that are far from each other decreases. Thus, the successfully delivered transmissions between the passive tags that are close to each other are considered, and in this case, the average number of hops of the communications is smaller than others. Additionally, although the passive tag density of the sectors changes, the path that contains the minimum number of passive tags between the sender and receiver passive tags is accepted for each case because we consider the first message that is received by the receiver passive tag. The path of the first received message includes the minimum number of passive tags for each case between the sender and receiver passive tags, and it is not directly affected by the communication range ratios. On the other hand, we can see the rising average number of hops value where the number of passive tags increases for each communication range ratio. The reason is that when we increase the passive tag density of the sectors for the same communication range ratio, the possibility of a successfully delivered transmission between the passive tags that are further from each other increases. Because the successfully delivered transmissions between the passive tags are considered only, the average number of hops of the communications in the same communication range ratio increases with the number of passive tags.

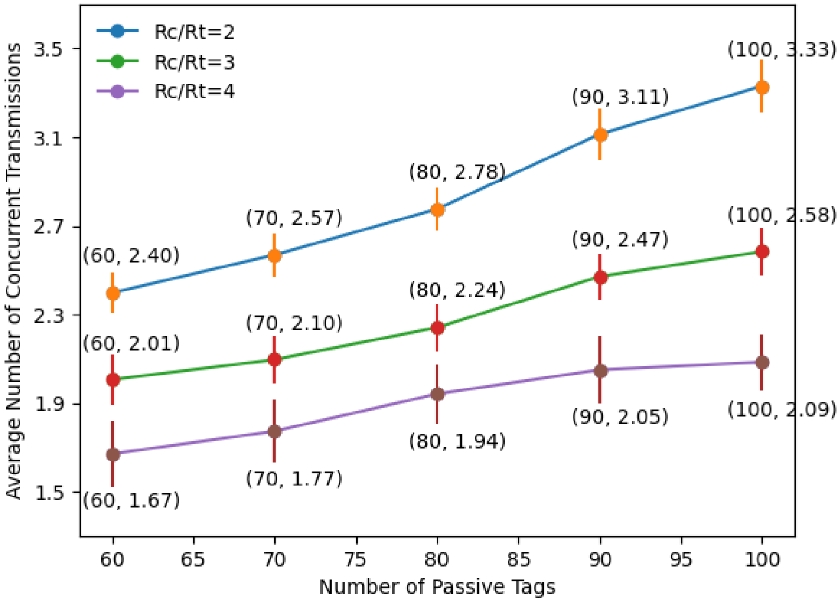

Figure 5.8: The effects of the number of passive tags and communication range ratio on the average number of concurrent transmissions with a 95% confidence interval applying RASSD are presented.

To calculate the average number of concurrent transmissions, we count how many times the message sent by the sender passive tag reaches the receiver passive tag. Each received message is hopped by different passive tags, and its path is unique. Considering the duplicate message prevention mechanisms implemented in the passive tags, the average number of concurrent transmissions is minimized; however, the applied controlled flooding algorithm in the sectors increases the average number of concurrent transmissions. When a message is transmitted between the neighbor sectors, the transmission between them is conducted by the different passive tags that are in neighbor sectors, and the number of passive tags that connects two neighbor

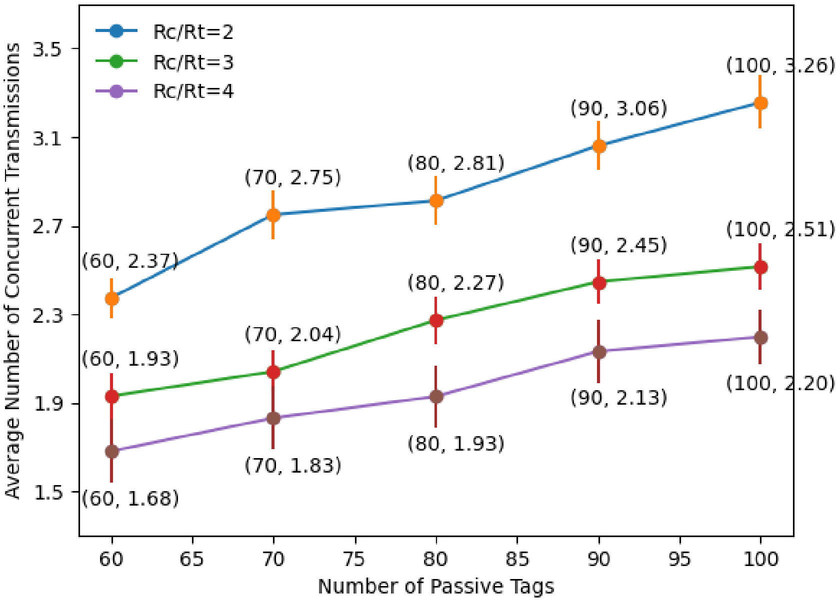

Figure 5.9: The effects of the number of passive tags and communication range ratio on the average number of concurrent transmissions with a 95% confidence interval applying RASSA are presented.

sectors is more than the neighbor passive tags of the receiver passive tag in a sector. Therefore, the effect of the controlled flooding algorithm in the last sector of the sectoral routing path is greater than the effect of having different paths through the sectors to the receiver passive tag. In Fig. 5.8 and 5.9, it is shown that the increasing number of passive tags or communication range ratio raises the average number of concurrent transmissions in our routing protocol, with a 95% confidence interval. The reason is that when these input parameters increase, the passive tag density of the sectors also increases, and both the numbers of routing paths through the sectors to the receiver passive tag and communications in the last sector in the sectoral routing path increments.

For the test cases where the effect of the number of sectors is observed, the beamwidth of the system is manually changed to have more or fewer sectors where the level width is determined by the system automatically, as explained in our protocol design. Additionally, to directly see the effect of the number of sectors, the number of passive tags and communication range ratio of the test cases are fixed, and their values are 100 and

3, respectively. In the average latency and the average number of hops calculations, the first received message by the receiver passive tag is considered. The effect of the number of sectors on the output parameters can be seen in the following figures.

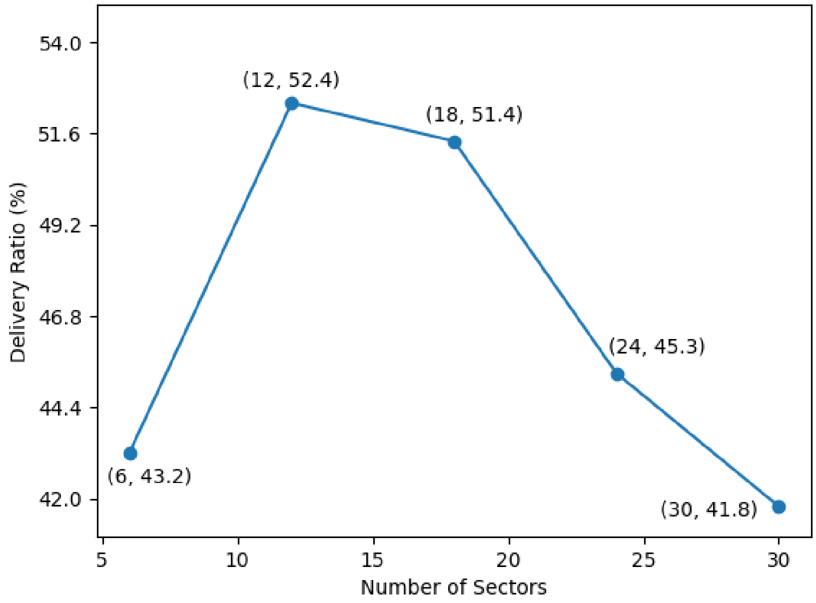

Figure 5.10: The effect of the number of sectors on the delivery ratio applying RASSD is presented.

By interpreting the Fig. 5.10 and 5.11, it is shown that the number of sectors is directly related to the delivery ratio of the system. It can be seen that there is an optimal value for the number of sectors in our system design to reach the maximum delivery ratio. When the number of sectors is more than the optimal value, the passive tag density of a sector decreases. Otherwise, if it is less than the optimal value, the passive tag density of a sector increases. In both cases, the delivery ratio decreases because the possibility of creating a disconnected path increases if the passive tag density is more or less than the optimal value. In the figures, when the number of sectors is 12, the maximum value for the delivery ratio is achieved. If the number of sectors is less or more than 12, the delivery ratio decreases. Therefore, 12 is the optimal value for our configuration, and it is automatically calculated by our protocol design for the configuration where the communication range ratio is 3.

In our routing protocol, the number of sectors in the sectoral routing path is the most

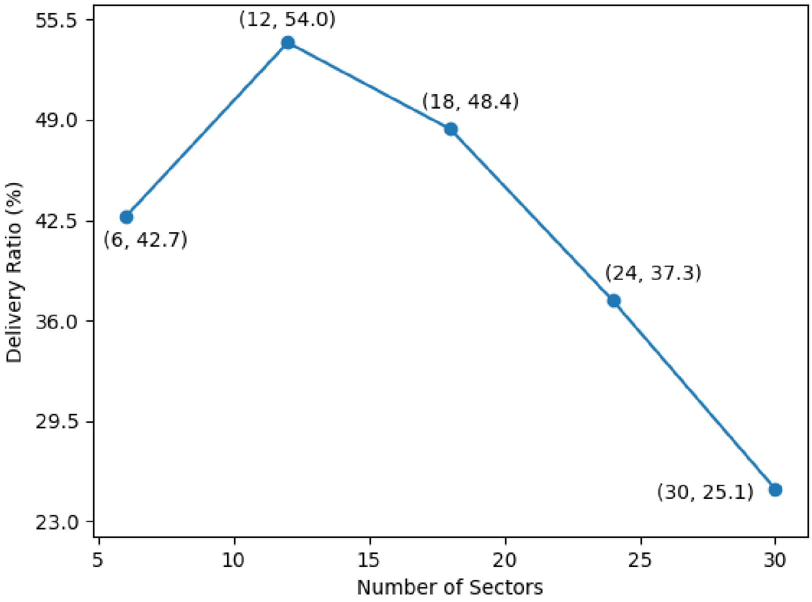

Figure 5.11: The effect of the number of sectors on the delivery ratio applying RASSA is presented.

significant factor that affects the average latency of the communications. Since the sectors are excited in a pairwise manner for a certain excitation time, which is directly related to the sector area, although a message is transmitted to the neighbor sector earlier than the total excitation time period of the sector, it waits until the end of the excitation time period. Therefore, the latency of a message is determined by the sum of the excitation times of the sectors in the routing path until the last sector. In the last sector, when the message is transmitted to the receiver passive tag in the excitation time period, the arriving time of the message is considered in the calculations independently from the excitation time of the sector. In Fig. 5.12 and 5.13, it is shown that the average latency of the communications increases with the number of sectors in the system with a 95% confidence interval. The reason is that if the total number of sectors in the system increments, the number of sectors in the sectoral routing path increases with the total excitation time of the communication. Additionally, the more number of sectors increases the possibility of creating disconnected routing paths and decreases the delivery ratio. In this case, successfully delivered transmissions occur when the sender and receiver passive tags are not far from each other. Since only the

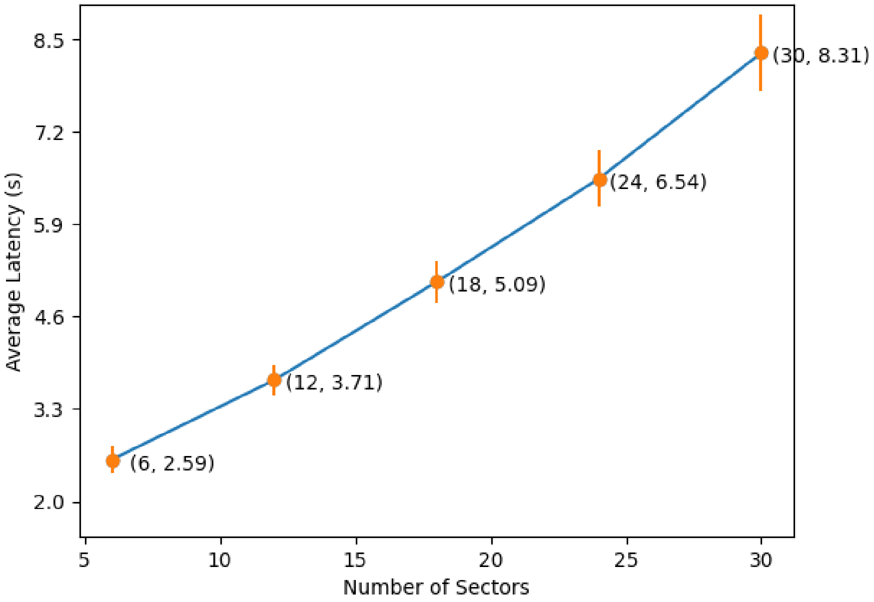

Figure 5.12: The effect of the number of sectors on the average latency with a 95% confidence interval applying RASSD is presented.

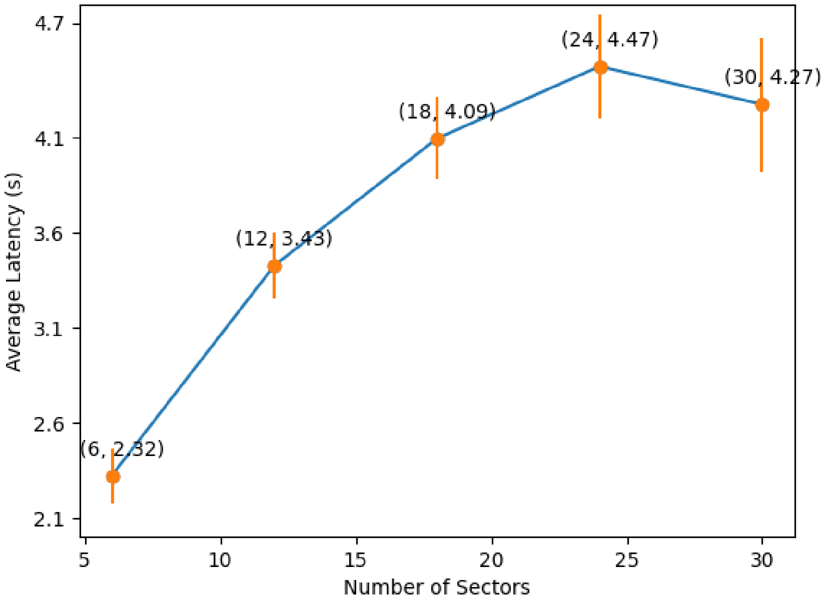

Figure 5.13: The effect of the number of sectors on the average latency with a 95% confidence interval applying RASSA is presented.

successfully delivered transmissions between the passive tags are considered while calculating the average latency, the communications between the passive tags that are close to each other are counted, and the average latency is decreased, as shown in Fig. 5.13.

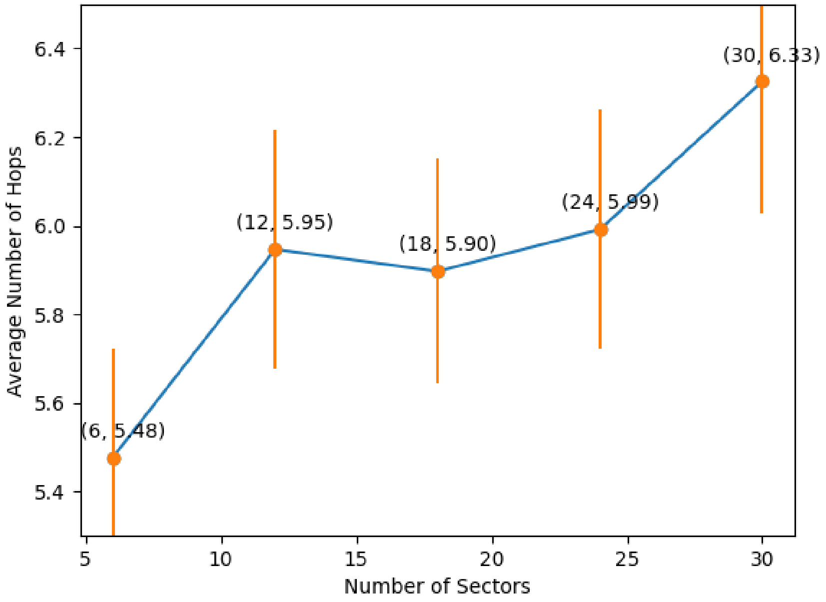

Figure 5.14: The effect of the number of sectors on the average number of hops with a 95% confidence interval applying RASSD is presented.

In Fig. 5.14 and 5.15, we can see the effect of the number of sectors on the average number of hops for the successfully delivered transmissions with a 95% confidence interval. When the number of sectors rises in the system, the communications between the passive tags that are not far from each other are accomplished mostly. Since only successfully delivered transmissions are considered in the calculations, the number of hops of the communications between the closer passive tags is counted; therefore, in Fig. 5.15, the average number of hops is decreased with the increasing number of sectors. In Fig. 5.14, it is shown that the values of the average number of hops according to the number of sectors are not affected significantly by considering the confidence intervals of the values. Although the effect is not significant, it is shown that the average number of hops increases with the number of sectors of the system. Considering the communication between the same passive tags, there is more

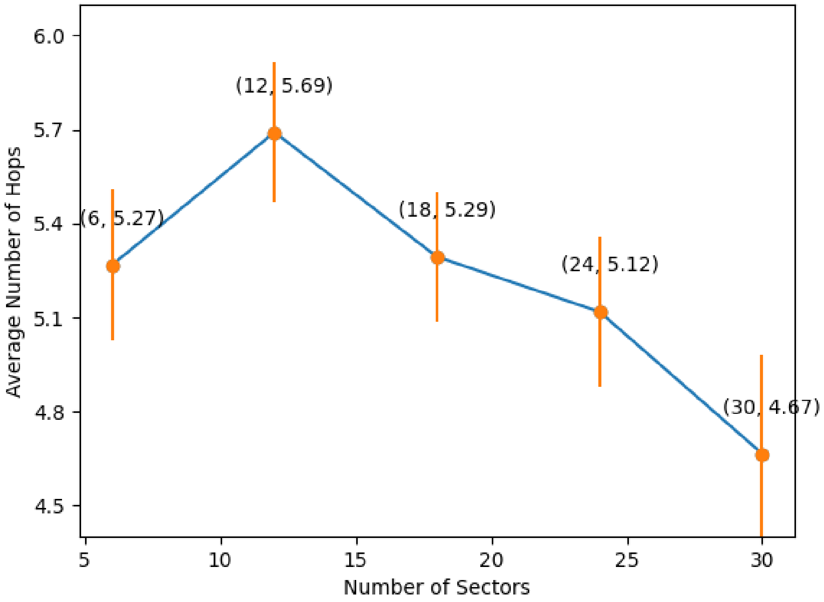

Figure 5.15: The effect of the number of sectors on the average number of hops with a 95% confidence interval applying RASSA is presented.

than one path between them, and by changing the number of sectors to pass through the receiver passive tag's sector, different paths can be preferred, and if there are more sectors to pass, the message is hopped more passive tags to reach the destination. The effects of the number of sectors on the average number of hops between our proposed algorithms are different, as shown in the figures. When the total number of sectors increases, the number of sectors in a sectoral path for a transmission between the passive tags increments, as expected. However, the number of sectors to pass in RASSA increases more than in RASSD because it finds the shortest sectoral path between the sectors. By considering the same passive tag density in the sectors, performing a successfully delivered transmission between the passive tags is more possible in RASSD because there are fewer sectors to pass.

As the number of passive tags and the communication range ratio, the number of sectors in the system directly affects the passive tag density of the sectors. The reason is that if there are more sectors with the same number of passive tags, the passive tag density is decreased. As explained previously, the passive tag density of the last sector in the sectoral routing path has a significant effect on the average number of

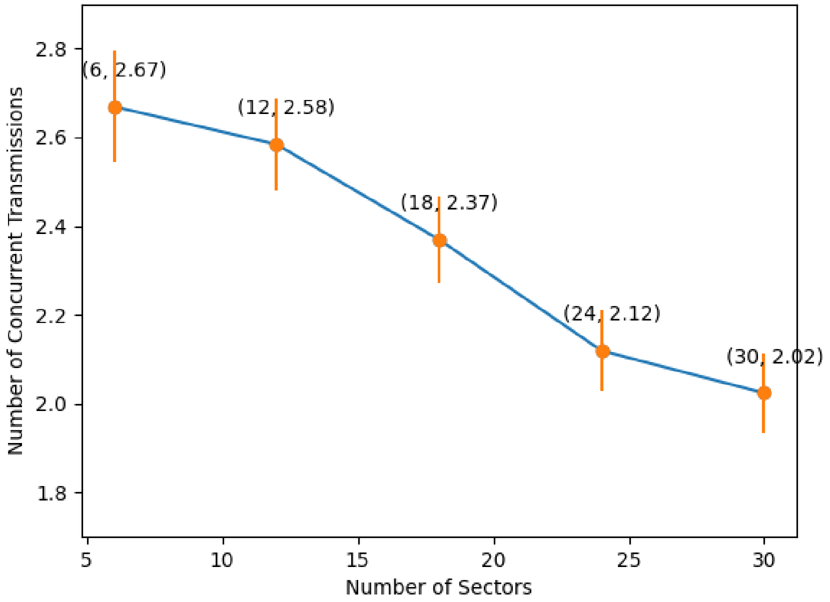

Figure 5.16: The effect of the number of sectors on the average number of concurrent transmissions with a 95% confidence interval applying RASSD is presented.

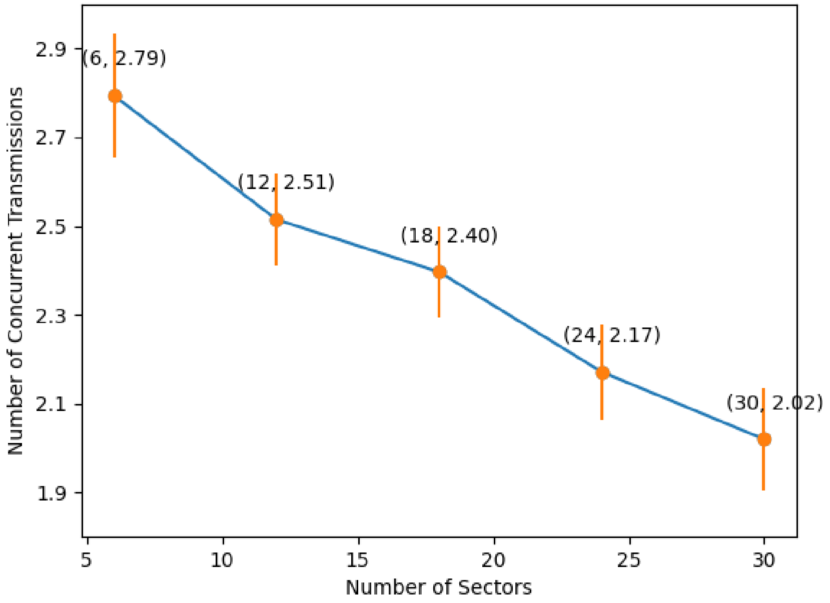

Figure 5.17: The effect of the number of sectors on the average number of concurrent transmissions with a 95% confidence interval applying RASSA is presented.

concurrent transmissions. If the number of sectors is decreased, the average number of concurrent transmissions is also decreased, as shown in Fig. 5.16 and 5.17 with a 95% confidence interval.

By considering the test results in the figures, we can compare the efficiency of our proposed routing algorithms in different output parameters. To compare them, we collect the data for the same output parameters from the different algorithms in the same figure:

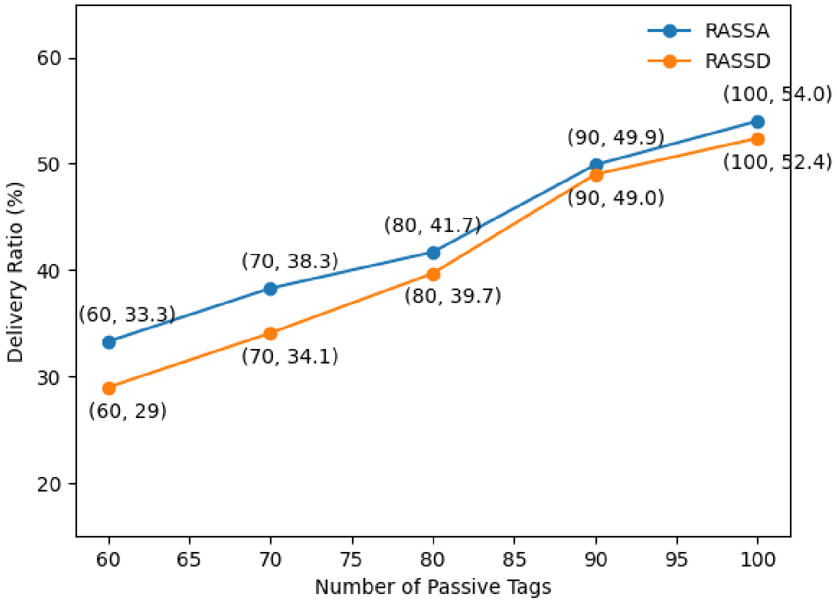

Figure 5.18: The effect of the number of passive tags on the delivery ratio is compared in RASSD and RASSA, where Rc/Rt=3.

- Delivery ratio: Considering the Fig. 5.18, 5.19 and 5.20 the performance of the algorithms are similar. Both of our proposed algorithms have advantages or disadvantages according to each other to have a better delivery ratio. When the number of passive tags is increased, the delivery ratio is also increased. If they are applied for the same test case, while the number of sectors is less in the sectoral path found by RASSD, the total size of the sectors to pass is more in RASSA. Having more sectors in the sectoral routing path increases the possibility of inter-sector disconnectivity, while having larger sectors in the

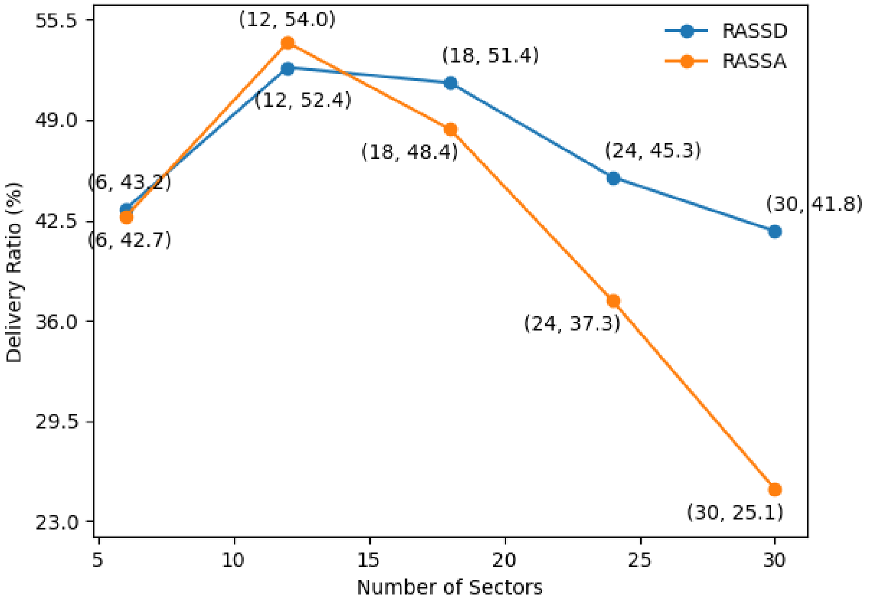

Figure 5.19: The effect of the number of sectors on the delivery ratio is compared in RASSD and RASSA, where the number of passive tags is 100 and Rc/Rt=3.

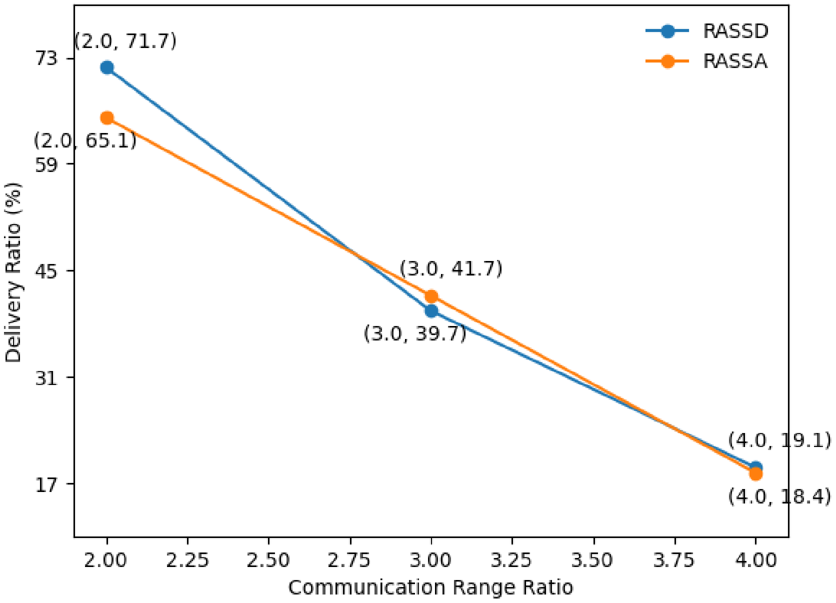

Figure 5.20: The effect of the communication range ratio on the delivery ratio is compared in RASSD and RASSA, where the number of passive tags is 80.

sectoral routing path increases the intra-sector disconnectivity. As shown in Fig. 5.19, there is an optimum number of sectors value to reach the best delivery ratio. However, increase in the number of sectors decrease the delivery ratio in RASSA more than RASSD. Because the algorithm determines the shortest sectoral path between the sender and receiver sectors in RASSD, increase in the total number of sectors rises the number of sectors in the sectoral routing path found by RASSA more than the path found by RASSD; therefore, the inter-sector disconnectivity increases more in RASSA than RASSD. Without considering the specified difference, the total performance of the algorithms in our test cases is similar for the delivery ratio.

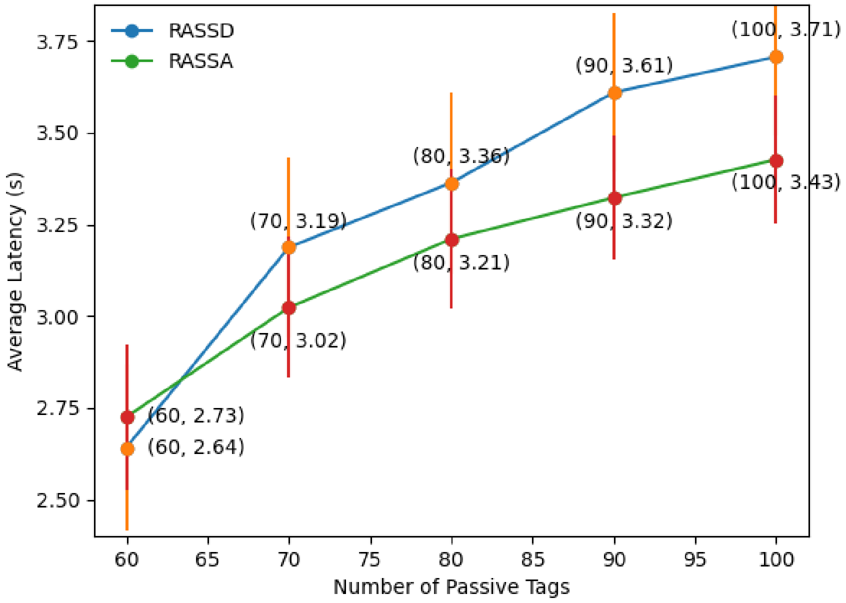

Figure 5.21: The effect of the number of passive tags on the average latency is compared in RASSD and RASSA, where Rc/Rt=3.

- Average latency: Considering the Fig. 5.21, 5.22 and 5.23 RASSA has a slightly better performance. The total excitation time of the sectors is directly related to the total size of the sectors in the sectoral routing path. Moreover, until the last sector in the sectoral routing path, the message transmission time is determined by the total excitation times of the sectors. Since the sectors are excited in a pairwise manner by the central controller, although a message is

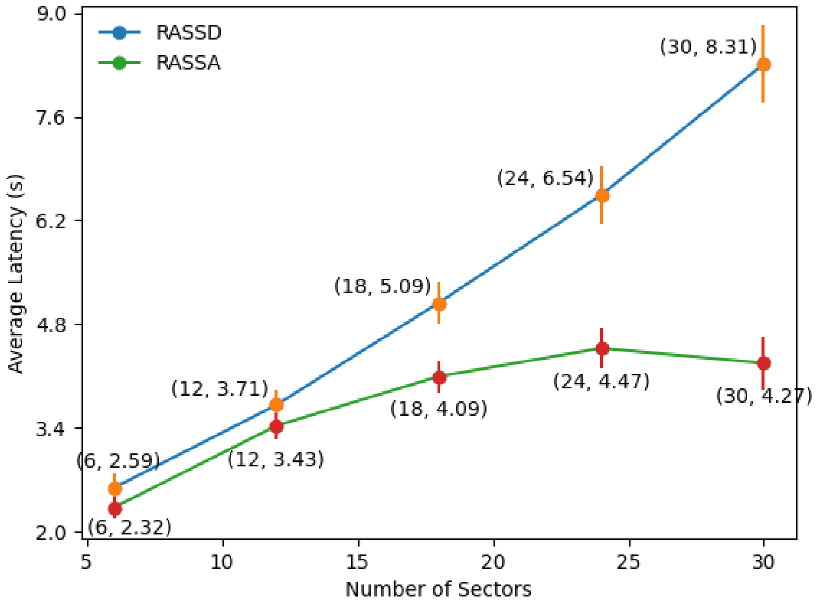

Figure 5.22: The effect of the number of sectors on the average latency is compared in RASSD and RASSA, where the number of passive tags is 100 and Rc/Rt=3.

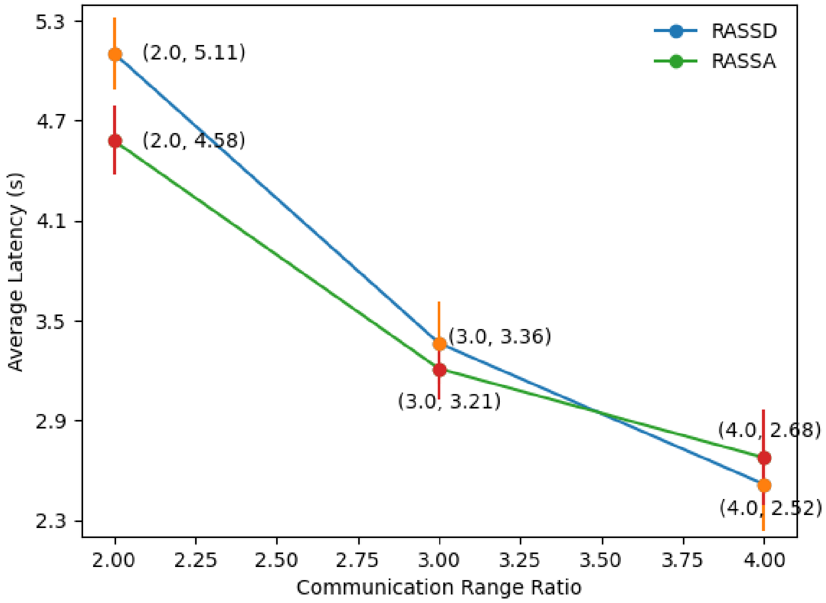

Figure 5.23: The effect of the communication range ratio on the average latency is compared in RASSD and RASSA, where the number of passive tags is 80.

transmitted to the passive tag in the next sector of the sectoral routing path, the transmission of the message in the next sector is not continued until the excitation period of the previous sector ends. Therefore, the smaller sectoral area in the sectoral routing path implies a shorter transmission time of a message, and RASSA finds the path whose total sector size is the smallest.

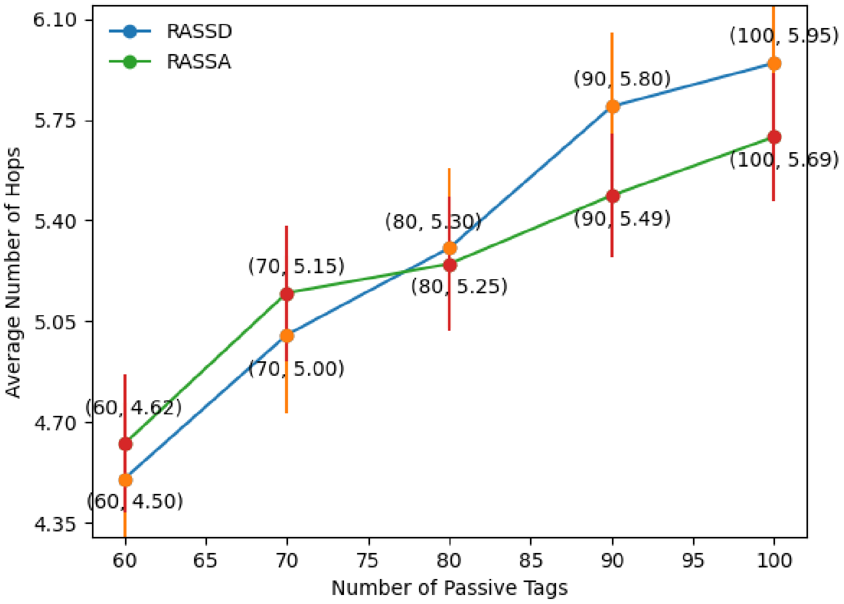

Figure 5.24: The effect of the number of passive tags on the average number of hops is compared in RASSD and RASSA, where Rc/Rt=3.

- Average number of hops: Considering the Fig. 5.24 and 5.26 the performance of the algorithms are similar. Changing the number of passive tags or the communication range ratio in the system affects the average number of hops; however, while determining the sectoral routing path, the effect of choosing RASSD and RASSA on the average number of hops are similar. Although the exact locations of the passive tags are not known by the central controller, both of our proposed algorithms try to determine a shorter path between the passive tag with their limited knowledge. By RASSD, the number of sectors of the sectoral path is minimized, and fewer sectors implies fewer passive tags to hop until the receiver passive tag. On the other hand, the total sector size in the sectoral routing path is minimized by RASSA. Because the passive tags are

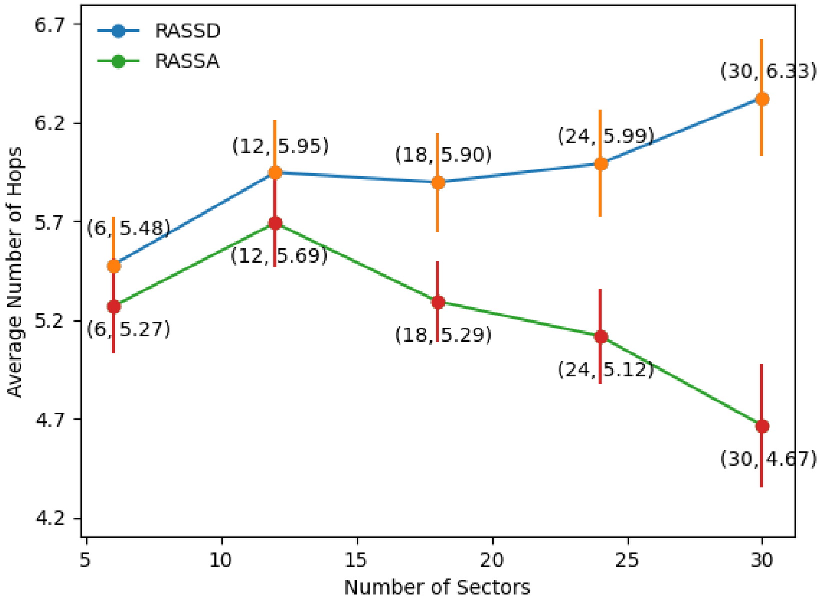

Figure 5.25: The effect of the number of sectors on the average number of hops is compared in RASSD and RASSA, where the number of passive tags is 100 and Rc/Rt=3.

distributed uniform randomly in the circular area, there are fewer passive tags in the smaller sectors, and the path whose total size of the sectors is minimum contains the minimum number of passive tags to hop until the receiver passive tag. According to the sector count, the average number of hops on the sectoral routing path found by RASSD is more than the path found by RASSA, as shown in Fig. 5.25. The decrease in the delivery ratio while the number of sectors increases is more in RASSA than the RASSD, as shown in Fig. 5.19. The successfully delivered transmissions are considered while calculating the hop count, and in this circumstances, the transmissions where the sectors of sender and receiver passive tags are close to each other is considered. Therefore, the decrease in the average number of hops is more in RASSA than RASSD. Additionally, average number of hops in the determined routing path by applying RASSD is more than the found routing path by applying RASSA in every circumstances. The reason is that considering the same passive tag density, the sectoral routing path determined by RASSD consists of more passive tags with

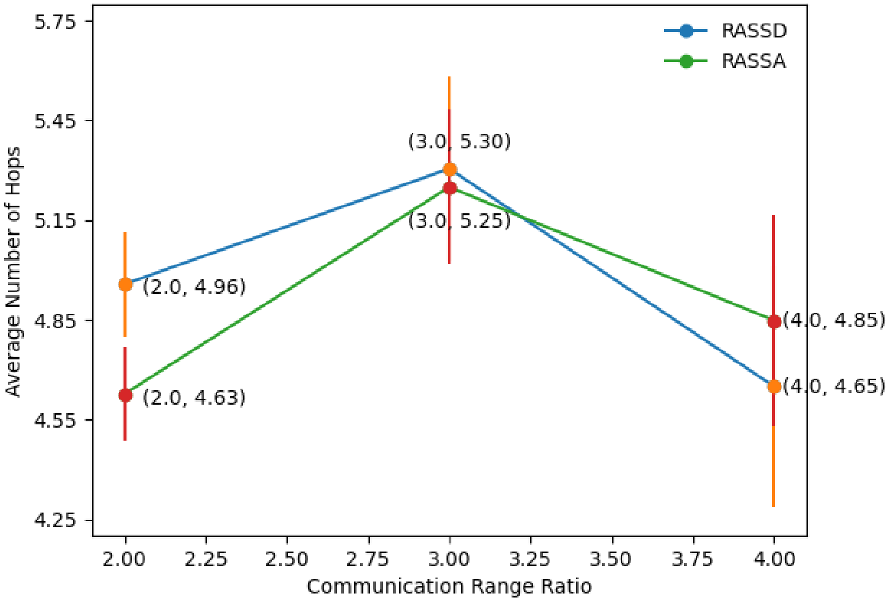

Figure 5.26: The effect of the communication range ratio on the average number of hops is compared in RASSD and RASSA, where the number of passive tags is 80.

respect to the RASSA, and the more passive tags in the routing path increases the number of hops.

- Average number of concurrent transmissions: Considering the Fig. 5.27, 5.28 and 5.29 the performance of the algorithms are similar. Considering the effect of the controlled flooding in the last sector on the average number of concurrent transmissions, because the last sector is the sector of the receiver passive tag and determined independently of the sectoral routing path, the average number of concurrent transmissions of the communications are similar although the routing path determination algorithms are different.

Our main motivation in this study is to propose a multi-hop routing protocol for tag-to-tag networks of passive tags with a complete system design that realizes energy-efficient device-to-device communications between the passive tags. To create an energy-efficient routing protocol, we utilize the batteryless environment of the passive tags first, which reduces the energy requirements of the system design significantly. The reason is that the only device in the system that consumes power is the

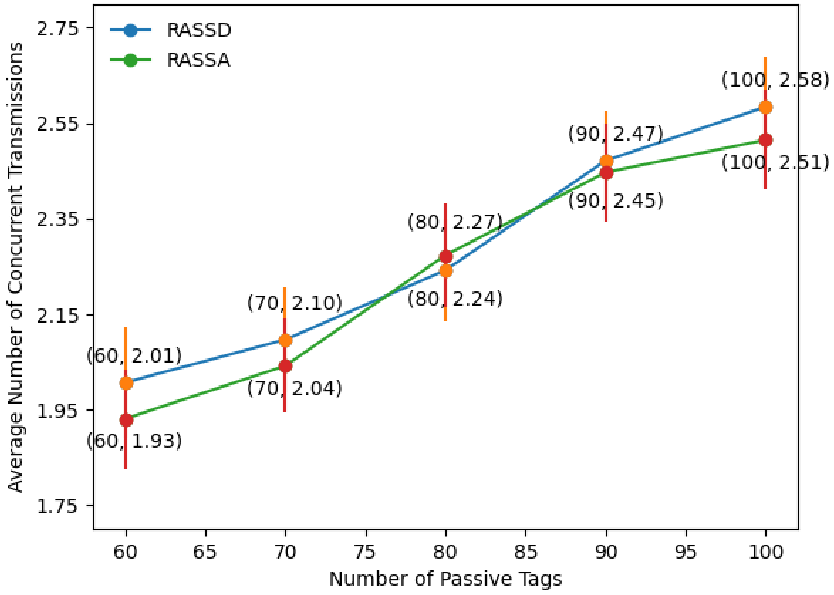

Figure 5.27: The effect of the number of passive tags on the average number of concurrent transmissions is compared in RASSD and RASSA, where Rc/Rt=3.

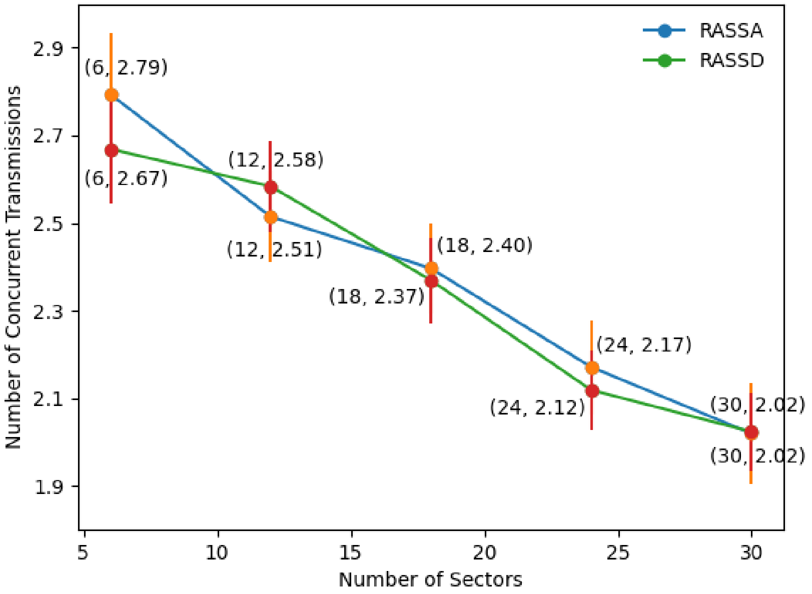

Figure 5.28: The effect of the number of sectors on the average number of concurrent transmissions is compared in RASSD and RASSA, where the number of passive tags is 100 and Rc/Rt=3.

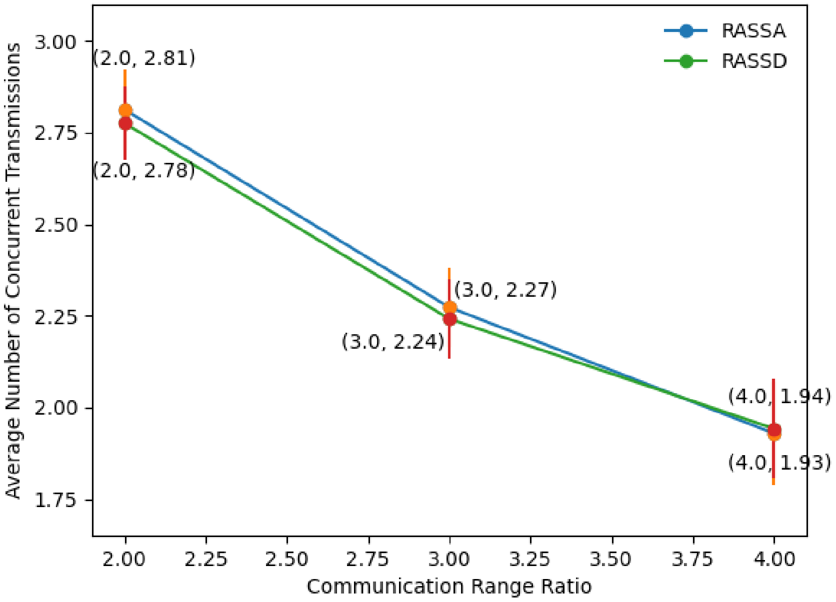

Figure 5.29: The effect of the communication range ratio on the average number of concurrent transmissions is compared in RASSD and RASSA, where the number of passive tags is 80.

central controller. On the other hand, for multi-hop tag-to-tag communication, all of the passive tags in the communication range of the central controller do not have to be excited. In our proposed routing protocol, we create a sectoral circular area according to the central controller by dividing the circular area into optimum-sized sectors. Instead of exciting the entire circular area, we excite the required sectors in a pairwise manner to route the message between the passive tags in a multi-hop fashion. To determine the required sectors, we present two algorithms that create sectoral routing paths. In total, to minimize the excitation power for a multi-hop tag-to-tag communication, we specify the minimum number of sectors and passive tags that should be excited in the routing path. Therefore, by exploiting the batteryless environment of the passive tags and determining the minimum number of the passive tags to excite while routing, we reduce the energy requirements of device-to-device communications significantly.

CHAPTER 6

CONCLUSION

With the Internet of Things and digital transformation paradigms in recent years, passive tags, which are required in many areas, have become a situation where they can talk not only with a reader but also with each other. Since these devices are power-limited, the need for a solution approach that can transmit messages over each other in a multi-hop fashion and thus enable them to talk effectively has been realized with this study. At this point, we have introduced a new routing algorithm that can fulfill this need and this system efficiently. This routing algorithm divides the circular area into sectors by consisting of a powered controller at its center and passive tags that are uniform randomly distributed around it. Considering a multi-hop tag-to-tag network of passive tags, different experiments involving different scenarios and examination of performance parameters such as passive tag count, and the communication ranges of the passive tags and central controller were carried out. With the light of the results, we can state that the proposed protocol has been utilized as an energy-efficient and easily applicable approach.

In this thesis, we propose our multi-hop tag-to-tag routing protocol design for stationary passive tags. On the other hand, with the advantage of the batteryless design of the passive tags, they can be used in mobile networks as wearable devices. For these scenarios, our work should be enhanced and applied to mobile tag-to-tag communications. Moreover, security concerns of tag-to-tag communications were not inspected in this study, and our next studies will focus on these concerns to present a secure multi-hop tag-to-tag network.

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