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Mobile Ad Hoc Network Protocols Based on Dissimilarity Metrics

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Mobile Ad Hoc Network Protocols Based on Dissimilarity Metrics

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Chapter 1
Introduction

The field of communications and computer networks changes rapidly with the development of various technologies and the progress of electronic manufacturing and integration. The ubiquitous availability of the Internet has changed the way of communication among people. Nowadays, Internet-based applications such as email, instant messaging, and social networks are used massively on daily basis. Therefore, ubiquitous Internet connectivity is a major necessity. For this, wireless communication which supports seamless connectivity without the necessity of cables is indispensable.

So far, the Internet has been primarily a network to inter-connect typical computers. However, there are several paradigms such as mobile networking, grid computing, and cloud computing, that enable a purposeful inter-connectivity between various devices, which may not be characterized as computers in the first place, such as cameras, smartphones, and sensors. The latest vision is to extend the inter-connectivity between devices making possible the formation of heterogeneous networks and contexts by inter-connecting virtual and real devices ranging from computers to simple sensors.

One of the trends is the connection of daily appliances to the Internet, which is denoted as the *Internet of Things* (IoT) [1, 2]. The IoT paradigm envisions a world full of networked electronic devices ranging from usual computers to very simple devices like sensors, coffee machines, smart meters, and wearables. This scenario will lead to a huge quantity of information (big data era) coming from the real world that needs to be efficiently processed. This connected world will expose many challenges from network related aspects such as connectivity, protocols, and security [3].

A networking paradigm that is not directly related to the IoT, but may be used very often in an IoT context, is the *ad hoc network*, which describes a local, temporary wireless network. Although, the IoT has been focused mostly on networks of static nodes with sensors, the *ad hoc network* paradigm may play an important role in the future [4].

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Machine-to-Machine communication (M2M) is another emerging concept in the telecommunication field [5]. It refers to scenarios where the communication between wireless machines can alleviate and even improve the congested scenario of infrastructure-based wireless networks [6]. It is well-known that cellular networks are being saturated due to high traffic (upload and download) originated by mobile devices. Therefore, solutions are needed to cope with the congestion in the near future. Under this congested scenario, M2M communications are envisioned to be suitable for alleviating such congestion.

Another networking paradigm is the *wireless multi-hop network* (WMHN) [7, 8]. In WMHN communications take place by nodes that cannot communicate directly, that is, a single-hop communication cannot be established between them. It is envisioned that the multi-hop paradigm will be presented in the aforementioned visions (IoT) and (M2M) where ubiquitous and seamless communications will be continuously present in our lives. Therefore, multi-hop communications will be so important in the near future for wireless pervasive and mobile communications. Although a great load of research about WMHNs can be found in the literature [7, 8], there is no consensus about the communication protocols to be used in such dynamic and uncertain scenarios. There is not a universal communication protocol that can be accepted as the most suitable for all possible scenarios. Most of the communication protocols proposed are only valid under major assumptions, can only be appropriated for a limited number of scenarios, and/or they consider global information, a requirement that is unlikely to be met in distributed networks like WMHNs. Many parameters have been used to determine how the information should be efficiently distributed throughout the network without exhausting the shared wireless medium.

Two widely used metrics in WMHN algorithms are *hop count* and *Euclidean distance* between the source and destination nodes. The idea in both cases is to reduce the number of nodes participating in the communication path by selecting distant nodes (in the case of Euclidean distance) and selecting the path with lower number of hops (in the case of hop count). However, these two metrics present clear limitations to be used in real world scenarios. For example, the Euclidean distance is only valid in outdoor scenarios, since it also requires that nodes must be equipped with *Global Positioning Systems* (GPS). Regarding hop count, it presents some limitation in dense scenarios where the number of nodes makes hop count inefficient to distinguish between close and distant nodes. Thus, efficient algorithms for the distribution of information in a WMHN is an active research topic and which mechanisms lead to an optimal solution is an open question [9].

In this book, we open a new research direction in WMHNs with the application of *dissimilarity metrics* to improve the performance of communication protocols [10]. Dissimilarity metrics have been proposed for other research areas such as biology, ecology, and economy, among others, to accomplish efficient classification of sets of features. For example, in the case of biology, two species can be categorized as the same family if they share many features. The question in such a case is to determine quantitatively how similar/dissimilar the two species are considering their common or different features, respectively.

In this book, we adapt and study the concept of dissimilarity metric to the features that can be easily obtained (measured) in a wireless multi-hop network using only local information. Therefore, the main contribution of this book is the adaptation of well-known dissimilarity metrics to enhance communication protocols such as broadcasting and routing in WMHNs [11]. Such adaptation has been achieved by using local topology information of nodes as the set of features to be compared.

1.1 Subject of the Book

The main subject of this book is the design of *efficient communication protocols* for wireless multi-hop networks. For this purpose, we first introduce the reader to the multi-hop network paradigm and existing communication protocols. Then, we introduce *dissimilarity metrics* and how to use them as a design parameter to develop new communication protocols for wireless multi-hop networks. We study and show that *dissimilarity metrics* can alleviate the issues and limitations of communication protocols based on *hop-count* and *Euclidean distance*.

Furthermore, we concentrate on a reliable *performance evaluation* of communication protocols, showing the importance of *simulation* and *real experimentation* in wireless multi-hop networks. To this aim, the proposed communication protocols based on dissimilarity metrics are studied in different network conditions, employing both simulations and a real wireless network testbed.

1.2 Intended Audience

The ideal target readers of this book are master students, PhD students, and researchers interested in the field of wireless communications and multi-hop networks. This book is self-contained, i.e., all information needed to understand the results is included in the first chapters. Nevertheless, some background in computer science and computer networks may be necessary to achieve a full comprehension of the presented communication protocols.

Therefore, we assume that the reader has a solid understanding of computer networks, wireless communications, and a basic understanding of wireless multi-hop networks. The reader can find an excellent introduction to computer networks in [12]. A good overview about MANET routing protocols can be found in [13] and [14], and a good overview about WSNs and WMNs in [15] and [16], respectively.

The first chapters are an ideal introduction for researchers interested in starting multi-hop ad hoc network research. The simulation analyses presented in Chaps. 6 and 7 are obtained using the NS-2 simulator [17]. Therefore, some knowledge about its use may be required to replicate the results.

This book shows all the steps needed to develop or modify existing communication protocols for wireless multi-hop networks. Therefore, this book is also suitable for communication protocol designers.

1.3 Structure of the Book

This book is structured in nine chapters. The first chapter is devoted to motivate and introduce the topic of the book. Chapter 2 presents an introduction of the different wireless multi-hop networks that can be found in literature. It is written in a survey manner; therefore, it should be easy to follow for all readers no matter their background on wireless multi-hop networks. Chapter 3 describes the main communication protocols for WMHNs, i.e., routing and broadcasting protocols. Chapter 4 introduces dissimilarity metrics used in the design of communication protocols. A well understanding of Chap. 4 is essential to understand the following chapters. Chapter 5 describes the first communication approach based on dissimilarity metrics. It presents the design of broadcasting protocols for WMHNs. Chapter 6 includes the evaluation of the proposed broadcasting protocols in VANET scenarios. This evaluation is based on a thorough simulation analysis using different network conditions and comparing the results of the proposed approach with other broadcasting protocols. Chapter 7 details the modification of a well-known routing protocol for MANETs using dissimilarity metrics. This chapter includes a meticulous simulation analysis and comparison between the modified and the original protocol. Chapter 8 evaluates the proposed broadcasting protocols in a real scenario using a testbed composed of more than 100 nodes. The experimental results presented in this chapter corroborate the goodness of the studied approaches. Finally, Chap. 9 summarizes our discussion, gives some conclusions about the discussed approaches, and some future research directions.

Chapter 2
Wireless Multi-Hop Networks

In this chapter, we introduce *wireless multi-hop networks* (WMHNs) in general and their variants, which are subject of our study.

For this we start in Sect. 2.1 with the simplest form of wireless networks namely single-hop wireless networks.

Subsequently, in Sect. 2.2 we introduce the general idea of multi-hop wireless networks.

Based on this, we classify various kinds of multi-hop wireless networks found in literature, that are subject of this book in Sect. 2.3. In Sect. 2.4, we discuss briefly the difficulties that rise from radio communication. In Sect. 2.5, we introduce metrics that are used in algorithms and protocols for multi-hop wireless networks. In Sect. 2.6, we introduce briefly the node and network model, which we have used in the studies. In Sect. 2.7 we tackle some issues that occur in multi-hop wireless networks in comparison to wired networks.

2.1 Single-Hop Wireless Networks

In recent decades, we have witnessed the rise of two different mobile communication technologies *cellular networks* and *wireless local area networks* (WLAN). The former is represented by 3G, UMTS, and LTE currently, and the latter, most prominently, is represented by the family of IEEE 802.11 standards [18]. Both of these technologies, although designed for totally different applications, share a fundamental characteristic; both are *single-hop wireless networks*. Thus, there is only a single wireless link between a source and a destination.

In cellular networks the wireless link is between a mobile device and the base station, in a WLAN the link is between a (mobile) station and the *access point* (*AP*). The base station and the access point are connected by means of wires to the next network segment. This simple network structure eases many issues in the design

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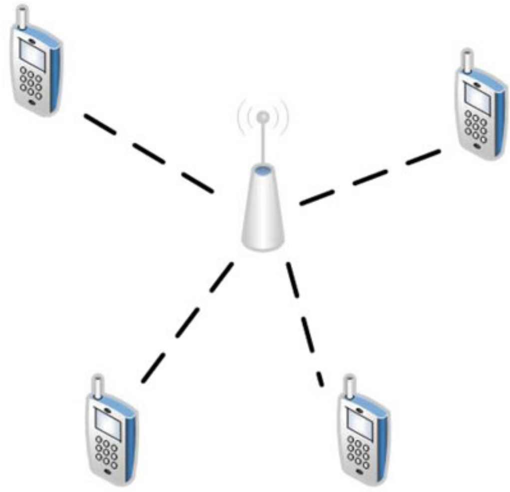

Fig. 2.1 Illustration of single-hop wireless communication. Several smartphones communicate with an access point. Between the smartphones and the access point is only a wireless link. The communication after the access point is wired

of the network protocol stack. However, this simple network structure comes at the cost of the required expensive infrastructure and the inflexibility of the system, since its deployment and maintenance are expensive. Figure 2.1 provides an example of single hop communication where several smartphones communicate with an access point.

2.2 Multi-Hop Wireless Networks

An alternative concept is the *wireless multi-hop network* (WMHN), which consists of only wireless links [19]. In a WMHN, two nodes can communicate with each other in two ways. First, if the source and destination nodes are mutually in their communication range, then both nodes can communicate directly. Second, the source and destination nodes are distant to each other and cannot communicate directly. In this case, other nodes—intermediate nodes—have to forward the data packets from the source node until they reach the destination node and vice versa. The latter case is called *multi-hop communication* [19]. Figure 2.2 illustrates a WMHN with a source node and a destination node.

We consider a WMHN as a set of nodes $V = \{v_1, v_2, \ldots, v_n\}$ and the wireless link $e_{ij} = \{v_i, v_j\}$ between two nodes $v_i, v_j \in V$. All wireless links between nodes in the WMHN determine the set $E = \{e_1, e_2, \ldots, e_k\}$. A *route* or *path* is a set of adjacent nodes $\{u_1, u_2, \ldots, u_l\}$ with $u_i \in V$ and u_1 being the source node and u_l the destination node. All other nodes are denoted *intermediate nodes*. When a node receives a packet and retransmits it, we denote it as *forwarding*.

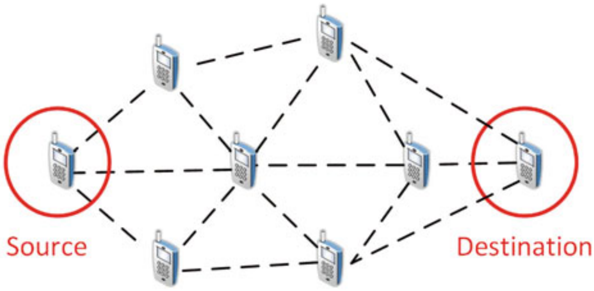

Fig. 2.2 Illustration of a WMHN. The source node and the destination node are not direct neighbors, thus the data packets have to be forwarded by the intermediate nodes of the network

2.3 Types of Wireless Multi-Hop Networks

The general concept of WMHN can be further elaborated, which results in different types of WMHNs. They all take the multi-hop paradigm as the mean of establishing a multi-hop path between a source and a destination node. The challenges of the different classes of WMHNs are mainly the same, with subtle differences, which are given by the class of network, e.g., routing in a *mobile ad hoc network* (MANET), energy in a *wireless sensor network* (WSN), and bandwidth in a *wireless mesh network* (WMN). The different WMHNs expose specific mobile conditions and network features for the design of communication protocols. Nevertheless, they share the same shortcomings and limitations, that is, the fact of using the wireless medium to communicate. In the following paragraphs, we present the main features of the different types of WMHNs.

First, we denote a WMHN as a *wireless mesh network* (WMN) if the nodes are static and do not move [20]. In some cases, the nodes participating in the last hop can be mobile. The main application area of WMNs is the extension of Internet connectivity in certain low connected areas. For example, in case of disaster scenarios, WMNs can be used to provide connectivity to ground nodes [21]. A reference work on WMNs can be found in [22]. The number of hops in WMNs is, in general, low with respect to other WMHNs.

If nodes in a WMHN are mobile and can move around, we denote it as a *mobile ad hoc network* (MANET). The main challenges of MANETs are the establishment of communication paths between nodes efficiently, self-organization in dynamic environments, and reduction of congestion [23], among others. MANETs are suitable for those cases where a dynamic and self-organizing network needs to be deployed quickly. Battlefields [24] and disaster scenarios [25–27] are clear examples of such situations. Routing and broadcasting protocols [28] are the main mechanisms to establish communications among nodes in MANETs. Dynamic topologies due to mobility [29] of nodes are by far the main issue to be solved in MANETs.

If the nodes in a WMHN are static, resources are scarce, and nodes are equipped with sensors, we denote it as *wireless sensor network* (WSN). The main challenges of WSNs are energy consumption, protocols for communications with limited bandwidth, network deployment for efficient topology (clustering), and routing among others [30]. With respect to previous WMHNs, WSNs are in general more focused on monitoring applications, where environment variables such as temperature, humidity, and CO2 emissions want to be measured and controlled. Hierarchical topologies can be easily found in WSNs. Normally, two types of nodes can be found in WSNs (1) *sensor node* and (2) *sink node*. Sensor nodes are particularly optimized to measure the (environmental) variables from the scenario, and sink nodes gather the information from sensor nodes. Furthermore, they are connected to a higher level network like the Internet.

Delay tolerant networks (DTNs) are one of the most interesting evolutions of MANETs in terms of connectivity and mobility. In DTNs, nodes do not require a high connectivity in order to communicate with each other [20]. The transmitted information is not delay-sensitive so nodes follow the carry-store-and forward paradigm in which nodes generate certain information and store it until they have a new opportunity to deliver it. That is, whenever they meet other nodes. Due to this feature, DTNs are also referred as *opportunistic networks* in literature, and each encounter between two nodes in the network is seen as a new opportunity to deliver information. In contrast to MANETs, mobility is seen as an advantage for disseminating information in DTNs, since the higher the mobility, the higher the probability of possible encounters with other nodes. Figure 2.3 shows an example of a possible DTN, a mobile source node wants to send a piece of information to a mobile destination node. As shown in Fig. 2.3, the relaying nodes take advantage of their mobility to forward the information from the source to the destination. An important difference with respect to MANETs is that, in DTNs there is not a communication path between the source and destination nodes at the time the information is generated by the source.

In DTNs there is no distinction between broadcasting and routing protocol based communications. There is only one way of communication between nodes which is used in every new encounter between two nodes [31]. In DTN communications, the information is sent in units called *bundles*. When a node generates some information, it is split into different bundles, and then, the node waits until encountering another node in order to deliver the information (*bundle protocols*). Consequently, while MANET routing protocols work on network layer, the bundle protocols for DTNs work on an upper layer, namely *bundle layer,* which is between the transport layer and application layer.

Another evolution of MANETs is to consider vehicles as the carriers of wireless transceiver so vehicles can communicate with each other. When wireless transceivers are included or embedded in vehicles, we refer to these ad hoc networks as *vehicular ad hoc networks* (VANETs) [32–34]. The idea behind VANETs is similar to that of MANETs, but with a higher degree of node mobility and with mobility limited to traffic lanes. There are also other clear differences in the wireless technologies used, MAC, and application layers. One important difference is related

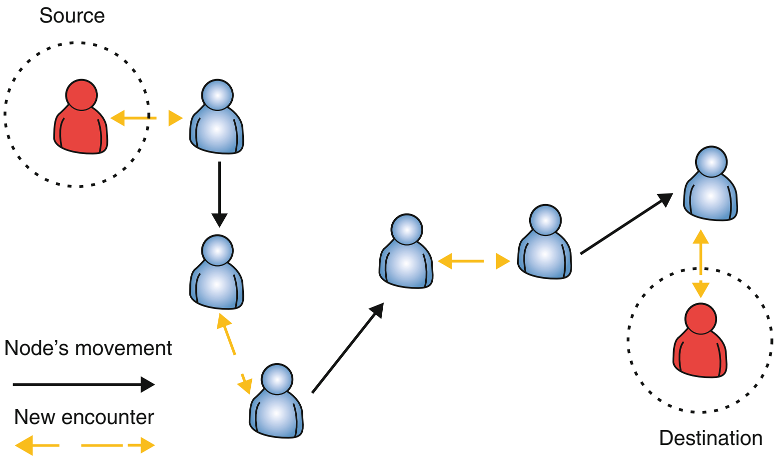

Fig. 2.3 A delay tolerant network (DTN) created consisting of a network of people. The communication between the source and destination will be forwarded by the intermediate nodes. However, the time for the forwarding of data is not tightly determined, i.e., a node forwards data to the next hop when they meet

to power consumption. While MANETs nodes are assumed to be battery powered, in VANETs, the wireless transceivers are self-charged by the batteries of the vehicles. Consequently, energy is not a key parameter in VANETs.

The basic types of communications in VANETs are the same mentioned above in MANETs. Nodes (vehicles) can use both broadcast communication and multi-hop communication via routing protocols [35], and both topics have been active research fields in the last decade [36]. However, there are significant differences in the design of broadcast and routing protocols for VANETs. First, since mobility is higher than in MANETs, a fast medium access is required in order to establish rapid communication among nodes. In this sense, the IEEE 802.11p MAC protocol [33] is preferred rather than using the traditional IEEE 802.11 a/b/g. In IEEE 802.11p several levels of prioritization are defined. Second, in VANET scenarios are also static nodes defined namely road units, which are intended for offering services to vehicles. Consequently, in VANET scenarios we can distinguish *vehicle-to-infrastructure communications* (V2I) and *vehicle-to-vehicle communication* (V2V). Both V2I and V2V are important components of *intelligent transportation systems* (ITS) and useful for a wide variety of applications such as incident detection, crash and congestion reporting, and traveler information dissemination [33]. The readers are referred to [37] for more information on projects and standardization actions in VANETs.

Figure 2.4 illustrates V2V communications in a VANET. This situation emulates a significant situation where one vehicle is aware of certain warning. This warning may be information about traffic or environment related conditions. In such situation, the node must inform others about the warning so as for other vehicles

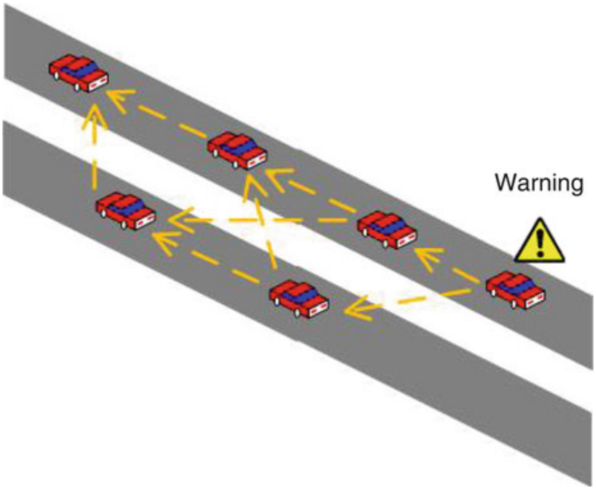

Fig. 2.4 Example of a vehicle-to-vehicle (V2V) communication. Vehicles can communicate with each other by forming a wireless multi-hop network without the ned of a fixed communication infrastructure

to adapt their behaviors appropriately. This dissemination should be done as fast and as effectively as possible. Since the density of nodes could be high, there is a tradeoff between reducing redundancy and increasing reliability of packets.

A WMHN in which nodes are *unmanned aerial vehicles* (UAVs) [38] is denoted a *flying ad hoc network* (FANET). There are two types of UAVs depending on the vehicle architecture: (1) fixed-wing and (2) rotary-wing UAVs. The fixed-wings UAVs [38] are characterized for performing *conventional take-off and landing* (CTOL) operations like commercial passenger's planes. Fixed-wing UAVs [39] are not able to hover in a specific position. Therefore, they require maintaining a minimum cruising speed in order to have lift forces.

Due to their flying properties, FANETs have the advantage of avoiding most of the obstacles that other terrestrial robots might find on the ground. This characteristic makes FANETs to be less affected by obstacles in many of their applications. Consequently, communication links suffer less from fading, multi-path propagation and other ground-like disturbances [40]. FANETs can be used in a wide variety of applications such as traffic monitoring, remote sensing, disaster monitoring, search operations, border surveillance, military operations, and relaying networks. Figure 2.5 shows an example of a FANET deployment for providing communication services to some ground nodes.

FANETs usually do not have a fixed topology. However, depending on the applications, different hierarchies and topologies may be needed. A FANET maybe organized in two groups [40]. On the one hand, groups with a high number of UAVs can be called based level UAVs. This one performs the main tasks related to the mission assigned, such as extending connectivity in disaster areas, remote sensing, and tracking targets. The other group consists of a few UAVs equipped with more powerful communication devices and computing resources. These UAVs create a high-level layer for long-range communication and processing purposes.

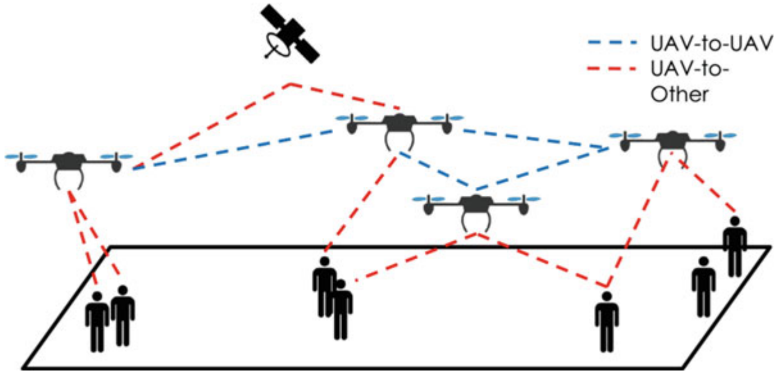

Fig. 2.5 Flying ad hoc network (FANET)

In general, FANETs are based on communication links established among UAVs, and other links with other higher level networks and/or ground base stations or command centers. Therefore, it is common to find UAVs-to-ground communication links in order to transmit data from the FANET nodes to ground stations and vice versa. However, the communication in multi UAV is either (1) in vehicle communications (IVC), (2) airplane-to-airplane (A2A), and (3) airplane-to-infrastructure (A2I).

2.4 The Wireless Medium

Wireless multi-hop networks have attracted a lot of attention from the research community in the last two decades. From a network perspective, the first idea was to employ the same communication protocols used in wired networks, e.g., the Internet. However, it was rapidly noticed that the underlying design of such communication protocols was not suitable for MANETs, WSNs, and WMNs. During the 90s and the first years of the new millennium, many researchers proposed new communication protocols at the lower layers of the ISO/OSI network model such as MAC and network layers. Those protocols are now well-known communication protocols for MANETs, e.g., AODV [41] and DSR [42] among others. They have been widely evaluated in simulations under different network conditions, showing shortcomings and limitations. Furthermore, when they were evaluated in real experimentation scenarios, e.g., in a *testbed*, the results were even more disillusioning. Even simple communication protocols like *flooding* do not work as expected under realistic network conditions.

Figure 2.6 depicts one of the main issues namely the transmission range of a node with a wireless transceiver. In many studies, an ideal circular transmission radius r_{ideal} is assumed. As a result, the node being considered can communicate with all nodes within a distance of r_{ideal}. However, a more realistic transmission range is

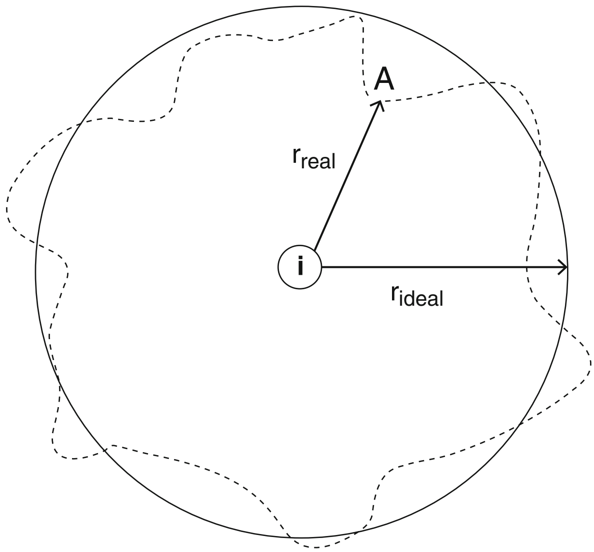

Fig. 2.6 Ideal and realistic wireless transmission range of a node

given by r_{real}, which is not a constant, but a random variable that changes over time and with the environment. The very same node may not be able to communicate to a neighboring node in this case.

Furthermore, there are many uncontrollable aspects in wireless communications that can impact negatively the communication, e.g., interference, noise, density of communicating nodes, and the environment. We refer the interested reader to [43] for an thorough discussion of wireless communication.

2.5 Metrics for Multi-Hop Networks

An algorithm or protocol for a multi-hop network may need one or more *performance metrics* to evaluate the current situation of the network. The performance of an algorithm or protocol may heavily be influenced by the used performance metric to describe the relationship between two nodes in a multi-hop network. Some metrics may be more appropriate for particular applications. Another important aspect is the cost involved with obtaining the value of a performance metric.

An example of such a performance metric is the quality of the wireless link between two nodes, denoted as the *link-metric*. The simplest link-metric is binary, i.e., a link is either available or not available at all. In Fig. 2.6 the node can communicate to another node within the communication radius. A wireless link between two nodes either exists or does not exist at all.

Another metric required for the routing in a wireless multi-hop network is the distance between the source node and the destination node, known as the *routing-metric*. The *number of hops* (*hop-count*) between the source node and the destination node is a well-known routing-metric. An alternative routing-metric is the *Euclidean distance* between the source node and the destination node, if available.

So far the *hop-count* is one of the most used metrics for various protocols and applications in wireless multi-hop networks, since it is simple to describe and easy to implement in a protocol. Furthermore, it is also easy to obtain, since every hop is counted as 1 unit of the metric. However, it is often difficult to map the unit of 1 hop to other means of performance measurement. For instance, the link between two adjacent nodes being 150 m in distance and the link between two nodes only 5 m distant counts the same 1-hop. Determining the Euclidean distance requires that nodes are equipped with a global positioning system like GPS, which may not be suitable economically or due to the application environment, like indoor applications.

Other routing metrics are *expected transmission count* (ETX), *expected transmission time* (ETT), and *weighted cumulative ETT* (WCETT). Each of these metrics incorporate features of the previous ones [44]. ETX is the estimated average number of transmissions required for the successful transmission of a packet. ETT is the time a data packet needs to be successfully transmitted. WCETT is based on ETT but addresses the issue of channel reuse along a path, considering the loss rate and the bandwidth of the link.

As an alternative to hop-count and Euclidean distance, dissimilarity metrics can also be used to determine the relative distance between two nodes in a wireless multi-hop network. Dissimilarity metrics measure the relative distance between two nodes in terms of the number of shared nodes in their transmission range. A node a is considered a neighbor of a node b, if a is located within the transmission range of b. Based on this definition, a node c is a shared neighbor of a and b, iff it is located within the transmission range of a and b at the same time (see Fig. 2.7). If the network is dense enough, those nodes sharing many neighbors must be very similar. The size of the intersection area shown in Fig. 2.7 depends on the relative distance between the nodes a and b. This fact is demonstrated in [45]. More details about dissimilarity metrics are given in Chap. 4.

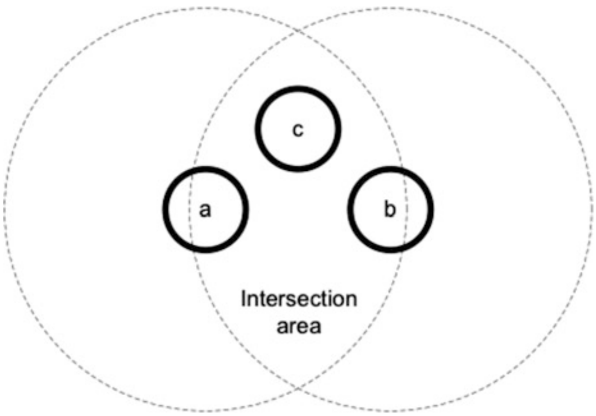

Fig. 2.7 Node c is a shared neighbor of the nodes a and b

2.6 Network Model

In this section, we provide a brief introduction of the protocol stack, node, and network models considered in this book.

2.6.1 Protocol Stack

Generally, the ISO/OSI (International Organization for Standardization/Open System Interconnection) protocol stack model is used for the description and discussion of networks. The ISO/OSI model consists of seven layers as shown in Fig. 2.8.

The *physical layer* is the lowest layer and deals with bit-level transmission between adjacent devices. The electromagnetic signals travel through a medium, e.g., air in wireless networks. The *data link layer* considers a number of bits as a frame and thus considers the transmission of frames between adjacent devices. For this, the frame structure, error detecting, and error correcting codes are considered. The *network layer* is the first layer that considers the communication between nodes which are not adjacent. The nodes can be distant in the network. The main issues on this layer are the *addressing* of nodes and the *routing* in the network. The *transport layer* considers the communication between a source node and a destination node, which is usually denoted as a flow. In the Internet the TCP (transmission control protocol) and UDP (user datagram protocol) are located on this layer. The *session layer* deals with the setup and maintenance of sessions between a source and destination node in the network. The *presentation layer* deals with the presentation of various data, which can be exchanged between source and destination nodes. The *application layer* deals with application protocols that provide higher-value services for applications by using the lower layer protocols.

However, in computer network literature a modified network stack layer is often used, since layers five and six are not implemented independently, particularly in the Internet. We follow this tradition and use the modified model illustrated in Fig. 2.9.

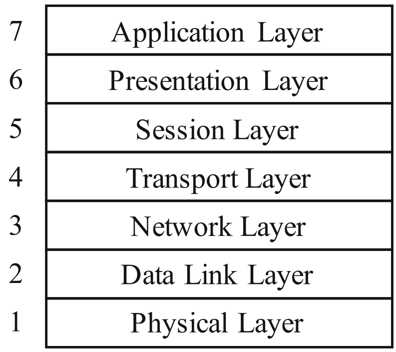

Fig. 2.8 ISO/OSI network stack model consisting of seven layers

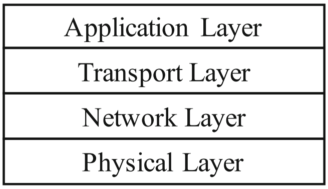

Fig. 2.9 Adapted ISO/OSI network stack model assumed for wireless multi-hop networks

An excellent introduction and discussion of computer networks and the ISO/OSI model is given in [12, 46].

2.6.2 Node Model

The node model considered in this book, and in general WMHN research, is a node equipped with a wireless transmission technology, e.g., Wi-Fi in the majority of cases. Nodes use omnidirectional antennas; it means that the electromagnetic signals are transmitted equally in terms of power transmission in all directions. Although there is research on the use of directional antennas in multi-hop networks [47, 48], the majority of the studies use omnidirectional antennas. The reason is that with omnidirectional antennas a node does not need to know the position/direction of other nodes, which greatly simplifies the protocols.

In this book, we consider a homogeneous network model, where all nodes are homogeneous from a functional point of view. Therefore, all nodes are equipped with the same wireless transceivers, i.e., have the same radio range and the same computational power. Although, in real-life portable devices such as smartphones and tablets can be different from one to another, this simplification is made in research for performance analysis purposes. Most simulation models implemented in network simulators to analyze WMHNs make such assumptions [49]. Nevertheless, the study of heterogeneous wireless networks is a hot research topic [49].

2.7 Wireless Multi-Hop Network Specific Problems on the OSI Layers

In this section, we briefly discuss problems of WMHNs on the various OSI layers. The most important issue on the *physical layer* is the communication range of a wireless node. Mathematical propagation models describe how the electromagnetic waves are attenuated during the travel between two nodes in the network. Friis [50], *two-ray*, and *multi-path* propagation models are some examples of models widely used in WMHNs [51]. Among them, the two-ray propagation model is widely used since it provides good results in urban environments with low number of obstacles. For instance, the two-ray model is suitable for VANET scenarios. In the case of indoor scenarios, the shadowing or multi-path propagation models are more suitable, since they take reflections into account. The performance on the physical layer is generally determined by the wireless technology used.

The *medium control access* (MAC) layer is a sublayer of the data link layer and plays an important role in WMHNs. The MAC layer deals with control access to the wireless medium. Therefore, this layer is very important in distributed networks like WMHNs, since nodes must share the wireless medium to communicate with each other. In dynamic networks like WMHNs, there is no central node that assigns the slot time at which each node in the network should use the wireless medium. Therefore, it is obvious that WMHNs require efficient MAC layers that avoid collision and contention among packets during transmission. For these reasons, the MAC layer design has attracted a lot of attention [50]. Power consumption is also an important matter in MAC layer design for WMHNs, since retransmissions due to collisions and erroneous packets consume more power. Additionally, the hidden-terminal problem and the exposed-terminal problem are likely to take place in WMHNs.

On the *network layer*, the design of routing protocols has been one of the most important issues for WMHNs [12–14]. The reason is that traditional routing protocols for wired networks cannot be used in such dynamic environments. The main objective of a routing protocol is finding an optimal communication path between a source and one or several destination nodes (*unicast* versus *multicast* protocols). Most routing protocols for WMHNs rely on broadcasting for the route discovery phase. Consequently, the design of efficient *broadcasting protocols* has also drawn the attention of many research studies [52, 53]. The main objective in broadcasting protocols is to avoid the well-known *broadcast storm problem* [54]. This problem appears when many nodes try to access to the wireless medium simultaneously. Both collisions and contention are the main problems caused by the broadcast storm problem [54].

One important difference of multi-hop networks with respect to wired network is the use of *Internet Protocol* (IP). IP addresses are the common mechanism to route information in wired networks like the Internet. However, its usage in multi-hop networks is not as clear as it is in wired network. The reason is twofold, first the dynamic of WMHNs, and second, the fact that all nodes perform as routers and hosts at the same time. Both features make the application of IP protocol difficult in WHMNs. For example, the implementation of *Domain Name System* (DNS) servers is not an easy task in such dynamic networks [55].

On the *transport layer*, two protocols are used in WMHNs such as the *Transport Control Protocol* (TCP) [55, 56] and the *User Datagram Protocol* (UDP) [57]. The selection of the transport protocol depends on the application that will be carried out by the multi-hop network. TCP is a connection oriented protocol that guarantees an error free, and consequently, the delivery of bytes from the source node to the destination nodes. TCP connections are bidirectional and widely used in the Internet. Another important feature of TCP connections is that lost packets are retransmitted to guarantee the reception at the destination node. In contrast, UDP is connectionless; it means that there is no guarantee that the packets sent by a source node will be received by the destination. In general, UDP connections are more suitable that TCP connections for multi-hop networks for several reasons. UDP connections are light-weight in comparison to TCP connections, and this is an important aspect in multi-hop networks where the dynamic of the network may result in short route life times. For the same reason, retransmissions of lost packets are difficult in WMHNs.

Application layer protocols are the less studied protocols in WMHNs. In general, *constant bit rate* (CBR) applications are studied to analyze the performance of multi-hop networks. In CBR applications, a source node sends a constant rate of bits to the destination node.

Chapter 3
Communication Protocols for Multi-Hop Ad Hoc Networks

In this chapter, we introduce two different approaches for communications in wireless multi-hop networks.

In Sect. 3.1, we introduce broadcasting to disseminate messages in a WMHN. In Sect. 3.2, we introduce routing for WMHN for the communication of two distant nodes and discuss classifications of routing approaches.

3.1 Broadcasting

Broadcasting is a dissemination mechanism in wireless multi-hop networks like MANETs, WMNs, and WSNs [20]. It is the operation used to transmit data in all-to-all fashion. Whenever a node broadcasts a message, all its neighbors receive it. The goal of a broadcasting approach is to maximize the reachability of a message in the network, i.e., the fraction of nodes in the network that receive a broadcasting message.

Many applications and network protocols require that all nodes in the network receive a broadcast message always. Otherwise, the protocol will not work properly. Among them are the discovery phase of routing protocols [58] and the dissemination of emergency messages in VANETs and disaster scenarios [59]. For instance, many routing protocols for wireless multi-hop networks assume that in the route discovery phase, all nodes receive the *route-request* message [60]. If some nodes, although available in the network, do not receive the route-request message, they will not respond and thus cannot be found by the source node. In that case, communications cannot be established between the source node and the destination node, even when both nodes are available in the network. In disaster and emergency scenarios, broadcasting also plays an important role. For instance, let us consider a crew-member taking part in a rescue operation that requires to disseminate the same information simultaneously to other crew-members. This has to be done in a reliable

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and efficient way. Other applications of broadcast communication are VANETs. For example, a vehicle informs other vehicles about a traffic accident, so that they can adapt their speed to the new traffic conditions in order to avoid further accidents.

Although broadcasting is simple to describe, it is not that easy to realize it cheaply in terms of communication resources [61]. Since there is no optimal solution employing only *local information* available to nodes, i.e., the required overhead is high and may not scale with the number of nodes in the network. Optimal solutions such as the *minimum connected dominating set* (MCDS) and *minimum spanning tree* (MST) are NP-hard problems [61] and they require global information. Although there are distributed algorithms to approximate the *connected dominating set* (CDS) [62] and MST in a wireless multi-hop network using only local information, those algorithms may perform inefficiently under mobility conditions, attacks, or bad performance of certain nodes. Consequently, a great variety of broadcasting approaches have been proposed [61–64].

3.1.1 Classification of Broadcasting Algorithms

Broadcasting algorithms can be classified [63] as (1) simple flooding, (2) probabilistic, (3) area-based methods, (4) counter-based methods, and (5) neighbor knowledge schemes.

Simple flooding is the simplest broadcasting method in which each node retransmits an incoming packet once. Unfortunately, it is inefficient in terms of redundancy, resulting in the well-known broadcast storm problem [45]. In *probabilistic* schemes, nodes rebroadcast an incoming packet with some probability [45]. The forwarding probability can be calculated by using numerous parameters such as density of nodes, distance between nodes, and the speed of nodes, among others. *Area-based approaches* require nodes to be equipped with a positioning system like GPS or an alternative system. *Counter-based* methods exploit the number of received copies of a given packet in order to estimate the density of nodes and to obtain feedback on the broadcasting process in the neighborhood of a node. The basic idea is that nodes do not need to retransmit if a certain number of neighbor nodes have already retransmitted a given packet. Finally, *neighbor knowledge* methods use topological information in order to select a set of neighbor nodes as potential forwarders.

An alternative classification of broadcasting approaches divides them into two main groups [52] (1) deterministic approaches and (2) probabilistic approaches. In *deterministic*, approaches a subset of all nodes in the network is selected as optimal forwarders, thus these nodes always forward an incoming packet. This type of broadcasting presents some shortcomings. First, node mobility may result that the algorithm used to select the optimal forwarders must determine the nodes belonging to this subset continuously. However, it can be difficult or costly in terms of data exchange depending on the dynamics of the network and the information required by the algorithm. Second, in networks with limited energy resources such as WSN, the subset of selected forwarder-nodes will deplete their energy quickly, resulting in network partitioning. Third, deterministic approaches are more prone to suffer from the presence of malfunctioning nodes and malicious nodes, e.g., in the case that a malicious node is selected as a forwarder.

3.1.2 *Probabilistic Broadcasting Algorithms*

In this section, we review some well-known broadcasting algorithms that will be used later on in the book.

3.1.2.1 Flooding

Flooding is the simplest broadcasting approach. A node retransmits an incoming packet once. Although very simple to realize, flooding is unfortunately inefficient in terms of redundancy, resulting in the well-known broadcast storm problem [20].

3.1.2.2 Gossip

Gossip is the simplest probabilistic approach. A node forwards an incoming packet with a probability p and does not forward the packet with probability $(1-p)$ [64]. There are plenty of different Gossip approaches that differ in how p is determined [52]. A thorough survey about Gossip broadcasting protocols can be found in [52].

3.1.2.3 *p*-Persistence

In p-persistence the forwarding probability p is determined linearly with the relative Euclidean distance d_{ik} between two nodes i and k as follows [65].

$$p = \frac{d_{ik}}{r}, \quad 0 \leq d_{ik} \leq r \tag{3.1}$$

In Eq. (3.1), r represents the radio transmission range of the nodes in the network and d_{ik} the Euclidean distance between nodes i and k. The larger the distance d_{ik} between the nodes i and k, the higher is the forwarding probability p.

3.1.2.4 Polynomial Broadcasting

The main objective of the polynomial broadcasting protocol is to reduce the number of retransmitted packets compared with the p-persistence algorithm [66]. The forwarding probability p is obtained as follows.

$$p = \left(\frac{d_{ik}}{r}\right)^g, \quad 0 \leq d_{ik} \leq r, \; g \in \mathbb{N} \tag{3.2}$$

The main difference of the p-persistence protocol is the exponent g. The forwarding probability function can be tuned by g.

3.1.2.5 Irresponsible Forwarding

The irresponsible forwarding algorithm combines the relative distance between two nodes i and k and the density of the neighborhood to obtain the retransmission probability [67]. The retransmission probability is given by the Eq. (3.3).

$$p = (1 - F_{x_{ik}}(r - d_{ik}))^{\frac{1}{c}} \tag{3.3}$$

In Eq. (3.3) c is a shaping parameter to determine the forwarding probability and $F_{x_{ik}}()$ is the cumulative distribution function (CDF) of the distance between two nodes i and k.

The main idea is that the forwarding probability of a node should be proportional to the probability that there is not a node in the distance $(r - d_{ik})$. It means that there is not a node located at a larger distance from the sender.

Exponential and lognormal distributions of nodes can be found in WMHNs [68]. In case of the exponential distribution, the forwarding probability can be calculated as follows:

$$p = \exp\left(-\frac{\varphi_s(r - d_{ik})}{c}\right) \tag{3.4}$$

Where φ_s is the spatial density of nodes in Eq. (3.4) measured as the ratio of nodes/meter and c the mentioned shaping parameter.

3.2 Routing

The goal of routing protocols in wireless multi-hop networks is finding an optimal communication path between a source node and a destination node. Due to the dynamics of these networks, routing protocols for wired networks cannot be used. Depending on the application area, different optimization criteria can be selected. For instance, the goal can be maximizing the throughput while minimizing packet loss, control overhead, and energy usage. In general, a routing approach for wireless multi-hop networks consists of three different subtasks (1) route discovery, (2) route maintenance, and (3) route error handling.

The *route discovery* task is responsible for the discovery of new routes between the nodes in the network. The *route maintenance* task is responsible for the maintenance of discovered routes during data exchange and when routes are not used for some period. Particularly, the detection of stall routes is an important sub-goal. The *route error handling* is responsible to handle errors in the data communication due to route errors, which may be caused by node mobility, and packet transmission errors, among others.

Routing protocols can be classified in different ways [69, 70]. The main classification distinguishes (1) reactive, (2) proactive, and (3) hybrid routing protocols.

In *reactive routing* protocols, if a route to the destination node is not known, the source node initiates a route discovery process. After discovering a route, the route maintenance is initiated to preserve it until the route is no longer required or the destination is not reachable. The main advantage of reactive routing protocols is the low overhead.

Proactive routing protocols maintain always up-to-date routing information to every other node in the network. Routing information is stored in the routing table of each node and route updates are propagated throughout the network to keep the routing information as recent as possible. Different protocols keep track of different routing state information. However, all of them have the common goal of reducing route maintenance overhead as much as possible. These types of protocols are not suitable for highly dynamic networks due to the extra control overhead generated to keep the routing tables consistent and fresh for each node in the network.

Hybrid routing protocols combine characteristics of both reactive and proactive routing protocols to make routing more scalable and efficient. Most hybrid routing protocols are *zone based*, i.e., nodes are clustered in different zones to make route discovery and maintenance more reliable.

In addition to these main classes of routing protocols, there are plenty of routing protocols with special characteristics.

Location aware routing algorithms assume that each node is aware of the location of all the nodes in the network. This requires that nodes are equipped with a GPS device or an alternative system to determine the exact coordinates of these nodes. The location information is then utilized by the routing protocol to determine the routes.

Multi-path routing algorithms discover and use more than one route between a source node and a destination node at the same time. The main advantage is that the bandwidth between links is used more effectively and thus, packet transmissions have higher delivery reliability.

Hierarchical routing protocols build a hierarchy of nodes, typically through clustering techniques. Nodes at the higher levels of the hierarchy provide special services, improving the scalability and the efficiency of the routing process.

Multicast refers in contrast to *unicast* to simultaneous transmission of the same data from one source node to multiple destination nodes. Thus, *multicast routing* protocols have more than one destination node. Audio-video teleconferencing, real time video streaming, and the maintenance of distributed databases are examples of application that need such a routing protocol.

Geographical multicast algorithms are a variant of multicast routing. The goal is to transmit the packets from a source node to destination nodes located within a specific geographical region.

3.3 Application of Broadcasting in Multi-Hop Networks

Broadcasting plays an important role in the performance of multi-hop ad hoc networks. Regardless of the type of WMHN (WSN, WMN, MANET, VANET), broadcasting is widely used as dissemination mechanism in which a node in the network has to transmit a message throughout the network, and also, within routing protocols, especially in the discovery phase of routing protocols.

Apart from these uses, broadcasting is also used for other operations such as the maintenance of routes, localization services, and the exchange of neighboring information in general.

3.3.1 Information Dissemination

Broadcasting is the main mechanism to disseminate information in all-to-all fashion. This is the case of spreading information in emergency or disaster scenarios [71, 72]. The main goal is to transmit the same information to all nodes forming the network or at least a target percentage of the network. By this, the number of broadcasting messages used to reach the target outreach should be as low as possible and, in addition to that, the messages should go along the network as fast as possible, since the delay can be an important parameter in the broadcasting-based application.

3.3.2 Route Discovery

When broadcasting is used in the discovery phase of routing protocols, the objective is to find a destination or several destination nodes (depending on whether it is unicast or multicast routing protocol) in the network. Notice that the objective is slightly different from the previous case (broadcasting as a stand-alone dissemination technique). In this case, a source node does not want to reach every node in the network. Instead, it requires only to know if a route is available to communicate with a target node. Consequently, the dissemination of the broadcasting message should be guided to the destination node. In most of the classical routing protocols for multi-hop ad networks such as AODV [41] and DSR [42], nodes use simple flooding as the broadcasting protocol to reach a destination node from a source node. However, it is well-known that flooding is both inefficiently and costly in terms of number messages exchanged, causing the broadcast storm problem [58]. For this reason, a number of broadcasting algorithms have been proposed to improve the discovery phase of routing protocols [73].

Chapter 4
Dissimilarity Metrics

In this chapter, we introduce dissimilarity metrics for wireless multi-hop networks. The dissimilarity metrics will be applied in the following sections to solve well-known problems of communication protocols in wireless multi-hop networks.

In Sect. 4.1, we introduce similarity and dissimilarity in general and discuss their properties. In Sect. 4.2, we introduce dissimilarity metrics for wireless multi-hop networks and the definition of some well-known dissimilarity metrics. Subsequently, we analyze the introduced dissimilarity metrics in random network topologies in Sect. 4.3, for vehicular networks in Sect. 4.4, and in a real testbed in Sect. 4.5.

4.1 Dissimilarity Metrics

Generally speaking, *similarity metrics* or *similarity coefficients* are aimed to match coincidences in two groups for any or some specific characteristics. In our case the similarity metric is aimed to find the coincidences between the neighborhood of two nodes in a wireless network.

For this, we first review the environment of two wireless nodes i and k as depicted in Fig. 4.1. The nodes i and k are separated by a distance d and share some neighboring nodes. A neighbor node m is shared by the nodes i and k, if m is located inside the radio transmission ranges of i and k. Notice that the probability of a node m of being in the *intersection area* (*IA*) of both nodes i and k depends on the Euclidean distance d between both nodes and the density of nodes in the network. The shorter the distance d between two nodes, the larger the *IA* will be, and consequently, the probability of finding more nodes in *IA* for a given density. This fact is demonstrated in [73].

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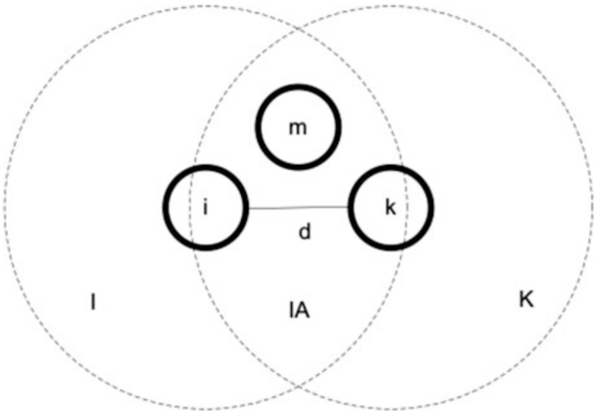


Fig. 4.1 Similarity between nodes *i* and *k*. Node *m* is a shared neighbor of both nodes

Based on this, we can define the *similarity coefficient* C_{ik} between two nodes i and k in a wireless network as the ratio between the number of neighbors that the two nodes i and k share and the total number of neighbors of both nodes. Equation (4.1) depicts C_{ik} between two nodes i and k.

$$C_{ik} = \frac{a_{ik} + \delta a_z}{a_{ik} + \delta a_z + \lambda(a_i + a_k)} \tag{4.1}$$

Where a_{ik} is the number of neighbors shared by the nodes i and k, a_i is the number of neighbors of the node i that are not neighbors of the node k, and similarly, a_k is the number of neighbors of the node k that are not neighbors of the node i. The terms $a_i, a_k, a_{ik}, a_z \in \mathrm{N}_0$, and $0 \leq C_{ik} \leq 1$. Therefore, most of similarity and dissimilarity coefficients are within the interval [0, 1]. Referring to Fig. 4.1, a_{ik} is the number of nodes inside the region IA, a_i is the number of nodes inside I, a_k is the number of nodes in the region K, and a_z is the number of nodes which are not neighbors of either i or of k. Furthermore, δ and λ are weighting factors. These factors determine the importance given to each term a_i, a_k, a_{ik}, and a_z their relationship. There are many *dissimilarity metrics* described in literature [74], which depend on the values of δ and λ. Therefore, different similarity coefficients can be obtained such as Jaccard ($\delta = 0$ and $\lambda = 1$) and Dice ($\delta = 0$ and $\lambda = 2$), among others. In WMHNs δ should be equal to zero as a rule since we cannot obtain easily global information such as a_z in a distributed network like a WMHN. The value of a_z can not be obtained in WMHNs since it represents those nodes out of the coverage range of nodes i and k. In general, nodes obtain neighboring information in WMHNs through exchanging Hello packets. These are single-hop broadcast packets that contain little information and are useful to maintain neighboring tables.

The *dissimilarity* D_{ik} between two nodes i and k is defined in Eq. (4.2).

$$D_{ik} = 1 - C_{ik} \tag{4.2}$$

The dissimilarity of two nodes can be seen as an estimation of the *Euclidean distance* between the two nodes. In fact, the Euclidean distance between two nodes is a dissimilarity metric of two continuous variables such as the coordinates x and y. In wireless networks the fact of sharing a neighbor by two nodes can be seen as a binary variable. Using the definitions of similarity and dissimilarity, several *distances* (or *dissimilarities*) can be defined.

In this book, we only consider dissimilarity metrics, that do not require global information ($\delta = 0$). The nodes are able to calculate the dissimilarity in a distributed fashion. Consequently, Eq. (4.1) simplifies to Eq. (4.3).

$$C_{ik} = \frac{a_{ik}}{a_{ik} + \lambda(a_i + a_k)} \tag{4.3}$$

Again, C_{ik} is within the interval [0, 1].

4.1.1 Properties of Dissimilarity Metrics

In the context of WMHNs, dissimilarity metrics are used as a distance, and there are some intuitive properties associated to the concept of distance. For example, the distance between distinct points is positive and the distance to the same point is zero, the distance from i to k is the same as the distance from k to i, and the triangle inequality means that the distance from i to k via j is at least as great as from i to k directly. These properties of a dissimilarity metric D_{ik} are formalized as follows:

1. Non-negativity: $D_{ik} \geq 0$.
2. Reflexivity: $D_{ik} = 0$ if and only if $i = k$.
3. Symmetry: $D_{ik} = D_{ki}$.
4. Triangle inequality: $D_{ij} + D_{jk} \geq D_{ik}$.

4.2 Dissimilarity Metrics for Two Nodes

In the following subsections, we describe the main features of some well-known similarity/dissimilarity metrics.

4.2.1 Jaccard Coefficient and Dissimilarity

The Jaccard coefficient J between two nodes i and k is a similarity metric, which is defined as:

$$J = \frac{a_{ik}}{a_{ik} + a_i + a_k} \tag{4.4}$$

The Jaccard distance $\overline{J}$ between the two nodes i and k is defined according Eq. (4.5).

$$\overline{J} = 1 - J = 1 - \frac{a_{ik}}{a_{ik} + a_i + a_k} = \frac{a_i + a_k}{a_{ik} + a_i + a_k} \tag{4.5}$$

The Jaccard distance accomplishes all the basic properties of a distance. If two nodes are identical, the Jaccard distance is zero and it reaches its maximum value when two nodes do not share any intermediate node. Notice that if two nodes are located at the same position, their term a_{ik} will be equal for both nodes, and the terms a_i and a_k will be zero. Therefore the coefficient J will be 1, and consequently, $\overline{J}$ will be zero. The Jaccard distance is also symmetrical and satisfies the triangle inequality. It is symmetrical because the term a_{ik} is equal to the term a_{ki}.

The Jaccard distance $\overline{J}$ has been studied in mobile ad hoc networks [73] to improve the discovery phase of the AODV routing protocol [75] and in opportunistic networks to enhance data dissemination [76].

4.2.2 Dice Coefficient and Dissimilarity

The Dice coefficient D and the Dice dissimilarity $\overline{D}$ between two nodes i and k are introduced in [18]. The Dice coefficient is defined as:

$$D = \frac{2a_{ik}}{2a_{ik} + a_i + a_k}$$

Based on this, the Dice dissimilarity is defined according Eq. (4.6).

$$\overline{D} = 1 - D = 1 - \frac{2a_{ik}}{2a_{ik} + a_i + a_k} = \frac{a_i + a_k}{2a_{ik} + a_i + a_k} \tag{4.6}$$

The Dice coefficient D is not very different in form from the Jaccard coefficient J. Since it does not satisfy the triangle inequality, it can be considered as a semi-metric version of the Jaccard coefficient. In this case the term a_{ik} is multiplied by 2. Therefore, it can be seen as scaled version of Jaccard distance, giving more importance to the shared term a_{ik}. The Dice coefficient is also known as Sorensen coefficient.

4.2.3 Kulczynski Coefficient and Dissimilarity

The Kulczynski coefficient K between two nodes i and k is defined as

$$K = \frac{1}{2}\left(\frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + a_i} + \frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + a_k}\right)$$

and the Kulczynski dissimilarity $\overline{K}$ [77] is given in Eq. (4.7)

$$\overline{K} = 1 - K = 1 - \frac{1}{2}\left(\frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + a_i} + \frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + a_k}\right) \tag{4.7}$$

In the Kulczynski coefficient K, the number of common neighbors is averaged by the sum of the neighbors of both nodes. As previous distances, the Kulczynski metric also accomplishes the properties of non-negativity, symmetry, and the triangle inequality. The terms a_{ik}, a_k, a_i cannot get negative values. The symmetry features is given by the fact that the terms a_{ik} and a_{ki} are equal, and the terms a_k and a_i are exchangeable.

4.2.4 Folkes-Mallows Coefficient and Dissimilarity

The Folkes-Mallows coefficient F between two nodes i and k is defined as

$$F = \frac{a_{\mathrm{ik}}}{\sqrt{(a_{\mathrm{ik}} + a_i)\left(a_{\mathrm{ik}} + a_j\right)}} \tag{4.8}$$

and the Folkes-Mallows dissimilarity $\overline{F}$ is given in Eq. (4.9).

$$\overline{F} = 1 - F = 1 - \frac{a_{\mathrm{ik}}}{\sqrt{(a_{\mathrm{ik}} + a_i)\,(a_{\mathrm{ik}} + a_k)}} \tag{4.9}$$

The *FMd* also satisfies the similarity features of non-negative, symmetry, and the triangle inequality for the same previously stated reasons.

4.2.5 Sokal-Sneath Coefficient and Dissimilarity

The Sokal-Sneath coefficient S between two nodes i and k is defined as

$$S = \frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + 2(a_i + a_k)}$$

and the Sokal-Sneath dissimilarity $\overline{S}$ is given by Eq. (4.10).

$$\overline{S} = 1 - S = 1 - \frac{a_{\mathrm{ik}}}{a_{\mathrm{ik}} + 2(a_i + a_k)} = \frac{2(a_i + a_k)}{a_{\mathrm{ik}} + 2(a_i + a_k)} \tag{4.10}$$

In the Sokal-Sneath coefficient the sum of dissimilar nodes ($a_i \neq a_k$) is the key factor for determining the similarity and dissimilarity between two nodes. As all previous distance metrics, the $\overline{S}$ distance accomplishes the similarity features of non-negative, symmetry, and the triangle inequality due to the fact that it is also based on the terms a_{ik}, a_k, and a_i.

4.2.6 BNR Dissimilarity

The *border node retransmission* (BNR) dissimilarity $\overline{B}$ between two nodes i and k is defined in Eq. (4.11).

$$\overline{B} = \frac{a_k}{a_i + a_{ik}} \tag{4.11}$$

In Eq. (4.11) the key parameter is a_k, which accounts for the number of nodes that the receiver does not share with the sender. Notice that $\overline{B}$ is not a symmetric distance between two nodes, thus $\overline{B}_{ik} \neq \overline{B}_{ki}$.

This metric is used in [78], where different probabilistic broadcasting approaches based on BNR metric for WMHNs are presented.

4.3 Dissimilarity Metrics in Networks

The objective of this section is to study the correlation between the introduced dissimilarity metrics and the Euclidean distance in networks with random topologies. In our study, we consider two connectivity models. First, the unit disk graph model (ideal) and subsequently, the probabilistic connectivity model (real).

4.3.1 Unit Disk Graph Model

In the simulation, a node can communicate with a neighbor node if it is located at a Euclidean distance equal or lower than the transmission range r of a node. This is the so-called unit disk graph model [79]. We study the correlation between distances using the Pearson Correlation coefficient for different levels of density of a wireless multi-hop network.

The results are depicted in Table 4.1, where n_b is the average number of neighbors of a node. In statistics, the Pearson product-moment correlation coefficient is a measure of the linear correlation (dependence) between two random variables X and Y, giving a value between -1 and $+1$ inclusive, where $+1$ is total positive correlation, 0 is no correlation, and -1 is total negative correlation [80]. For each density level (number of neighbors), 50 simulation replications have been conducted. The simulation area is a square of $1000\,\text{m} \times 1000\,\text{m}$ where the nodes are randomly placed throughout the simulation area, and the transmission range of a node is 250 m.

Table 4.1 Correlation analysis between the Euclidean distance and the dissimilarity distances in random networks

Nodes	n_b	Jaccard	Dice	Folkes	Kulczynski	Sokal
25	3.76	0.53	0.50	0.49	0.48	0.54
50	7.80	0.65	0.62	0.62	0.61	0.66
75	11.94	0.74	0.72	0.72	0.71	0.75
100	16.44	0.79	0.77	0.76	0.76	0.80
125	19.72	0.82	0.80	0.79	0.79	0.83
150	23.73	0.84	0.82	0.82	0.81	0.85
175	27.47	0.87	0.85	0.84	0.84	0.87
200	31.15	0.89	0.87	0.87	0.86	0.88

As the density level increases, the correlation between a dissimilarity distance and the Euclidean distance also increases. Beyond 75 nodes, all dissimilarity metrics are highly correlated to the Euclidean distance (Pearson coefficient higher than 0.75). That means that for medium and high density networks the presented dissimilarity metrics are good estimators of the Euclidean distance. Among the discussed metrics, the Sokal distance shows in general the highest correlation to the Euclidean distance. In contrast, the Kulczynski distance shows the least correlation to the Euclidean distance. However, in any case, the obtained results demonstrate the correlation between the dissimilarity distances and the Euclidean distance.

Figure 4.2 shows the results for the Sokal distance obtained via simulations with a network consisting of 100 nodes (the network density was 0.001 nodes/m^2). Figure 4.2 depicts the histograms of the Euclidean distance among nodes in the simulations, the scatter plot between the Sokal distance and the Euclidean distance, and the QQ-Plot between the distributions of the Sokal distance and the Euclidean distance. The QQ-Plot is particularly useful to study the relationship between both distributions. As it can be seen from the graph there is a high linear relationship between the Sokal distance and the Euclidean distance in the range of [0.2, 0.9]. This means that we can use the Sokal distance to estimate the Euclidean distance with high precision in this range.

As mentioned in the previous section, the dissimilarity metrics between two nodes depend basically on two factors such as the Euclidean distance between the two nodes and the density of nodes. A way to study the effect of the density of nodes on the linear relationship of dissimilarity metrics, like the Sokal metric and the Euclidean, is to represent the QQ-plot for different levels of density as depicted in Fig. 4.3. We observe that the linear relationship between the Sokal metric and the Euclidean distance increases as the density grows as well. In fact, there are not noticeable differences for a number of nodes higher than 100. Therefore, and regardless of the density level, we still observe a linear relationship between the Sokal metric and the Euclidean distance. It means that in any case the dissimilarity metric is a good estimator of the Euclidean distance.

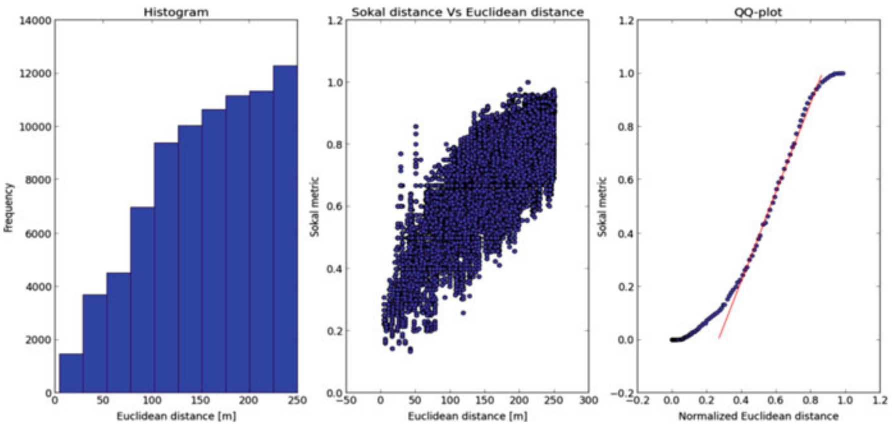


Fig. 4.2 Results for the Sokal distance, based on simulations with a network consisting of 100 nodes and communication range $r = 250\,\text{m}$

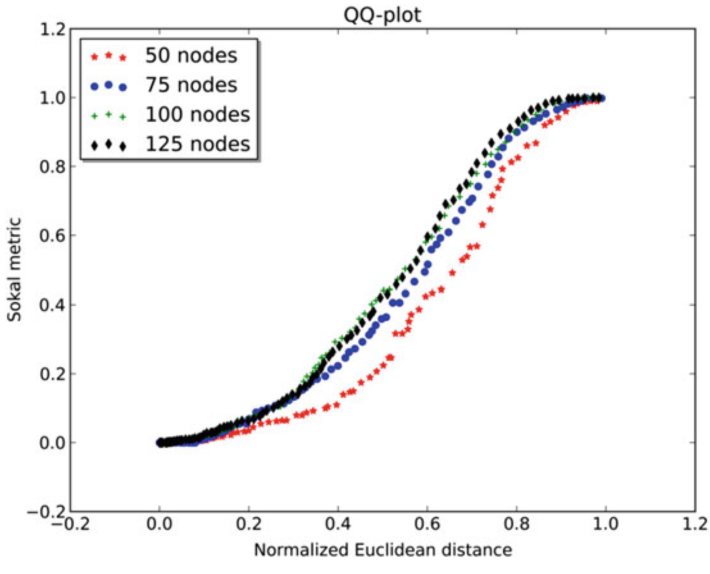


Fig. 4.3 QQ-plots of Sokal metric and normalized Euclidean distance for different density levels in a random topology with the unit disk model

4.3.2 Probabilistic Connection Model

We considered the unit disk graph model in the previous subsection. This model, although widely used, is not realistic since many studies have demonstrated that the probability of the existence of a wireless link between two nodes depends on Euclidean distance between them [81]. The higher the distance between the two nodes, the lower the probability of existence of a wireless link. In this section, we consider a probabilistic connection model in which two nodes can communicate wirelessly depending on the Euclidean distance between them. We consider a simple probabilistic wireless connection model with the following properties:

- Two nodes can communicate with each other (unit disk graph model) if the Euclidean distance between them is shorter than $2/3r$, i.e., the radio transmission range r.
- If the Euclidean distance is larger than $2/3r$, the probability of being connected decreases inversely proportional with the Euclidean distance.

Figure 4.4 shows the results for the probabilistic wireless connection model. We still observe a linear relationship between the Sokal metric and the Euclidean distance. However, in this case we observe an exponential relationship between the Sokal and Euclidean distance for lower values of the Euclidean distance (lower than 0.7). Notice that now the distribution of the Euclidean distance has changed in the network as shown in the first graph of Fig. 4.4. The reason is that higher values of Euclidean distance are lower probably due to the probabilistic wireless connection model. Therefore, the main finding from Figs. 4.2, 4.3, and 4.4 is that the connection model strongly affects the relationship between the Euclidean distance and the dissimilarity metric.

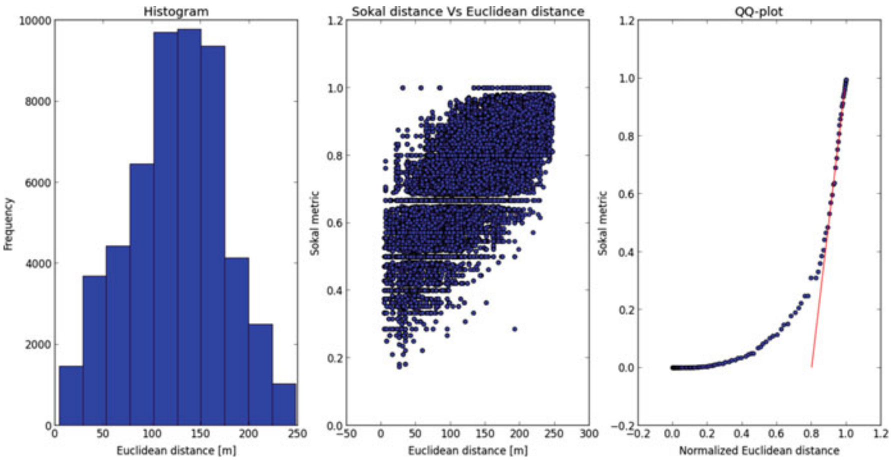


Fig. 4.4 Results for the Sokal distance, based on simulations with a network consisting of 100 nodes, communication range $r = 250$ m and probabilistic model

Table 4.2 Correlation analysis between the Euclidean distance and the discussed dissimilarity distances in VANET scenarios

Nodes	Jaccard	Dice	Folkes	Kulczynski	Sokal
75	0.23	0.22	0.25	0.22	0.25
100	0.34	0.33	0.33	0.37	0.34
125	0.40	0.36	0.36	0.38	0.37

4.4 Dissimilarity Metrics in VANETs

In this section, we study the dissimilarity metrics in VANET scenarios. The focus of the application is on urban scenarios. In that case, vehicles are in a city where the speed of vehicles is low and, at the same time, the density of vehicles is high.

4.4.1 Correlation Analysis of VANET Scenarios

To conduct the correlation analysis, we have used the Manhattan grid mobility model, since this mobility model is appropriate for cities. The used mobility model generator is BonnMotion [82]. The scenario is composed of a number of vehicles (75, 100, and 125) moving in an urban area. The radio propagation model used is the two-ray propagation model. For more details about the scenario considered see Sect. 6.2.1 (Table 6.1 and Fig. 6.1).

Table 4.2 contains the obtained results. In VANET scenarios, the Kluczynski dissimilarity metric is the one that achieves the best correlation with respect to the Euclidean distance.

Figure 4.5 shows the QQ-plot for the Kulczynski metric and the normalized Euclidean distance. The graph shows a good lineal relationship between the distribution of the Kulczynski metric and the normalized Euclidean distance for almost the full range of values of both metrics. Only for values close to 1, there is an exponential relationship.

4.5 Dissimilarity Metrics in the DES-Testbed

In this section, we conduct the same correlation analysis presented in previous subsections in the DES-Testbed. The DES-Testbed is composed of more than 120 mesh routers, which are equipped with three IEEE 802.11 a/b/g network adapters that can be configured in ad hoc mode. More details about the DES-Testbed are given in Chap. 8 and [81].

Notice that the mesh routers in the DES-Testbed are not equipped with GPS, however, their coordinates have been determined by using an accurate GPS. This

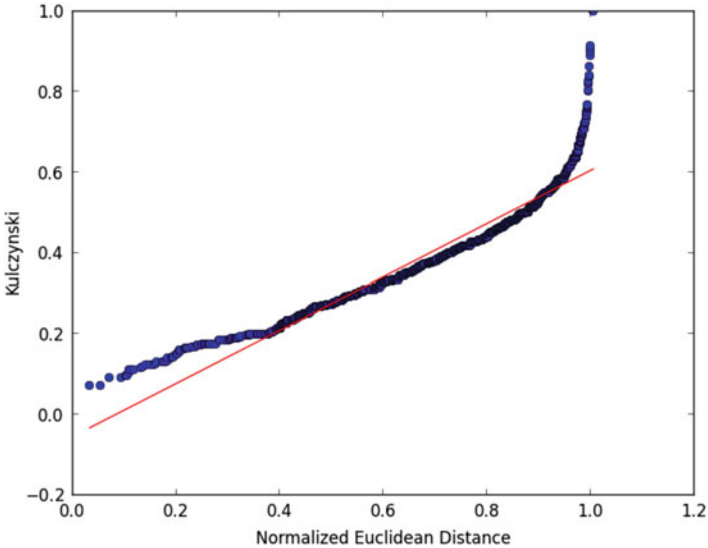
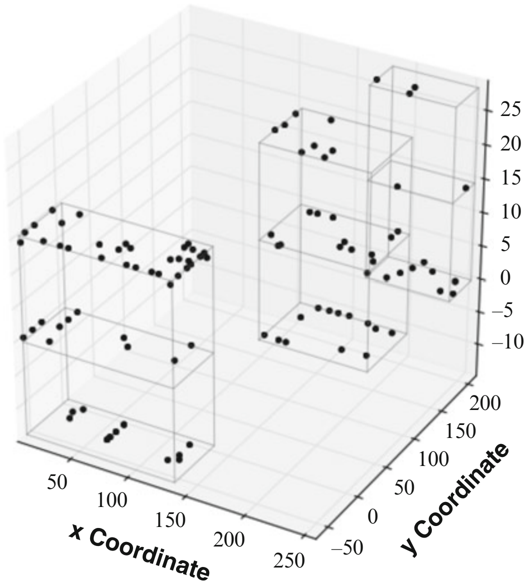


Fig. 4.5 QQ-plot for Kulczynski metric and normalized Euclidean distance for a VANET consisting of 125 nodes, communication range $r = 250\,\text{m}$

Fig. 4.6 Coordinates of the nodes in the DES-Testbed. The nodes are distributed on three different buildings and various levels of the building



information is stored in the central server of the DES-Testbed and has been used to calculate the relative distances between every pair of nodes in the network. Figure 4.6 shows the coordinates of the nodes in the DES-Testbed.

Table 4.3 Correlation analysis between dissimilarity distances and the Euclidean distance in the DES-Testbed

Dissimilarity distance	Pearson coefficient
Jaccard	0.22
Dice	0.21
Folkes	0.23
Kulcynzski	0.25
Sokal	0.22

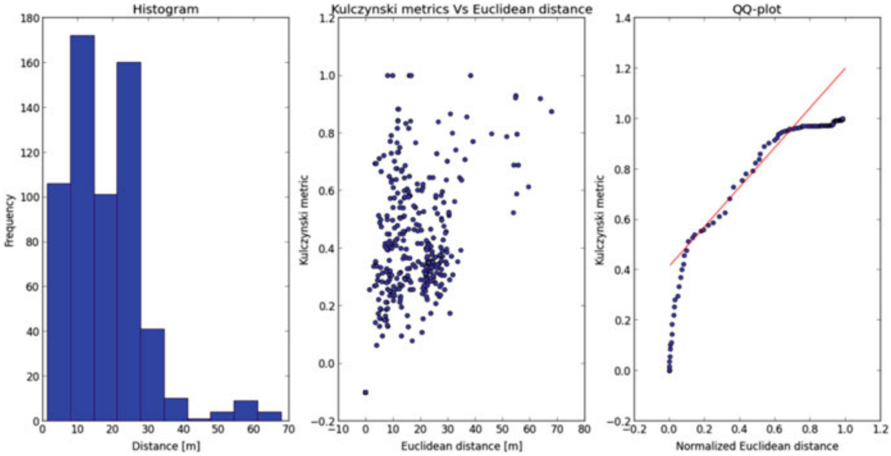


Fig. 4.7 Correlation results in DES-Testbed

4.5.1 Correlation Analysis in the DES-Testbed

Table 4.3 includes the correlation results. The main reason for the low values of correlation is the distribution of nodes, since most nodes are located at short distances from each other. As it is shown in Fig. 4.6, the relative distance between two nodes is lower than 50 m for the majority of the measurements. Consequently, the distribution of nodes is affecting the correlation analysis.

Figure 4.7 depicts the data used for the correlation analysis between the Kulczynski metric and the Euclidean distance. The figure represents the Kulczynski metric versus the Euclidean distance, and finally the QQ-Plot between the distribution of the Kulczynski metric and the Euclidean distance. It is interesting to see in the QQ-Plot that the dissimilarity metric reaches a saturation region close to 1 when the normalized Euclidean distance is 0.6. Consequently, for higher Euclidean distances we will obtain very high values of the Kulczynski metric. In addition, there is a region of normalized Euclidean distance within [0.2, 0.6] in which we can observe a good linear relationship between both the Euclidean distance and the Kulczynski metric. For lower values of the normalized Euclidean distance, we observe a linear relationship between both distances, but with a higher slope.

Although the results for the correlation analysis are worse in the DES-Testbed, we still observe a positive correlation between the dissimilarity distance and the Euclidean distance. This feature will be exploited in the next section to present several probabilistic broadcasting algorithms based on the dissimilarity distances.

The discrepancies between both distributions are mainly due to two factors: (1) the existence of nodes that only have one neighbor (there are 4 nodes in the current topology of the DES-Testbed with such connectivity). In those cases, the dissimilarity distance is 1 regardless of the Euclidean distance between the two nodes. (2) The real radio transmission ranges of nodes in the DES-Testbed are not as circular as it is assumed in the unit disk model used in the analysis presented in Sect. 4.5. The real transmission ranges of nodes are more similar to that presented in Fig. 2.6.

Chapter 5
Probabilistic Broadcasting Based on Dissimilarity Metrics

In this chapter, we study the first application of dissimilarity metrics in wireless multi-hop networks. The idea is to apply the introduced dissimilarity metrics to well-known probabilistic broadcasting algorithms based on the Euclidean distance.

In Sect. 5.1, we present the main limitations of the use of the Euclidean distance in probabilistic broadcasting approaches. In Sect. 5.2 we discuss the probabilistic broadcasting algorithms based on dissimilarity metrics.

5.1 Limits of Euclidean Distance-Based Probabilistic Broadcasting Algorithms

Although the usage of the relative Euclidean distance between two nodes can be a suitable parameter to adjust the forwarding probability in broadcasting operations, it also presents several drawbacks. The assumption that all nodes in the network have the same radio transmission range does not hold in reality [83]. In addition, obtaining the real transmission range of a wireless device is not a trivial task, since it varies notably from the nominal value determined by the manufacturer, which is normally measured in ideal conditions. Even knowing the nominal power transmission of the wireless transceiver, the real transmission range of a node can depend on many factors such as the density of nodes, using the same and/or different frequency band (wireless noise), and obstacles like humans, doors, and walls in the vicinity of the nodes. In the probabilistic schemes based on Euclidean distance, the forwarding probability is determined considering a nominal and ideal radio transmission r (r_{ideal} in Fig. 2.6).

If the real transmission range of a node deviates from the nominal, the ratios used in equations in p-persistence algorithm Eq. (3.1) and in polynomial algorithm Eq. (3.2) will result in erroneous forwarding probabilities, since these equations

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use r_{ideal}. Figure 2.6 illustrates the differences between the ideal radio transmission range r_{ideal} and the real transmission range r_{real} of a node i. Let us consider that node i is using p-persistence and there is a node located at the point A, where $r_{\text{real}} < r_{\text{ideal}}$. The expression Eq. (3.1), which uses r_{ideal}, will provide a forwarding probability lower than 1, but as it is depicted in Fig. 2.6, the node is actually located at the border of the real transmission range, thus the forwarding probability should be 1.

5.2 Application of Dissimilarity Metrics to Probabilistic Broadcasting

In this subsection, we introduce several probabilistic broadcasting algorithms based on the dissimilarity distances described in Chap. 4. The main idea is to use the same approaches employed by p-persistence [65, 83] and irresponsible forwarding approaches, but using a dissimilarity distance instead of the Euclidean distance. Notice that in this subsection, we will refer to D_{ij} as the general term for a dissimilarity distance between two nodes i and j. In the next section, we will show the particular results for the described dissimilarity distances (Jaccard, Dice, Kulzcynski, etc.).

5.2.1 Dissimilarity-Persistence

The idea of *dissimilarity-persistence* is to determine the forwarding probability p linearly based on D_{ij}. A node j receiving a broadcast packet from node i will rebroadcast the packet with probability according to Eq. (5.1).

$$p = D_{ij} \tag{5.1}$$

It is worth pointing out that the radio transmission range used in the original formula for p-persistence Eq. (3.1) is set to 1, since this is the maximum value for all dissimilarity distances considered. This change makes the forwarding scheme more robust against possible variations of the radio transmission range of the node, and in addition to that, nodes are not required to know their radio transmission ranges, as it happens with the original p-persistence scheme.

5.2.2 Dissimilarity-Polynomial

In the *dissimilarity-polynomial* the forwarding probability p is obtained according to Eq. (5.2)

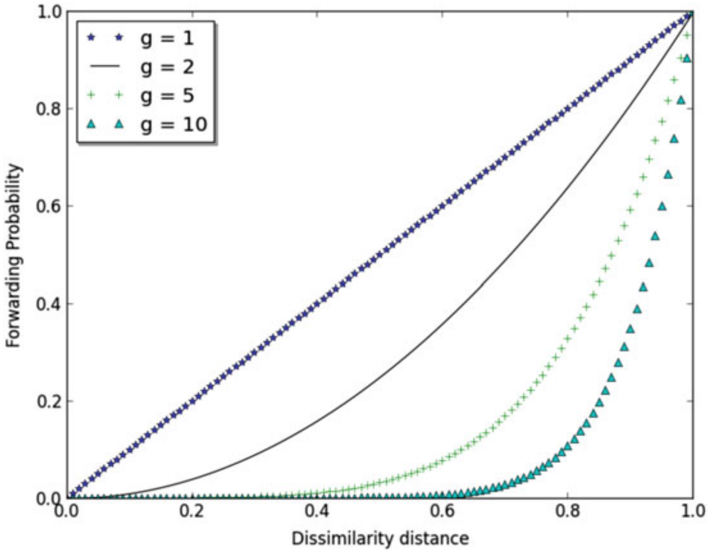

Fig. 5.1 Probability functions for the dissimilarity-polynomial approach. Larger exponents g result in the selection of more similar forwarders

$$p = \left(D_{ij}\right)^g \tag{5.2}$$

where g is the shaping parameter used in the original polynomial approach in Eq. (3.2). Figure 5.1 shows the different probability functions resulting by varying the shaping parameter g of Eq. (3.2). Notice that $g = 1$ is the probability function for the dissimilarity-persistence. As the value of g is increased, the forwarding probability is reduced for all nodes, but only the most dissimilar nodes. They have a high forwarding probability p.

5.2.3 Dissimilarity-Irresponsible Forwarding

In this case Eq. (3.3) is modified to include a dissimilarity distance. As in the previous approaches, the radio transmission range r is set to 1 for the same reason. In addition, the spatial density φ_s is replaced by the number of nodes n_b so nodes are not required to know their radio transmission ranges. Thus, the forwarding probability is calculated according to Eq. (5.3).

$$p = exp\left(-\frac{n_b\left(1 - D_{ij}\right)}{c}\right) \tag{5.3}$$

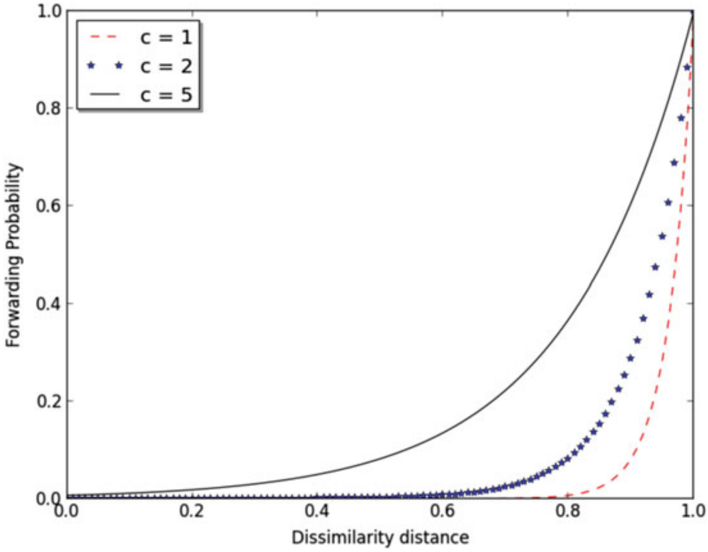

Fig. 5.2 Forwarding probability vs dissimilarity metric for irresponsible forwarding based on dissimilarity distance, $n_b = 25$

Figure 5.2 depicts the forwarding probability of the irresponsible forwarding approach based on dissimilarity distance versus the dissimilarity distance between two nodes for different values of the shaping parameter c. The number of neighbors n_b is constant and set to 25.

Figure 5.2 shows that as the dissimilarity distance between the two nodes increases, the forwarding probability also grows exponentially. Figure 5.3 represents the forwarding probability of irresponsible forwarding scheme based on dissimilarity distance versus the number of neighbors n_b for different values of c. The value of the dissimilarity distance D_{ij} is 0.6.

Notice how the forwarding probability decreases exponentially as the number of neighbors increases. Consequently, the forwarding probability will be exponentially adjusted by both the number of neighbors n_b and the dissimilarity metric D_{ij}.

5.2.4 Silencing Mechanism Based on Dissimilarity Metrics

In this subsection, we study the silencing mechanism proposed in [84]. Nodes more dissimilar will forward before other nodes and with higher probabilities. The main idea is that dissimilar nodes silence similar nodes. For this purpose, the retransmission delay r_d for every potential forwarding node depends on the dissimilarity metric between it and the previous sender. The value of r_d is determined according to Eq. (5.4), where $t_{\min}$ and $t_{\max}$ are two constants to be adjusted.

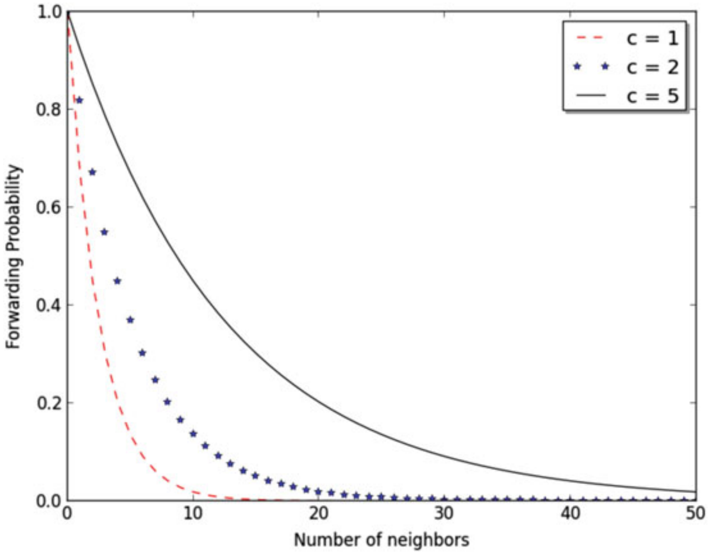

Fig. 5.3 Forwarding probability vs. number of neighbors for Irresponsible Forwarding based on dissimilarity distance, $D_{ij} = 0.6$

$$r_d = t_{\min} + \left(1 - D_{ij}\right) t_{\max} \tag{5.4}$$

Dissimilar nodes will silence other nodes since nodes only forward incoming packets once in broadcasting algorithms. Therefore, if we favor dissimilar nodes to retransmit packets before similar nodes, we will save an important number of redundant retransmissions.

Chapter 6
Probabilistic Broadcasting in VANETs

In this chapter, we introduce an adaptation of several probabilistic algorithms for VANETs such as p-persistence, polynomial, and irresponsible forwarding to use dissimilarity metrics to overcome the limitations of the Euclidean distance.

In Sect. 6.1, we introduce the adaptation of the approaches. In Sect. 6.2, we discuss the performance of the approaches by simulation results and finally, in Sect. 6.3, we summarize the main findings of this chapter.

6.1 Probabilistic Algorithms Based on Dissimilarity Metrics

In Chap. 3 we introduced the calculation of the forwarding probability based on the distance between two nodes. The main idea is now to replace the Euclidean distance d_{ik} in Eqs. (3.1), (3.2) and (3.4) by each dissimilarity metric given in Eqs. (4.5)–(4.7) and (4.9)–(4.11).

The proposed probabilistic approaches based on dissimilarity metrics are given in Eqs. (6.1)–(6.3).

$$\text{For } p\text{-persistence} \quad p = D_{ik} \tag{6.1}$$

$$\text{For polynomial} \quad p = (D_{ik})^g \tag{6.2}$$

$$\text{For irresponsible} \quad p = \exp\left(-\frac{n_b\,(1 - D_{ik})}{c}\right) \tag{6.3}$$

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The term D_{ik} in the Eqs. (6.1)–(6.3) is the dissimilarity metric between two nodes i and k and it can be calculated by using any of the above expressions Eqs. (4.5), (4.6), (4.7), (4.9), (4.10), and (4.11) for Jaccard, Dice, and the other mentioned dissimilarity metrics. The exponent g in Eq. (6.2) is used to tune the shape of the polynomial probability function. The term n_b in Eq. (6.3) is the number of neighbors of the receiver and c is a constant to adjust the shape of the exponential probability function. Notice that the spatial density of nodes φ_s, which is originally proposed in Eq. (3.4), is replaced by n_b. This modification has already been proposed in [85] because the real value of φ_s requires global information. Therefore, the local spatial density of nodes can be estimated as the number of neighbors in the vehicle's transmission range. In the proposed algorithms, vehicles exchange *hello-packets* periodically in order to maintain neighbor tables. Algorithm 1 outlines the operation of the proposed probabilistic broadcasting algorithms based on dissimilarity metrics.

According to Algorithm 1, on receiving a new message m, vehicles should include their list of neighbors in the broadcast packets in order to calculate the terms a_{ik}, a_i, and a_k. Then, the node calculates the forwarding probability determined by Eqs. (4.9)–(4.10) and (4.5)–(4.8). If a node decides to retransmit the incoming packet, it will wait for a random period of time in the interval $[0, t_d]$ before retransmitting. This is done to avoid possible collisions at the receivers. The value of t_d is chosen as 0.010 s. This value has been evaluated to be suitable for VANET scenarios. Before retransmitting the packet, it should include its list of neighbors. If the received packet is not new or the node decides not to retransmit the packet, it will drop it.

Algorithm 1: Probabilistic forwarding of a message m at a node in the network

```
On receiving a message m;
begin
    if m is new then
        Extract list of neighbors from m;
        Determine terms a_ik, a_i, a_k;
        Calculate p using Equations (4.9) to (4.10) and Equations (4.5) to (4.8);
        if p ≥ Random(0, 1) then
            Update list of neighbors in m;
            Retransmit m after Random(0, t_d);
        else
            Drop m;
        end
    else
        Drop m;
    end
end
```

6.2 Simulation Results

In this section, we study the proposed probabilistic algorithms based on dissimilarity metrics in simulations. First, we present the simulation environment used to conduct the simulations. Subsequently, we discuss the simulation results.

6.2.1 *Simulation Environment*

The main simulation parameters used are included in Table 6.1. We used the Network Simulator 2 (NS-2) [21], which is one of the most popular event driven network simulators for multi-hop ad hoc networks. We implemented the proposed probabilistic algorithms in the *pampa agent* developed in [86]. For the mobility of vehicles, we use the Manhattan mobility model [82]. The Manhattan mobility model uses a grid road topology in which the urban scenario is divided into different blocks as shown in Fig. 6.1. Each color in Fig. 6.1 represents the movement of a different vehicle. We study the proposed algorithms under different density conditions. We consider three density levels: low, medium, and high density using 75, 125, and 175 nodes, respectively.

Furthermore, we consider two performance metrics to evaluate the proposed algorithms such as reachability and broadcast efficiency. They are defined as follows:

- **Reachability (*Re*):** The reachability is defined as the fraction of nodes in the network receiving a given broadcast packet. As a rule, a high reachability is a basic requirement for a broadcasting scheme.

Table 6.1 Simulation parameters

Parameter	Value
Network simulator	NS-2.34
Mobility model	Manhattan (BonnMotion)
No. of blocks	10
Size of scenario [m×m]	1000×1000
Average speed of nodes [km/h]	50
Pause time [s]	0
No. of nodes	75, 125, 175
No. of broadcast packets	25
Size of broadcast packets [bytes]	1000
Transmission range [m]	250
Period of hello packets [s]	Random [0,1]
MAC layer	IEEE 802.11
Propagation model	Two-ray ground
Simulation time [s]	250

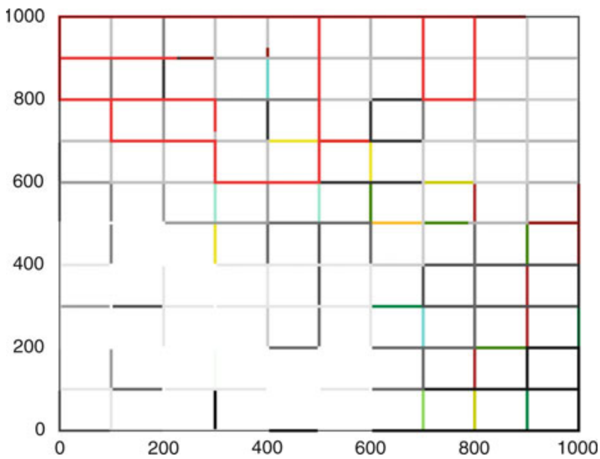

Fig. 6.1 Vehicles moving according to the Manhattan mobility model

- **Broadcast efficiency (*Be*):** The broadcast efficiency is defined as the ratio between the reachability and the normalized number of retransmissions *NR*. Consequently, *Be* is given by *Re/NR*. We use *Be* in order to determine which approach balances better both *Re* and *NR*, which are two counterbalanced performance metrics. Generally, a high *Re* incurs in a high *NR*, so a good broadcasting approach should achieve a high value of *Re* with a moderate/low number of *NR*.

The results depicted in Figs. 6.2, 6.3, and 6.4 are obtained by averaging out the results of 10 simulation replications. The nodes that begin the broadcasting procedures are selected randomly among all the nodes in the network.

6.2.2 p-Persistence Algorithm Based on Dissimilarity Metrics

Figure 6.2 shows the results of the *p*-persistence algorithm when using the dissimilarity metrics. The best *Re* value is achieved by the Sokal-Sneath metric. However, if we look at the *Be* performance metric, the Kulczynski metric is the best one.

Since the Kulczynski metric also achieves acceptable results in terms of *Re*, we consider the Kulczynski metric as the most suitable one to determine the forwarding probability. From now on, we use the Kulczynski metric as a baseline to test the other proposed probabilistic broadcasting algorithms based on dissimilarity metrics. Notice that the Kulczynski dissimilarity metric was the one that achieved the best results in the correlation analysis conducted in Sect. 4.4 in VANET scenarios. For this reason, we consider the Kulczcynski metric as the baseline for the study of other approaches.

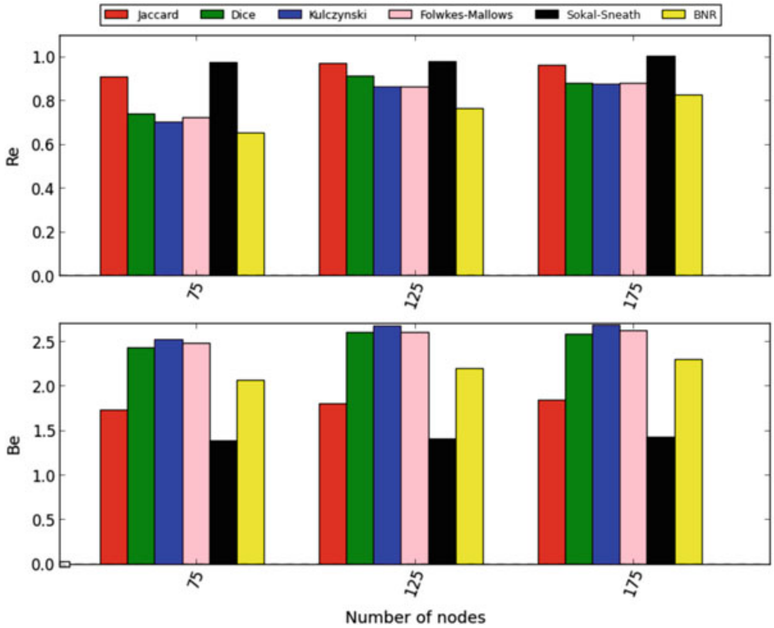

Fig. 6.2 Simulation results for *p*-persistence algorithm based on dissimilarity metrics

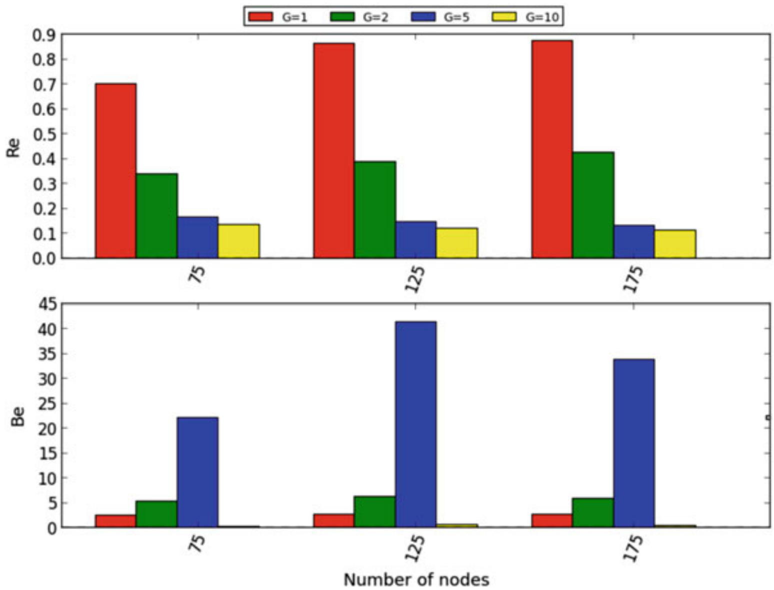

Fig. 6.3 Simulation results for polynomial algorithm based on dissimilarity metrics

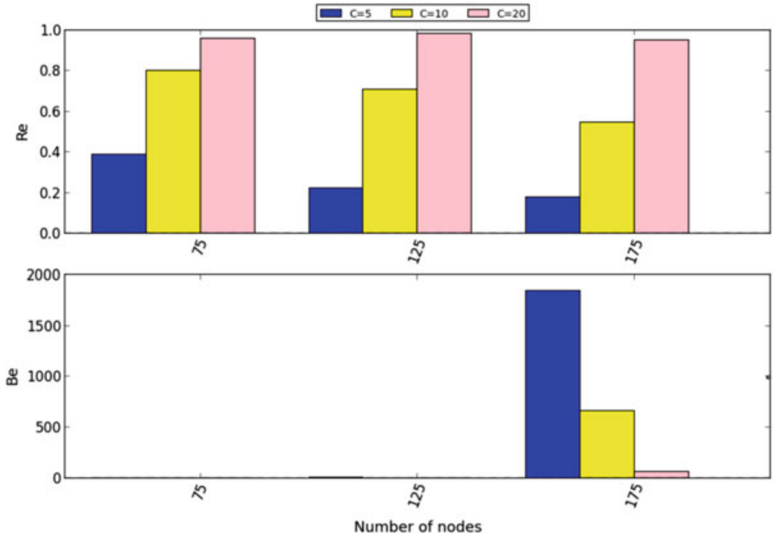

Fig. 6.4 Simulation results for polynomial algorithm based on dissimilarity metrics

6.2.3 Polynomial Algorithm Based on Dissimilarity Metrics

Figure 6.3 shows the results of the polynomial algorithm using Kulczynski dissimilarity metric. It is easy to see that this algorithm does not achieve good results. As the exponent g is increased, Re becomes very low. For $g = 2$, the Re value is reduced by half. An Re value lower than 0.5 is not acceptable for a broadcasting algorithm. Therefore, it seems that the polynomial algorithm is not suitable for the VANET scenario considered.

6.2.4 Irresponsible Algorithm Based on Dissimilarity

Figure 6.4 shows the results obtained by the Irresponsible algorithm using the Kulczynski dissimilarity metric. We consider three different values of c such as 5, 10, 20. As for the results, c equal to 10 is the best option since this value balances Re and Be. Low values of c get very low Re (below 0.5). On the other hand, if c is very high, Be decreases considerably.

6.2.5 Comparison with Other Broadcasting Algorithms

To get an overall idea about the performance of the proposed algorithms, we compare them to two well-known algorithms namely the p-persistence algorithm based on the Euclidean distance (Euclidean in Fig. 6.5), and the flooding algorithm.

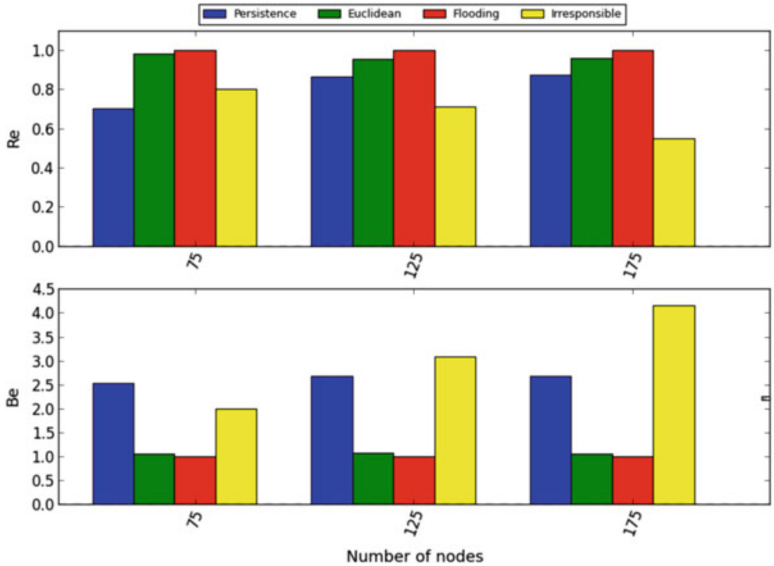

Fig. 6.5 Comparison of probabilistic algorithms based on dissimilarity metrics with other well-known approaches

We do not include the polynomial algorithm based on dissimilarity metric, because it has already been shown in the previous section that it is not suitable for the considered VANET scenario. The results for the comparison are shown in Fig. 6.5.

As the density of nodes increases, the *p*-persistence algorithm based on the Kulczynski metric (Persistence in Fig. 6.5) is the algorithm that better balances *Re* and *Be* performance metrics. It achieves a value for *Re* around 0.8, which is good, and it doubles the value of *Be* in comparison to other approaches such as Euclidean or flooding. Moreover, the Irresponsible algorithm based on the Kulczynski metric (Irresponsible in Fig. 6.5) with $c = 10$ can be suitable for 75 nodes. However, for higher densities, *Re* gets lower.

6.3 Discussion of the Results

The main findings of the obtained simulation results are:

- The dissimilarity metrics are suitable for improving broadcasting algorithms in terms of reducing the redundancy with respect to the number of transmitted packets. The *Re* of the proposed algorithms is lower than in the case of flooding but it compensates this due to the reduction in packet redundancy.
- Among the studied dissimilarity metrics, the Kulczynski dissimilarity metric achieved the best results. These results corroborate the previous correlation analysis conducted in Sect. 4.4. Therefore, it seems that the correlation with respect to the Euclidean distance has a big influence on the results.

Chapter 7
Routing in VANETs

In this chapter, we study the application of dissimilarity metrics in order to improve the discovery phase of reactive routing protocols. The goal is to reduce the number of *route request packets* sent by the routing protocol to find a route between a source node and a destination node. Although we selected AODV as the example for the study of the performance, the approach is on principle applicable to all reactive routing protocols.

In Sect. 7.1, we describe the original version of the route discovery phase of AODV [41]. In Sect. 7.2, we introduce the probabilistic route discovery phase based on dissimilarity metrics. In Sect. 7.3, we discuss the results obtained via simulations with NS-2. Finally, in Sect. 7.4, we discuss the main findings of the chapter.

7.1 The Route Discovery Phase of AODV

The *ad hoc on-demand distance vector* (AODV) [41] is one of the best studied routing protocols for wireless multi-hop networks [52]. AODV is a reactive unicast routing protocol [41], i.e., a new entry in the routing table of the source node is only created on demand. A source node may need to find a new communication path to a given destination node mainly for two reasons, (1) there is not a route to communicate with the destination node in its routing table, and (2) the route included is out-of-date or obsolete. It is important to highlight that both situations are likely to happen in mobile ad hoc networks due to node mobility.

The route discovery in AODV as the majority of reacting routing protocols is based on flooding [41]. Whenever a source node initiates a route discovery phase, it sends out or floods the network with a *route request* packet, which contains data fields such as a sequence number, time-to-live (TTL), number of hops, id of the

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destination node, among others (see [41] for more details about the AODV packet fields). The sequence number is used to avoid loops in the network, while the TTL is used to limit the number of times that the route request packet is retransmitted.

On receiving a route request packet for the first time, an intermediate node checks whether it has an active route to the destination node. If it has an active route, it will send back a route reply packet to the source node. Otherwise, it will retransmit the incoming route request packet to its neighbors. If the route request packet has already been received by the node, it discards the route request packet. This operation is repeated until a route request packet reaches the destination node. Then, the destination node sends back a route reply packet to the source node. At this point it is relevant to indicate that nodes in reactive routing protocols do not store the complete communication route in their routing tables, they only store the *next hop* in the routing path.

On receiving a *route reply packet*, the source node creates the new entry in its routing table. Thus, the source node may start to send application packets to the destination node. The route is considered active until it is not used any more or the route is broken, e.g., due to node mobility.

7.2 Route Discovery Based on Dissimilarity Metrics

One of the major problems of the route discovery phase of AODV is the use of *flooding* to disseminate *route request packets* throughout the network. Flooding has been demonstrated many times to be inefficient in terms of traffic load in wireless multi-hop networks [54, 65]. This fact is even worse in congested networks. In order to operate properly, a WMHN needs a higher density of nodes to establish communication paths between a source node and a destination node. Such redundancy can be exploited by an efficient broadcasting algorithm that reduces the number of retransmitted route request packets without affecting negatively the delivery of application packets. It has been demonstrated in [23] that the congestion of the network plays an important role in the optimal forwarding probability, and it affects differently the broadcasting and routing algorithms.

As mentioned in previous chapters, dissimilarity metrics can be used to select distant nodes from a source node to spread out information efficiently. The idea is that by selecting dissimilar nodes, we reduce redundancy of retransmissions.

In the modified route discovery approach, whenever an intermediate node receives a new route request packet, it applies a probabilistic broadcasting algorithm such as *p*-persistence or the polynomial algorithm to decide whether to retransmit the route request packet. Some changes need to be done to adapt the studied probabilistic broadcasting algorithms to the route discovery phase of AODV. The most important modification is that nodes have to include the list of their neighbors in the route request packets in order to calculate the dissimilarity between the sender and the receiver of the packet. Notice that this calculation needs to be done in every hop the route request packet travels. The list of neighbors can be easily obtained, since in AODV nodes use *hello-packets* to collect local information.

The proposed route discovery approach works as follows. On receiving a new route request packet an intermediate node will calculate the dissimilarity between itself and the previous sender (source node or intermediate node). This is done by comparing the list of neighbors included in the route request packet and the current neighbors of the node. Subsequently, depending on the dissimilarity metric used, nodes will apply to Eqs. (4.4)–(4.11). The second design decision is how to calculate the forwarding probability. This question will be answered in this chapter by comparing the previous studied broadcasting schemes (see Chap. 6). Once the forwarding probability is calculated, nodes randomly check if they have to retransmit the route request packet. For this, they generate a random number and compare it with the calculated dissimilarity metric. If the random number generated is lower or equal than the calculated dissimilarity, they will retransmit the route request packet. Otherwise, they will discard the route request packet. As a rule, the higher the dissimilarity, the higher the probability of forwarding an incoming route request packet. In case of retransmission, the node includes its current list of neighbors in the route request packet and forwards it to its neighbors. The rest of the AODV routing protocol is not affected. Therefore the broadcasting operation is repeated until reaching the destination node or an intermediate node with an active route to reach the destination.

7.3 Simulation Results

In this section, we discuss the evaluation of several probabilistic broadcasting schemes based on dissimilarity metrics as part of the route discovery process of AODV. Furthermore, the new approaches have been compared with the original route discovery phase of AODV based on flooding.

7.3.1 Simulation Environment

The NS-2 simulator [17] is used for the simulations and the global simulation parameters are depicted in Table 7.1. As in Chap. 6, we use the Manhattan mobility model for VANET scenarios (see Fig. 6.1). However, we increase considerably the complexity of the simulation scenario. The reason is that in this case we want to evaluate a routing protocol instead of broadcasting algorithms. Therefore, we seek higher separations between the source and destination nodes in terms of hops. It has been demonstrated that the separation in number of hops between the source and the destination nodes impacts importantly on the performance of reactive routing protocols [32]. As MAC layer, we use IEEE 802.11p, which is envisioned to be

Table 7.1 Global simulation parameters to evaluate the proposed route discovery phase approaches

Parameter	Value
Network simulator	NS-2.34
Mobility model	Manhattan (BonnMotion)
No. of blocks	10
Size of scenario [m × m]	4000×4000
Average speed of nodes [km/h]	50
Pause time [s]	0
No. of nodes	75, 125, 175
No. of communication flows	5
Application traffic	CBR
Rate [packet/s]	1
Transport protocol	UDP
Size of packets [bytes]	512
Type of queue	DropTail
Size of queue	50
Transmission range [m]	250
Period of hello packets [s]	Random [0,1]
MAC layer	IEEE 802.11p
Propagation model	Two-ray ground
Simulation time [s]	300

used in VANET scenarios. As traffic pattern, we use CBR with a rate of 1 packet per second; and 5 flows between sources and destinations. It means that, we consider a network with low congestion. The propagation model is two-ray ground, which is widely used for VANET scenarios.

The following routing metrics are used to evaluate the performance of the routing protocol:

- **Packet Delivery Fraction (*PDF*):** The PDF is defined as the ratio of application packets received successfully by the destination node to the total number of packets generated at the source node and gives an idea of the general performance of the network. It is desirable that a routing protocol achieves a high value of PDF.

$$\text{PDF} = \frac{\sum \text{Delivered Application Packets}}{\sum \text{Sent Packets}}$$

- **Throughput:** The *throughput* is the ratio of the total number of delivered application packets and the simulation time. The objective of a routing protocol is to achieve a high throughput. Notice that we calculate the throughput metric as an average value during the simulation time.

$$\text{THR [kbps]} = \frac{\sum \text{Delivered Application Packets}}{\text{Simulation time}}$$

- **Normalized Routing Load (*NRL*):** The NRL is defined as the number of routing packets transmitted for every data packet sent. The routing load of a routing algorithm should be as low as possible. A high routing load causes congestion and high delays in the network. Also, the power consumption is related to the routing load.

$$\text{NRL} = \frac{\sum \text{Routing Packets}}{\sum \text{Delivered Application Packets}}$$

- **End-to-end delay (*E2E*):** The end-to-end delay is the time it takes an application packet to travel across the network from the source node to the destination node. It is desirable to have a low E2E delay.

$$E2E[s] = \frac{\sum(\text{Delivered Time} - \text{Transmitted Time})}{\text{Number of packets successfully delivered}}$$

Although there are more performance metrics to evaluate routing protocols, we consider that these four metrics are enough to evaluate how the proposed discovery phase approaches impact on the performance of the AODV. In order to obtain significant statistical results up to 200 simulation replications have been run.

7.3.2 Route Discovery Based on p-Persistence

Figure 7.1 shows the results for AODV when its route discovery phase is based on p-persistence and different number of nodes is considered. Each point in the following plots has been obtained by averaging 200 simulation runs. In addition, 95% confidence intervals have been included as error bars. Figure 7.1 shows the results achieved by three different dissimilarity metrics such as Dice, Jaccard, and Kulczynski. According to the obtained results, the Jaccard dissimilarity metric is the best one. It reaches the best PDF and throughput. Also, it achieves a lower NRL than the other dissimilarity metrics.

It is important to highlight that the most suitable dissimilarity metric for the p-persistence broadcasting approach is different with respect to the study conducted in Chap. 6, where broadcasting was studied as a dissemination approach. In Chap. 6, the best dissimilarity metric for p-persistence algorithm was the Kulczynski metric. The reason for such selection was that the *Be* obtained by the Kulczynski metric based on p-persistence compensates for the reduction in terms of *Re*. However, in this case, the Jaccard-based approach outperforms the other dissimilarity metrics in terms of *PDF* and *NRL*. We think that the main reason for this is that, when a dissimilarity metric is used in the route discovery phase of a routing protocol, it is necessary to have higher values for the forwarding probabilities. The Kulczynski metric in this case reduces the forwarding probability too much making very difficult to reach the destination node. This impacts negatively in the routing load because,

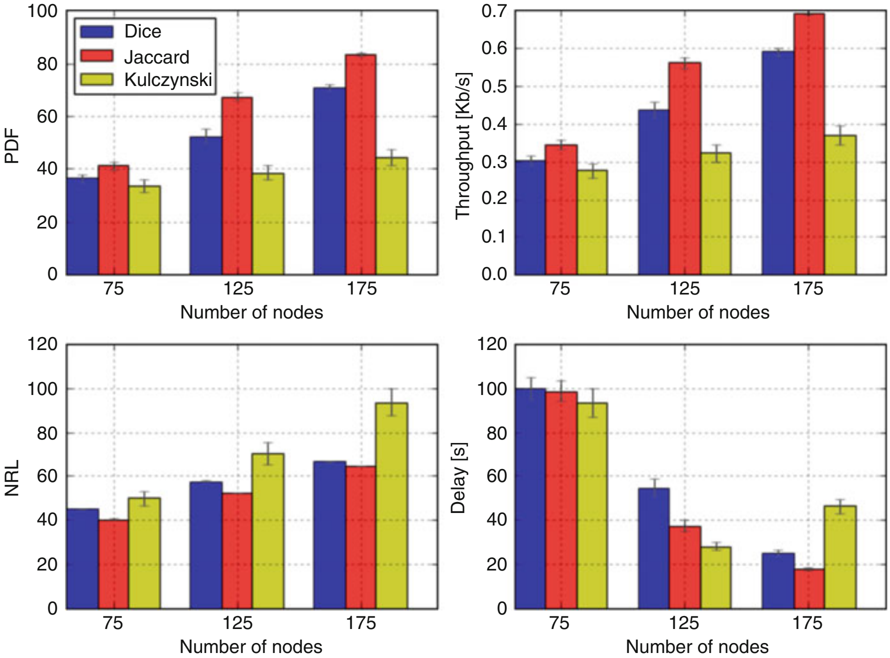

Fig. 7.1 Comparison of the results for AODV with p-persistence as the route discovery phase and different levels of network density

whenever a discovery procedure fails to reach the destination, a new one has to be started, and consequently, it increases the routing load significantly. This issue is called the die out problem of probabilistic broadcasting [52]. These results also corroborate the ones presented in [23], where the role of congestion in the performance of Gossip probabilistic broadcasting algorithm was studied.

7.3.3 Route Discovery Based on Polynomial

Figure 7.2 shows the results for AODV when polynomial scheme is used in the route discovery phase. The results have been obtained for different levels of network density. We study the mentioned three dissimilarity metrics to determine the forwarding probability. As in the previous case, the Jaccard dissimilarity metric is the most suitable to determine the forwarding probability. According to the results, Jaccard dissimilarity metric is the best one to determine the forwarding probability for polynomial scheme. However, as it was observed in Chap. 6, the polynomial scheme is not suitable for the VANET scenarios.

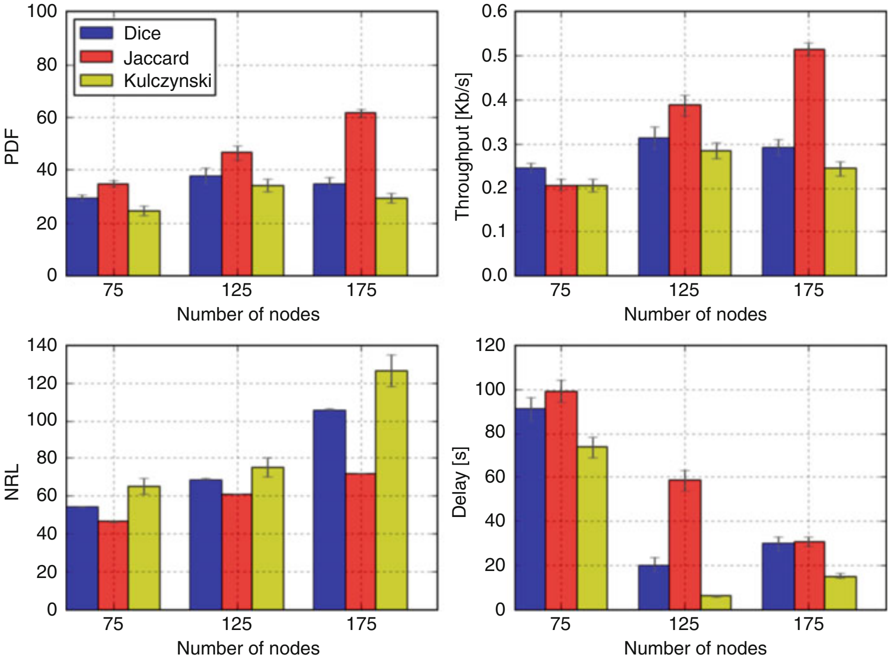

Fig. 7.2 Comparison of the obtained results for AODV with *p*-polynomial scheme in the route discovery phase and different levels of density

The PDF and throughput obtained by the polynomial approach are significantly lower than the ones achieved by the *p*-persistence. Similarly, *NRL* is worse compared with the results previously shown for the *p*-persistence scheme.

7.3.4 Comparison with the Original AODV Route Discovery

Now we compare the results obtained for AODV based on *p*-persistence algorithm with the Jaccard distance, which was the best scheme and dissimilarity metrics, to the original version of the route discovery phase of AODV. Figure 7.3 shows the comparison between the protocols. In general, the original version of AODV obtains better results in terms of PDF and throughput. In contrast, the NRL is reduced if the *p*-persistence scheme is used during the route discovery procedure.

To highlight how *p*-persistence can be used to reduce the routing load of AODV, we have studied the performance of *p*-persistence scheme as part of the route discovery phase of AODV under different congestion levels. We have varied the number of communication flows used to evaluate the routing protocol. A communication flow is established between a source node and a destination node by using constant bite rate traffic.

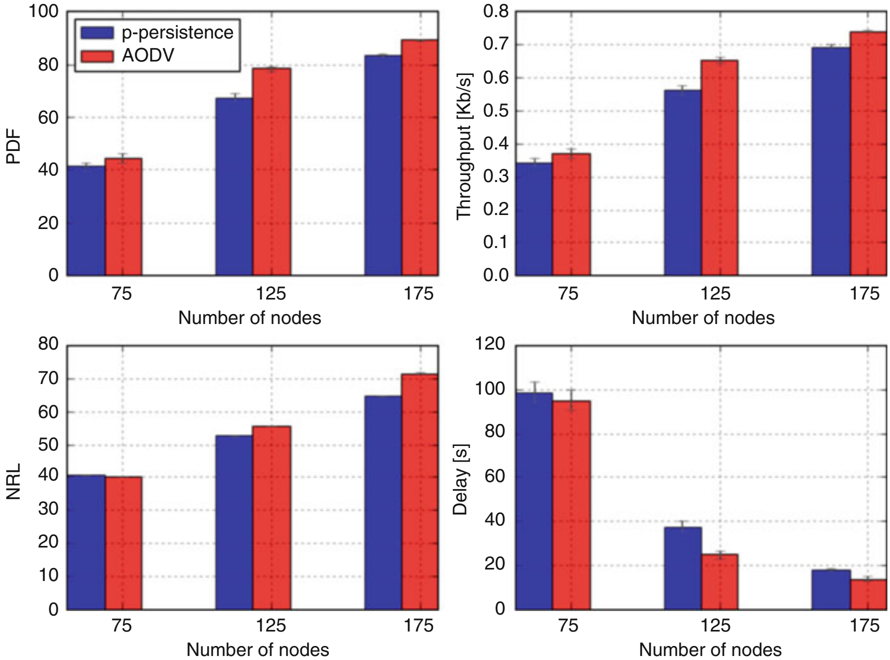

Fig. 7.3 Comparison of the results for AODV with *p*-persistence scheme with Jaccard dissimilarity metric and the original version of AODV for different network density levels

Figure 7.4 shows the results for different number of communication flows. As expected, the benefit of using *p*-persistence in terms of routing load is more noticeable as the number of communication flows is increased. However, it can be observed that the original AODV outperforms in terms of PDF, throughput, and delay. Therefore, it seems that more research is required on how to adapt the use of dissimilarity metrics in the discovery phase of routing protocols to maintain or even improve the PDF and throughput level obtained by the original AODV, while maintaining low the obtained routing load.

7.4 Discussion of the Results

The main findings of the study in this chapter are:

- The *p*-persistence scheme is the most suitable to be used as the route discovery procedure of AODV. In addition, the Jaccard dissimilarity metric is the best one to determine the forwarding probability in *p*-persistence.
- As discussed in Chap. 6, the polynomial scheme is not suitable in the VANET scenarios considered in this book.

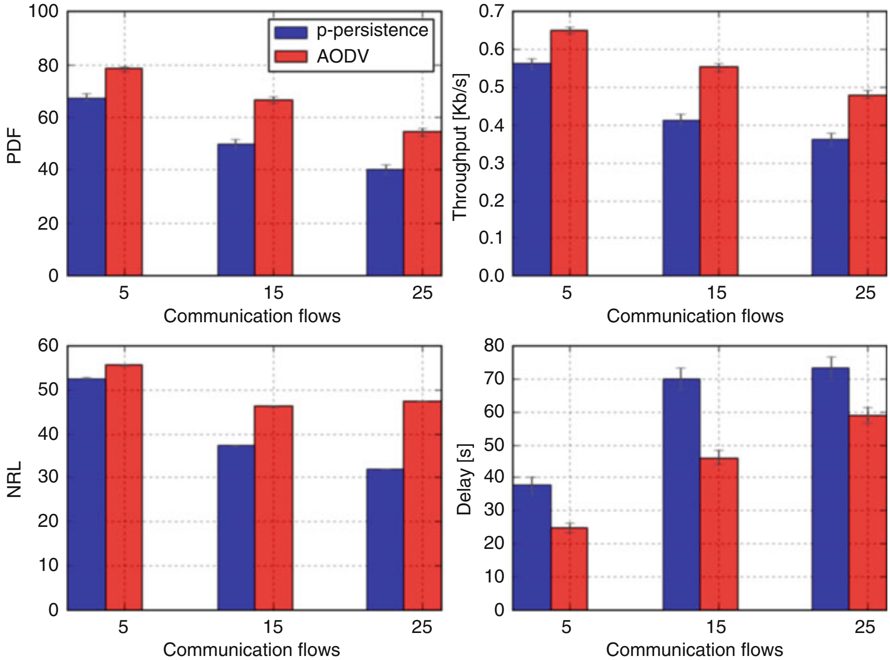

Fig. 7.4 Comparison of the obtained results for AODV with *p*-persistence scheme with Jaccard dissimilarity metric and the original version of AODV for different congestion levels

- The *p*-persistence scheme can be used to reduce the routing load of a reactive routing protocol like AODV. However, its use worsens the performance of AODV in terms of PDF and throughput. Therefore, more research is required to adapt the *p*-persistence scheme and the dissimilarity metrics to improve the performance of reactive routing protocols.

Chapter 8
Dissimilarity-Based Protocols in the DES-Testbed

In this chapter, we study dissimilarity metrics in a real-world wireless multi-hop testbed. In contrast to the previous chapters in which we used a simulation environment to study dissimilarity metrics, the testbed provides us with a realistic wireless multi-hop environment. From a methodical point of view, the testbed is the closest to a real deployed wireless multi-hop network that can be used in research.

In Sect. 8.1 we describe briefly the DES-Testbed and its main characteristics. In Sect. 8.2 we discuss the obtained experimental results of the proposed broadcasting algorithms based on dissimilarity metrics in the DES-Testbed. Finally, in Sect. 8.3 we summarize and conclude the findings from the experimental study.

8.1 The DES-Testbed

The DES-Testbed is a hybrid wireless multi-transceiver testbed for long-term studies. It consists of a *wireless mesh network* and a *wireless sensor network* [81]. We use only the WMN part of the testbed for our study. The WMN is composed of more than 120 mesh routers, which are equipped with three IEEE 802.11 a/b/g wireless network adapters that can be configured in ad hoc mode. Figure 8.1 depicts the topology of the DES-Testbed and some experiment metrics during the performance of an experiment.

The DES-Testbed has already been characterized in terms of packet delivery ratio, link asymmetry, node degree, node diameter, and average shortest path between each node in the testbed, among other parameters [81].

In this section, we measure the introduced *dissimilarity distances* between the nodes forming the DES-Testbed. In order to collect information about the dissimilarity distances between nodes, each node runs a program, which is responsible for sending periodically a *hello-message*. In addition, each node stores the list

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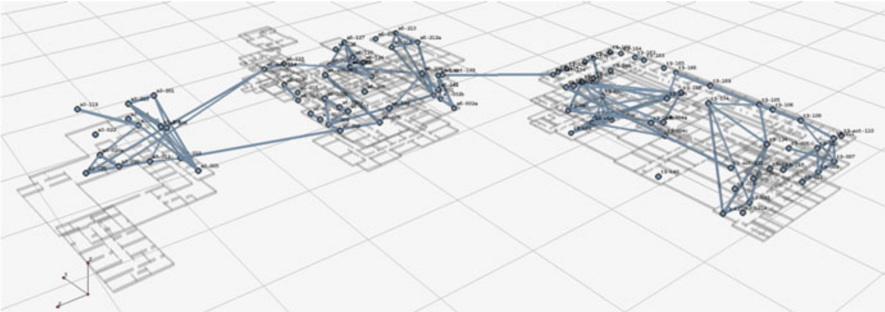

Fig. 8.1 DES-Testbed network topology during an experiment run

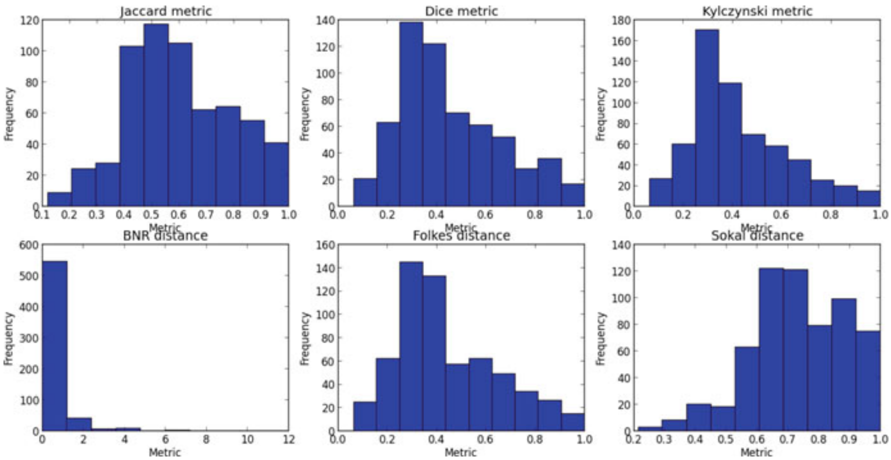

Fig. 8.2 Histograms of dissimilarity distances studied in the DES-Testbed

of its neighbors periodically in a log file that is later processed to compute the dissimilarity distances.

Figure 8.2 shows the histograms for the considered dissimilarity distances. Notice that the BNR metric [78] has been included for completeness. As observed in Fig. 8.2, the distribution of the Folkes, Dice, and Kulczynski metrics are very similar.

Beside the BNR metric, all the metrics show similar distributions. We interpret the results that short distances are favored and occur more often in the network. The BNR metric shows rather an extreme case (may be exponentially distributed) where nodes are either connected or disconnected. This could be a hint for a bimodal distribution in this case.

Figure 8.3 shows the *cumulative distribution function* (CDF) of the considered dissimilarity distances in the DES-Testbed. The dissimilarity distances range from 0.1 to 1 and it is also noticeable that it is very unlike to find a dissimilarity distance lower than 0.3. For comparison, we have also included the BNR metric and the Euclidean distance, which has been normalized.

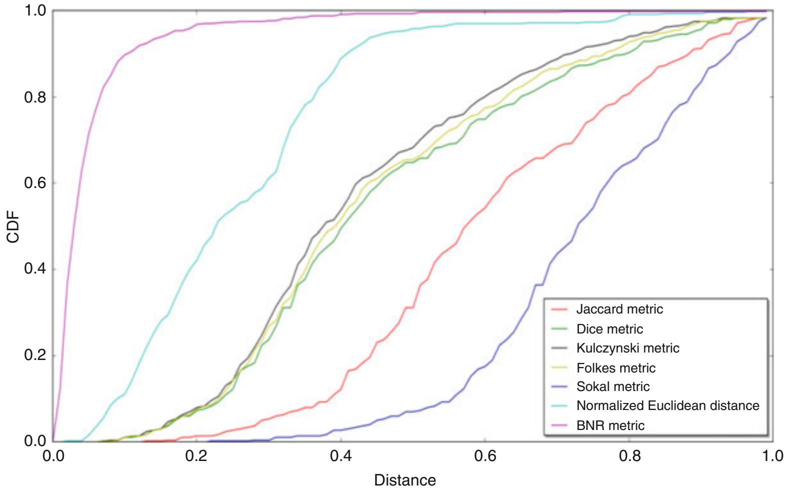

Fig. 8.3 CDF of the dissimilarity distances studied in the DES-Testbed

The best is to begin with the normalized Euclidean distance, since it represents the exact measurements in the testbed. The Euclidean distance shows that most of the nodes (85%) are in a distance of [0.1, 0.4] and the remaining nodes (15%) in a distance of [0.4, 1.0]. This means, that we have some nodes separated by long distances, but most of the nodes are in shorter distances. In comparison to the Euclidean distance, we see that all metrics, beside BNR, show a similar CDF as the normalized Euclidean distance. However, the dissimilarity metrics are more conservative and predict higher distances than the Euclidean distance. Thus, if we want to use the dissimilarity metrics as a substitute we have to use a linear transformation of the distances.

8.2 Experimental Probabilistic Broadcasting

In this subsection we study probabilistic broadcasting approaches based on the dissimilarity distances introduced in Chap. 5 in the DES-Testbed [81]. For this, we have implemented the approaches based on DES-SERT [87–89], which is a framework to implement routing protocols for wireless multi-hop networks.

8.2.1 Communication Traffic

We use `arping` [90] to generate the traffic in the experiments. It generates packets at the data link layer between a source node and a destination node in the network. Since we are interested in evaluating the broadcasting protocols as a stand-alone dissemination mechanism, we force the broadcasting packets to travel along the whole network hop-by-hop. This is achieved by using an IP address for the destination node that is not reachable from any node in the network, i.e., in the `arping` tool the destination IP address. Ten source nodes are randomly selected among all nodes in the network and each source node generates 100 packets, so in total 1000 broadcast packets are generated in the network.

8.2.2 Performance Evaluation Metrics

The following performance metrics are used to study the approaches:

- **Reachability (*Re*):** The reachability is defined as the fraction of nodes in the network receiving a given broadcast packet. In our case, the DES-Testbed network is a connected network, so the total number of nodes will be used. As a rule, a high reachability is a basic requirement for a broadcast scheme. The basic objective of a broadcast algorithm is to disseminate the information throughout the network and the reachability measures this feature. Consequently, a high value of *Re* is always desirable.
- **Number of retransmissions (*NR*):** A retransmission is the resending of an incoming packet by a node. A broadcasting scheme with a low number of retransmissions is desirable, since a high number of retransmissions can cause collisions and, as a consequence, the degradation of the performance of the broadcasting scheme. We use the normalized *NR* to study this performance metric. The lower the *NR*, the better it is.
- **Number of redundant packets (*NRed*):** A packet is considered as redundant when a node receives more than one copy of the same packet. The lower the number of redundant packets is, the better it is. Furthermore, the number of redundant packets also explains the energy efficiency of a broadcast scheme. We use the normalized *NRed* to study this performance metric.
- **Broadcast efficiency (*Be*):** The broadcast efficiency is defined as the ratio between the reachability and the normalized number of retransmissions *NR*. Consequently, *Be* is determined as $\frac{Re}{NR}$. We use *Be* in order to determine which approach balances better both *Re* and *NR*, which are two counterbalanced performance metrics. Generally, a high *Re* incurs in a high *NR*, so a good broadcasting approach should achieve a high value of *Re* with a moderate/low number of *NR*.

8.2.3 Performance of Dissimilarity-Persistence

In the *dissimilarity-persistence* approach the forwarding probability is calculated by using Eq. (5.1) where D_{ij} is the used dissimilarity metric. On receiving a new packet, a node calculates the dissimilarity metric (Jaccard, Dice, etc.) and stores it in a table with the identification ID of the received broadcast packet. The broadcast packets include the list of neighbors, thus nodes can easily calculate the dissimilarity metric between the node and the previous node by applying Eqs. (4.5)–(4.7), (4.9) and (4.10), respectively, depending on the used dissimilarity metric. Then, the nodes wait for a random time in the interval [0, 100] ms, and they calculate the dissimilarity metric for each new broadcast packet received with the same ID and from a different node. Nodes update the stored dissimilarity metric if the new value is lower than the stored value in the broadcast packet. After the random waiting time, nodes use the dissimilarity metric, which is the lowest one received, and apply Eq. (5.1). It is important to highlight that although the mesh network deployed in the DES-Testbed is static, the real topology suffers from variations due to wireless conditions such as interferences, noisy links, etc. This fact justifies that nodes include their list of neighbors in each broadcasting packet.

Figure 8.4 depicts the results of dissimilarity-persistence for different dissimilarity metrics. All the dissimilarity metrics achieve good results in terms of *Re*, above 80% in all cases. The best metric in terms of *Re* is the Sokal metric, that achieves a *Re* value of 0.95 and the worst result is achieved by the Folkes metric with a *Re* of 0.88. The Sokal metric achieves the highest values of *NR* and *NRed*. These results penalize the good results achieved for *Re*. In terms of *NR* and *NRed*, the Kulczynski metric is the best metric, achieving the lowest values. In addition, in terms of *Be*, again the Kulczynski metric is the best dissimilarity metric with a *Be* of 2.91. As a

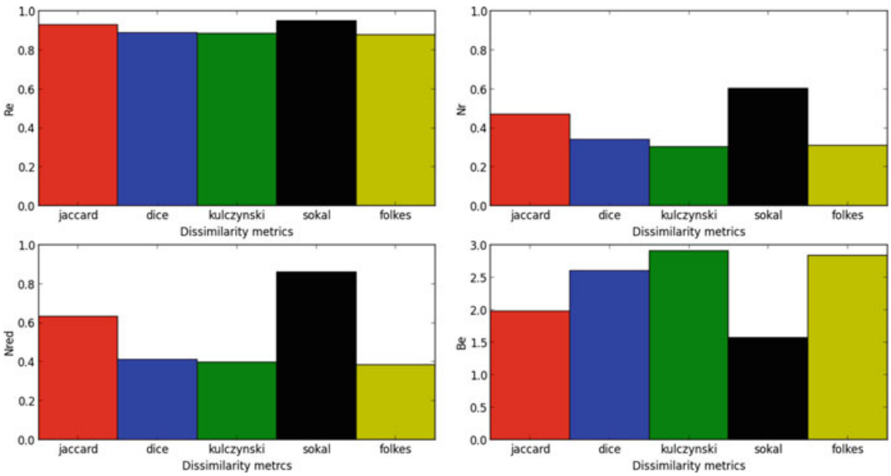

Fig. 8.4 Results for the dissimilarity-persistence approach

conclusion of this comparison, we select the Kulczynski metric as the most suitable metric to determine the forwarding probability, since it balances a high *Re* with the lowest value of *NR* and *NRed*. Notice that the Kulczynski metric achieves the best correlation with respect to the Euclidean distance in the DES-Testbed as it is shown in the correlation analysis presented in Sect. 4.5.1. Therefore, we incorporate the Kulczynski metric into the polynomial and irresponsible approaches in the following sections.

8.2.4 Performance of Dissimilarity-Polynomial

In the *dissimilarity-polynomial* approach, the forwarding probability is determined by using Eq. (5.2), where D_{ij} is the dissimilarity metric used and g is the exponent in Eq. (6.2) used to adjust the forwarding probability. The following values of g are studied $g \in \{1, 2, 5, 10\}$. We have selected these values because they are used in [84], where the polynomial approach is presented. Thus, we can compare our results with theirs. The implementation of the approach is the same as described in the previous section, but using Eq. (5.2) instead of Eq. (5.1) to calculate the forwarding probability and using the Kulczynski metric as D_{ij}.

Figure 8.5 shows the results. The best results in terms of *Re* are achieved when the polynomial approach is configured with $g = 1$ (p-persistence). For higher values of g, *Re* drops considerably, with $g = 2$, *Re* decreases until 0.57, which may be an unacceptable value for some applications. If we set $g > 2$, the achieved *Re* is even worse, $Re = 0.28$ for $g = 5$ and $Re = 0.21$ for $g = 5$. Regarding the other studied metrics, the results improve with higher values of g, since *NR* and *NRed* are much lower for higher values of g. *Be* is also better for higher values of g, but it is achieved by penalizing *Re*.

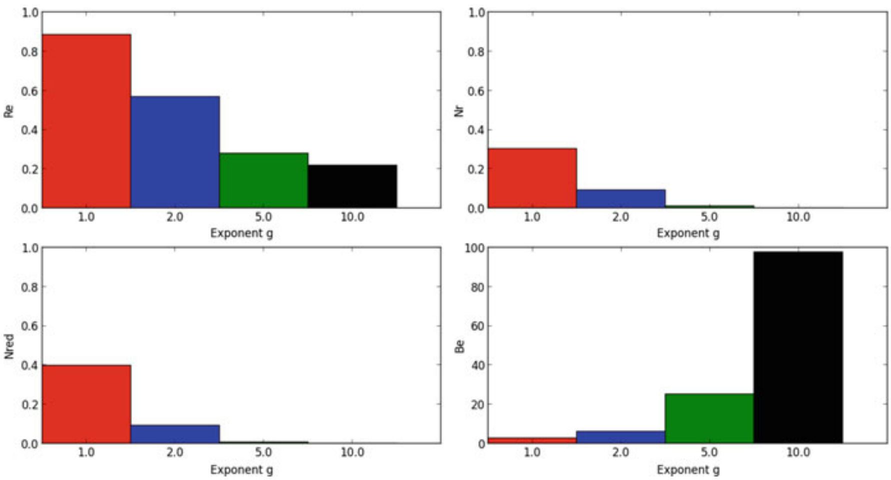

Fig. 8.5 Results for dissimilarity-polynomial approach

Summarizing, we consider $g = 1$ as the best option for the topology of the DES-Testbed, since we consider that Re below 0.8 is not acceptable for the majority of the broadcasting applications. Furthermore, the obtained results corroborate those presented in [67], where the polynomial approach is studied by simulation considering different network density levels. In [84] the results show that only when the spatial distribution of nodes is higher than 20 nodes/transmission range, it is possible to maintain Re high while increasing the value of g. However, the average node degree of the DES-Testbed during the experiments is 12.

8.2.5 Performance of Irresponsible Forwarding Based on Dissimilarity Distance

In *Irresponsible forwarding* approach the forwarding probability is calculated by using Eq. (5.3), where D_{ij} is the dissimilarity metric used, n_b is the number of neighbors, and c is the constant in Eq. (3.3) used to adjust the forwarding probability. We set c in our studies to these values $\{1, 2, 5, 10\}$. These values are also used in [67], where the irresponsible approach is introduced. We deploy Eq. (5.4) instead of Eq. (5.3) or (5.2) to calculate the forwarding probability and the nodes check their neighbor tables to calculate the number of neighbor n_b when they receive a new broadcast packet. The Kulczynski metric is also used as D_{ij}.

Figure 8.6 depicts the results. We have also included the results of p-persistence for comparison purposes. Considering Re, the best configuration of this approach is $c = 10$, achieving a Re of 0.86. For other values of c (lower values), the Re is worsened considerably, $Re = 0.55$ for $c = 5$ and much lower values for $c < 5$.

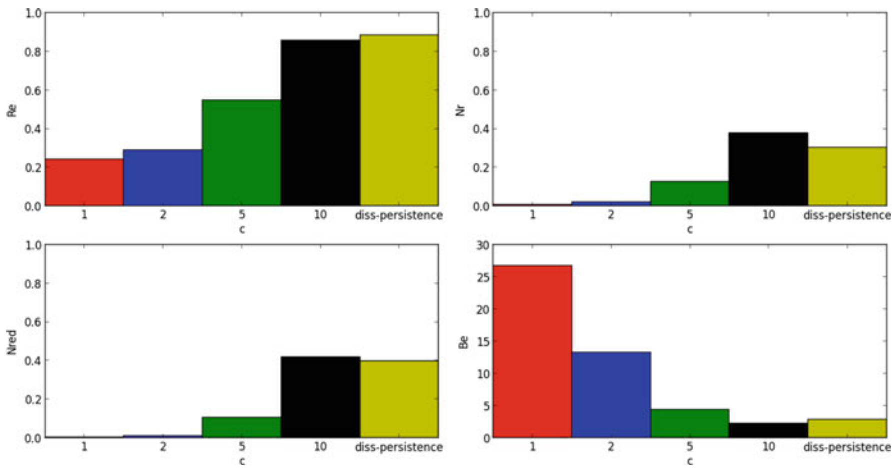

Fig. 8.6 Results for irresponsible approach based on dissimilarity metrics

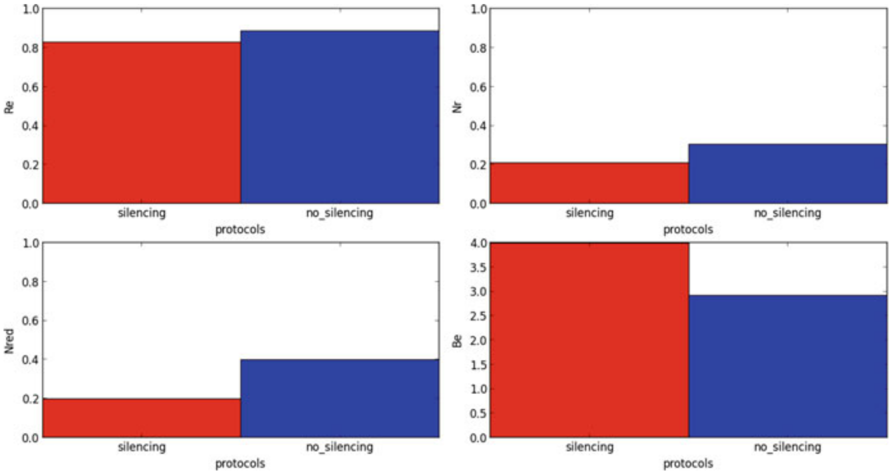

Fig. 8.7 Results for dissimilarity-persistence approach with silencing mechanism

This behavior is similar to that shown by polynomial approach for higher values of g. Comparing the irresponsible approach with p-persistence, we can observe that, although in terms of *Re* both approaches achieve similar results, 0.88 for the p-persistence and 0.86 for the irresponsible approach, the p-persistence protocol obtains better results in terms of *NR* and *NRed*. This is also observed in terms of *Be*, the p-persistence approach achieves 2.91, whereas irresponsible approach with $c = 10$ achieves 2.26. As a result of this comparison, p-persistence approach with Kulczynski dissimilarity metric is the best approach.

8.2.6 Silencing Based on Dissimilarity Metrics

In this section, we study the silencing mechanism along with the dissimilarity persistence protocol. The main idea is that nodes delay their retransmissions based on dissimilarity metrics instead of using random times. In addition, a node waiting for retransmitting a packet will not retransmit it if it receives a copy of such a packet.

Figure 8.7 shows the comparison between dissimilarity-persistence approach studied in the previous sections (no_silencing in Fig. 8.2) and the dissimilarity-persistence approach with silencing mechanism (silencing in Fig. 8.2). Regarding the obtained results, the silencing mechanism is suitable for reducing the values of *NR* and *NRed*. A reduction of 50% is achieved for *NRed* and 30% for *NR*. *Re* is slightly worsened, but it is still higher than 0.8, an acceptable value.

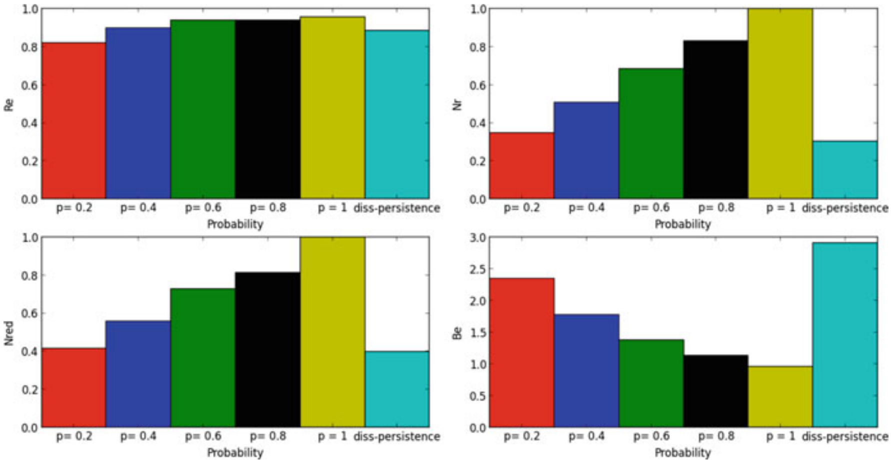

Fig. 8.8 Results for the comparison of Gossip 1 and dissimilarity-persistence

8.2.7 Comparison with Probabilistic Broadcasting

In this section, we study other approaches in order to compare the proposed dissimilarity-based approach. For this, we use the dissimilarity-persistence approach with the Kulczynski metric, since it has shown the best results in the previous sections. In order to make an unbiased comparison, the silencing mechanism is not applied in this section, since the other approaches do not use such a feature.

8.2.7.1 Gossip 1

First we study the simplest probabilistic broadcast approach Gossip 1 in the DES-Testbed. In this approach, nodes retransmit an incoming packet with a constant probability p. Consequently, all nodes in the network use the same forwarding probability. We consider different values for the forwarding probability $p \in \{0.2, 0.4, 0.6, 0.8, 1\}$. Notice that $p = 1$ is simple flooding, where nodes always retransmit. We have included the dissimilarity-persistence (diss-persistence in Fig. 8.8) for comparison to Gossip 1.

Figure 8.8 depicts the results. Considering *Re*, it is noticeable, that although the forwarding probability is 1, an *Re* value of 1 is not reachable. These results corroborate the results presented in [87, 88], so $Re = 1$ is difficult to achieve even in a well-connected network as it is the case of the DES-Testbed.

For the comparison between Gossip 1 and dissimilarity-persistence, the latter achieves much better results in terms of *Be*. Only if we can reach maximum *Re*, it makes sense to use flooding ($p = 1$) with a high cost in terms of *NR* and *NRed*, as it is shown in Fig. 8.8.

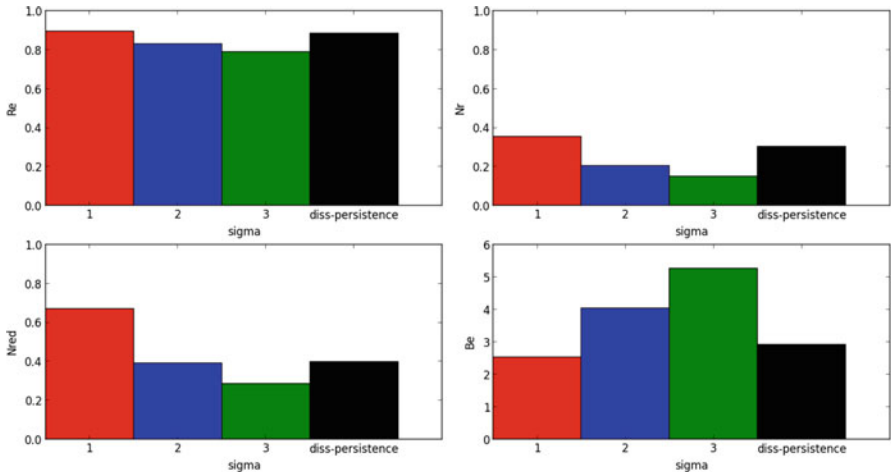

Fig. 8.9 Results for the comparison of BNR and dissimilar-persistence approaches

8.2.7.2 BNR

Next, we study BNR in the DES-Testbed. In the BNR protocol, nodes forward an incoming packet with a forwarding probability determined by Eq. (4.11). We have selected the same configuration presented in [78], thus $A = 1$ and $\alpha = 0$. We study BNR with different exponents σ such as 1, 2, and 3 (σ in Fig. 8.9).

Figure 8.9 shows the results for the BNR protocol. We have also included the dissimilarity-persistence (diss-persistence in Fig. 8.4) approach for comparison. The best configuration for BNR in terms of *Re* is when $\sigma = 1$, achieving a *Re* value of 0.9. Notice that this configuration is similar to *p*-persistence. As the value of σ increases, *Re* decreases, similarly to what occurred with the exponent g in dissimilarity-polynomial approach. When $\sigma = 3$, *Re* drops below 0.8. However, the other metrics are considerably improved, especially the *NR*. Regarding the comparison between BNR and dissimilarity-persistence approaches, dissimilarity-persistence achieves a better *Be* for maximum *Re*. On the other hand, if the target broadcast application can permit an *Re* close to 0.8, BNR approach with $\sigma = 3$ is the best option. The results of the dissimilarity-persistence approach in terms of *NRed* are also remarkable.

8.2.7.3 *p*-Persistence Based on Euclidean Distance

The next approach we study is the *p*-persistence approach in the DES-Testbed, as originally presented in [65, 91]. Notice that the nodes in DES-Testbed are not equipped with a GPS. However, their coordinates have been obtained with a GPS and are available for the nodes.

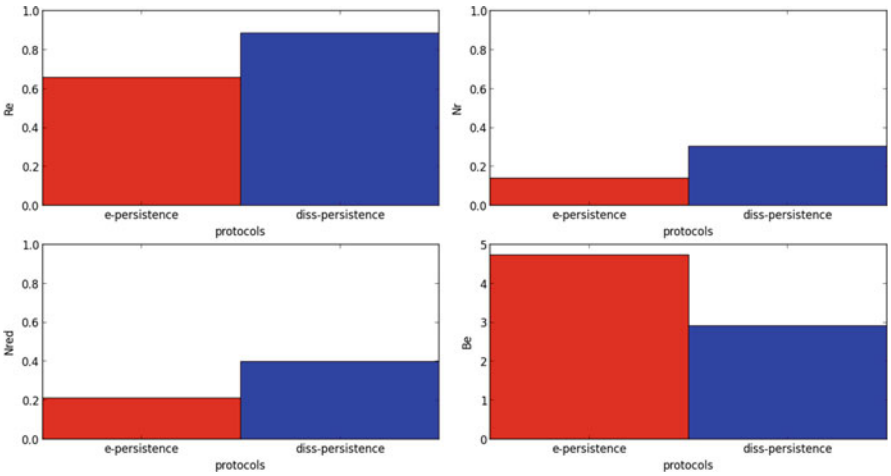

Fig. 8.10 Comparison of dissimilarity-persistence and *p*-persistence based on Euclidean distance approaches

In this case the forwarding probability is calculated by using Eq. (3.1), where D_{ij} is the Euclidean distance between two nodes i and j, and r is the radio transmission range of nodes. The sender of a packet includes its coordinates (x, y, z) in the broadcast packets, thus the receiver is able to calculate the relative distance between them. One important issue to be solved was how to determine the real value of r. In previous studies carried out in the DES-Testbed [92], it has been demonstrated that the connectivity of nodes is variable and it depends on many external factors such as interferences, walls, windows, people, etc. These external factors are very difficult or almost impossible to control during a running experiment. Consequently, it would not be useful to employ the nominal radio transmission range using the power transmission determined by the manufacturer of the wireless transceiver. Therefore, we use the maximum distance between two connected nodes in the testbed as the value of r. This value can be obtained from the histogram presented in Fig. 4.5, and is equal to 78 m.

Figure 8.10 shows the results for *p*-persistence based on Euclidean distance (e-persistence in Fig. 8.10). For comparison purposes, the dissimilarity-persistence (diss-persistence in Fig. 8.10) is also included. The dissimilarity-persistence approach based on Kulczynski metric clearly outperforms the Euclidean based approach in terms of *Re*. The *Re* obtained by Euclidean based approach is only 0.65, which is very low. The other metrics are better for Euclidean distance-based approach but with a notably penalization in terms of *Re*.

Consequently, we arrive at the conclusion that the dissimilarity metrics studied in this paper are more suitable to determine the forwarding probability.

8.3 Discussion of the Results

The main findings of the conducted experiments in this chapter are:

- The experimental results obtained in DES-Testbed corroborate the simulation results obtained in Chaps. 6 and 7. It means that the dissimilarity metrics are suitable parameters to designing communication protocols for WMHNs.
- The *p*-persistence approach is the best algorithm also in the experimental study. Therefore, it is the best way to determine the forwarding probability in probabilistic approaches for WMHNs.
- As shown in the simulation study for VANETs, the Kulczynski dissimilarity metric also shows the best performance.
- The application of the silencing mechanism enhances the performance of probabilistic approaches in terms of reduction of retransmitted messages.

Chapter 9
Conclusions and Future Directions

In this book, we have presented the design, implementation, and analysis of communication protocols for wireless multi-hop networks under different network conditions and different multi-hop networks (MANETs and VANETs). The simulation results obtained have demonstrated that dissimilarity metrics can be an interesting approach to design new broadcasting protocols for wireless multi-hop networks. Besides, we have shown that routing protocols can be improved by applying dissimilarity metrics in the route discovery phase.

The simulation results have been corroborated by implementing the proposed approaches in a real testbed. Therefore, the proposed broadcasting approach can be applied in real applications to disseminate messages in wireless multi-hop networks.

Several promising future directions can be considered from the obtained results.

The dissimilarity metrics used in this book have already been used in other research areas such as biology and economy. However, we think that new dissimilarity metrics must be proposed tailored for the objectives of communication protocols for wireless multi-hop networks. For instance, genetic programming can be a useful tool to develop dissimilarity based topological parameters [93].

The dissimilarity metrics can be applied to other important research problems such as clustering and network deployment. In clustering problems, the objective is to divide nodes into different clusters to efficiently disseminate messages throughout the network. Dissimilarity metrics can be easily applied to clustering formation in wireless multi-hop networks. Additionally, in network deployment, the objective is to spread out nodes in the given area to cover it. Dissimilarity metrics can be used to determine the optimal positions of nodes to solve the coverage problem.

As discussed in Chap. 7, more research is required to adapt properly the probabilistic broadcasting algorithms based on dissimilarity metrics to be used as part of the discovery phase of routing protocols. For this, other probability distributions could be considered.

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The idea is to extend the simulation results and compare them with real experimentation as it has been done with broadcasting algorithms. To apply the dissimilarity metrics to improve the communication protocols of other recent WMHNs such as DTNs [76] and FANETs [38].

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