Chapter 4
Routing Information Enhanced Cooperative Transmission

4.1 Introduction

The idea of performing cooperative relaying with the use of Virtual Antenna Arrays and on the basis of Distributed Space-Time Block Coding seems very appealing and beneficial, as discussed in the previous chapter. The question arises, however, how to enable and organise such cooperation among devices in a networked system. This issue is addressed with the aid of the proactive Optimised Link State Routing Protocol featuring the Multi-Point Relay selection heuristic. In particular, it is shown how Virtual Antenna Arrays may be seamlessly integrated into such an existing protocol and then the necessary modifications are outlined together with certain algorithmic extensions, as well as performance and overhead analysis is carried out. The presented solution already displays readiness for being integrated into the bigger picture of an autonomic cooperative system design framework, what will be exploited in the next chapter.

4.2 Optimised Link State Routing Protocol

The Optimised Link State Routing protocol [5], [9] was primarily designed for Mobile Ad-hoc Networks (MANETs) [14]. Such environments are usually characterised by very dynamic changes in network topology, and, therefore, the protocol should be tailored accordingly so that, keeping the overhead at a reasonable level, it would be able to follow these changes and provide accurate routing information. Generally, there are three fundamental routing concepts [1], [12] known for MANETs. First of all, there is a proactive approach where each network node performs topology recognition on a regular basis, so the routing tables are always up-to-date. Unfortunately, unless optimised, this approach may be costly in terms of protocol overhead. Secondly, one may distinguish the reactive approach, where topology recognition is performed once the routing table needs to be updated. Hence, the pro-

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tocol overhead is reduced, but, in turn, the delay related to route selection, increases. Last but not least is the hybrid approach combining the advantages of the aforementioned methods, depending on the activity of mobile nodes in specific regions of the network. As long as the topology changes are rather insignificant, the reactive attitude may be more appropriate, otherwise the proactive one is used.

In this book, special emphasis is laid on the Optimised Link State Routing (OLSR) protocol. Not only does OLSR belong to the proactive class, but it also features the Multi-Point Relay (MPR) selection heuristic. This heuristic aims to reduce the protocol overhead understood as the number of control messages broadcast for the purposes of network topology information dissemination [5], [11]. Generally, the idea is to transmit the Topology Control (TC) messages exclusively through the selected neighbour nodes, which belong to the one-hop neighbourhood of a given node and have been selected to cover the whole strict two-hop neighbourhood of this node. Such one-hop neighbours are recognised with Hello messages, which are received by each of them, but are not retransmitted. Hello messages, generated on the basis of the information stored in the Local Link Set, Neighbour Set and MPR Set [5], are broadcast by nodes on all their interfaces in a periodic manner. The operation of link sensing is necessary for the purposes of detecting whether a radio link exists in both directions, merely in one or even none of them. There is a direct association between the existence of a link and the existence of a neighbour. Therefore, Hello messages allow each node to discover both its entire one-hop and two-hop neighbourhoods, while the data gathered with their aid are exploited by the MPR selection heuristic.

In order to provide sufficient context for the OLSR protocol extensions to be presented later in this chapter (see Section 4.6), below the formats of the OLSR packet and Hello message are briefly described on the basis of [5]. In fact, also the above-mentioned Topology Control messages are encapsulated in OLSR packets but their description is not provided here and, instead, the reader is referred directly to [5]. As depicted in Figure 4.1, each OLSR packet starts with the Packet Length field (16

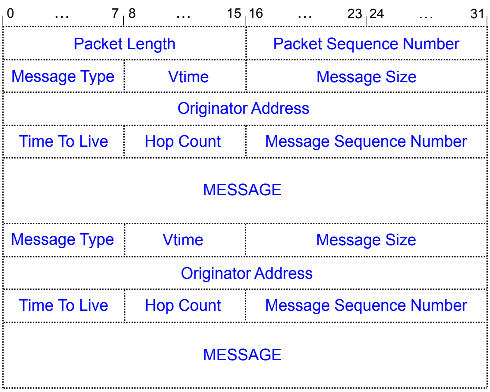

Fig. 4.1 OLSR packet format

bits) specifying its length in bytes. It is followed by the Packet Sequence Number field (16 bits), which is incremented by one each time a new OLSR packet is transmitted. Then distinct messages follow, preceded by a header containing a number of fields. First, there is the Message Type (8 bits) indicating the type of the carried message. One should note that the size of this field is sufficient to make future attempts at defining new message types possible. Second is the Vtime field (8 bits), also known as Validity time, which defines for how long the received information is to be considered valid in case there is no update to it in the meantime. This time is represented in the form of the mantissa a (four most significant bits) and the exponent b (four least significant bits), and based on this, the target validity time can be calculated according to the following formula (4.1) (also compare formula 4.3):

$$V_t = C\left(1 + \frac{a}{16}\right)2^b \tag{4.1}$$

where C is a constant scaling factor assumed to be equal to (4.2) [5]:

$$C = \frac{1}{16} = 0.0625s \tag{4.2}$$

Next is the Message Size field (16 bits) containing the size of the message in bytes, as counted from the beginning of a given Message Size field until the beginning of the next Message Size field, or in case there are no more messages, until the end of the OLSR packet. What follows is the Originator Address field (32 bits) with the main address of the node being the original issuer of this message. It is also crucial to note [5] that this address does not correspond to the Source address of the Internet Protocol (IP) header, which is changed each time to the address of the intermediate interface retransmitting this message. Then, there is the Time To Live (TTL) field (8 bits) pointing out the maximum number of hops a given message may be retransmitted. It is decremented by 1 before retransmission occurs and a given message may not be retransmitted, if its TTL is equal to 0 or 1. Following comes the Hop Count field (8 bits) indicating the number of hops the packet has traversed so far, as well as the Message Sequence Number field (16 bits) containing a unique identification number, exploited for the purposes of ensuring that a specific message is transmitted once only. Finally, the MESSAGE field of variable size contains the relevant message, such the Hello one.

As depicted in Figure 4.2, Hello messages also comprise a number of important fields [5]. Firstly, there is the Reserved field (16 bits) which must be set to 0000000000000000[1]. It is followed by the Htime field (8 bits), also known as the Holding time, which is used for specifying the Hello message emission interval over a given interface. This interval is represented in the form of the mantissa a (four most significant bits) and the exponent b (four least significant bits). Based on this, the emission interval can be calculated according to the following formula (4.3) (see also formula 4.1):

[1] In the case of the specification [5], 13 zeros are given instead of 16, while there is no point in leaving 3 of them unset.

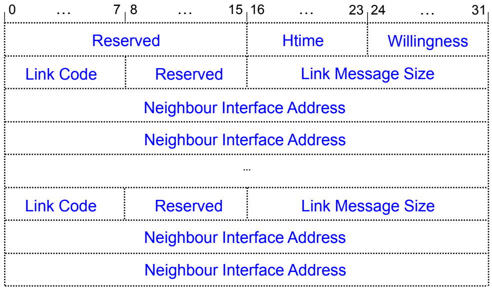

Fig. 4.2 Hello message format

$$H_t = C\left(1+\frac{a}{16}\right)2^b \tag{4.3}$$

where C is a constant scaling factor assumed to be equal to (4.2). Although the predefined Hello message emission interval amounts to 2 seconds, it can range from 62.6 milliseconds up to almost 2.28 hours. Next, there is a Willingness field (8 bits) specifying whether a given node is willing to carry and forward traffic to other nodes or not. There are the following levels of willingness available: WILL_NEVER (0), WILL_LOW (1), WILL_DEFAULT (3), WILL_HIGH (6) and WILL_ALWAYS (7). One should note that, as long as Willingness is set to 0, a given node must never be selected as MPR. On the contrary, in case the willingness is equal to 7, such a node must always be selected as an MPR. Afterwards, comes the Link Code (8 bits) defining the type of the link between an interface of a given node and the listed interfaces of its neighbours, as well as the neighbour type, as depicted in Figure 4.3. Currently 16 different combinations are recognised, however, future extensions are

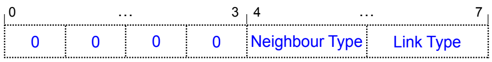

Fig. 4.3 *Link Code* format

also possible and, in fact, this option will be exploited later in this chapter. This field is structured so each the Neighbour Type and the Link Type field is assigned two bits. Following, all the specified Link Type and Neighbour Type values are given in Table 4.1 and Table 4.2, respectively. One should also note that a symmetric link is defined as a verified bi-directional link between two OLSR interfaces, whereas an asymmetric link is defined as link between two OLSR interfaces but verified in one direction only [5]. Last but not least appears the Neighbour Interface Address (16 bits) denoting the address of an interface of a given neighbour node.

Table 4.1 Link types

Link Type	Value	Description
UNSPEC_LINK	0	Indicates that no information about given links is specified.
ASYM_LINK	1	Indicates that given links are asymmetric which means that they are only heard.
SYM_LINK	2	Indicates that given links are symmetric.
LOST_LINK	3	Indicates that given links have been lost.

Table 4.2 Neighbour types

Neighbour Type	Value	Description
NOT_NEIGH	0	Indicates that given nodes are no longer considered as or have not yet become symmetric neighbours of this node.
SYM_NEIGH	1	Indicates that there exists at least one symmetric link between this node and each of the listed neighbours.
MPR_NEIGH	2	Indicates that there exists at least one symmetric link between this node and each of the listed neighbours, additionally selected as MPRs.

4.3 Multi-Point Relay Station Selection Heuristic

One of the main advantages of the Optimised Link State Routing protocol is its ability to use the selected nodes only for the purposes of the control data dissemination. These nodes are called Multi-Point Relays (MPRs), and they are chosen by a given node x out of its all symmetric one-hop neighbours. In consequence, all other neighbours in the range of this node, which do not belong to its MPR Set, also receive and process the control messages this node broadcasts, but do not retransmit them (Figure 4.4). Such an approach aims to minimise the number of redundant retransmissions and so to optimise the global control traffic. In order to perform the MPR selection heuristic, the node x must first collect all the necessary information regarding its one-hop and two-hop neighbourhoods. To this end, it exploits the data acquired through the reception of the aforementioned Hello messages, periodically transmitted by its one-hop neighbours. More specifically, each one-hop neighbour n of this node advertises its one-hop neighbourhood, as well as the status of the corresponding links. Consequently, the node x can identify both its symmetric neighbourhoods and then perform the MPR selection heuristic. In fact, there are three different neighbourhood types [5], as outlined in Table 4.3.

Prior to outlining the MPR selection heuristic [5], let us define $N(x)$ as the set of one-hop neighbours and $N^{(2)}(x)$ as the set two-hop neighbours of a given node x. Let us also define $MPR(x)$ as the set of Multi-Point Relays of this node x, where a Multi-Point Relay is a node which was selected by its one-hop neighbour x to

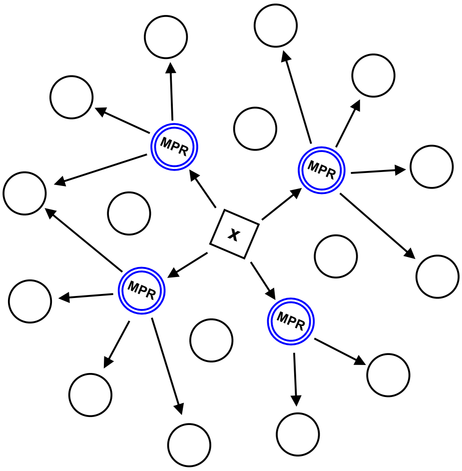

Fig. 4.4 Multi-point relaying

Table 4.3 Neighbourhood type

Neighbourhood Type	Definition
Symmetric one-hop neighbourhood of the node x	A set of nodes which have at least one symmetric link to the node x.
Symmetric two-hop neighbourhood of the node x	A set of nodes, excluding the node x itself, which have a symmetric link to the symmetric one-hop neighbourhood of the node x.
Symmetric strict two-hop neighbourhood of the node x	A set of nodes, excluding the node x and its neighbours, which have a symmetric link to a symmetric one-hop neighbour of the node x, characterised by the willingness different from WILL_NEVER.

retransmit all the broadcast messages that it receives from this node, provided that a message to be retransmitted is not a duplicate and its Time To Live (TTL) field carries value greater that one [5]. The MPR selection heuristic is performed with the use of both the sets of one-hop and two-hop neighbours. First, node x includes in the $MPR(x)$ set these of its symmetric one-hop neighbours n that are the only ones to provide reachability to a node n^2, located in the strict symmetric two-hop neighbourhood, and additionally are always willing to carry and forward traffic [11]. Next, while there still exist any uncovered nodes in $N^2(x)$ the heuristic keeps on selecting this node n in $N(x)$, which has not been inserted into the $MPR(x)$ set so far, and is characterised by the highest willingness to carry and forward traffic. In the case of multiple choices, the one is chosen which provides the highest reachability $R(n)$, i.e. through which the highest number of still uncovered nodes in $N^2(x)$ may be reached. Otherwise, if it is impossible to select one node only, the node with the highest degree is chosen, where the degree $D(n)$ of a one-hop neighbour denotes the number of its symmetric neighbours, excluding all the members of $N(x)$ and the node x performing the computation [5]. Once the MPR selection procedure is completed, Topology Control messages can be disseminated solely via this limited set of identified MPR nodes and as a result the protocol overhead may be significantly reduced [11].

4.4 Integration of Virtual Antenna Arrays

The OLSR protocol is well suited to large and dense mobile networks. This feature, together with its proactive flavour and link state nature, makes OLSR an ideal candidate for incorporating the concept of Virtual Antenna Arrays [6]. In fact, it resulted in the development of the Routing information Enhanced Algorithm for Cooperative Transmission (REACT) [15], [16]. REACT is based on the classic MPR selection heuristic, and it facilitates the process of the organisation of VAA-aided cooperative transmission. The main idea is to execute the classic MPR selection heuristic iteratively to identify nodes which can act together as VAAs. Additionally, extra MPR sets are created, ready to be exploited, if adaptive increase in protocol overhead is necessary to guarantee its proper functioning [5]. Of course, one needs to remember that, typically, relay nodes may cooperate at the Link layer according to more or less sophisticated schemes (see Chapter 3). However, their knowledge about the network topology and the parameters of separate radio links is limited to the closest, one-hop neighbourhood only. While it is still possible to imagine a more complex approach, able to collect additional details at the Link layer, it seems way more straightforward to utilise the information readily available at the Network layer instead.

In fact, such a goal may be achieved with the aid of the OLSR protocol which, thanks to its inherent mechanisms, allows each of the nodes to acquire the knowledge about their one-hop and two-hop neighbourhoods. What is more, it is possible to identify these one-hop neighbours in $N(x)$ which can provide connectivity to some two-hop neighbours in $N^{(2)}(x)$. This is one of the main reasons for basing REACT on the MPR selection heuristic, as there exists an obvious common aspect between the two. Namely, only these nodes are identified as MPRs which provide connectivity to a two-hop neighbour $n^{(2)}$. This assumption also holds true for the nodes to be pre-selected as the VAA set elements. An example is given in Figure 4.5, where it is shown that the nodes identified as Multi-Point Relays can also function as Mobile Relay Nodes and therefore form a Virtual Antenna Array.

4.5 Algorithmic Description

Following the notation introduced in Section 4.3, based on additional link-state information provided by the OLSR protocol, the REACT algorithm attempts to assign

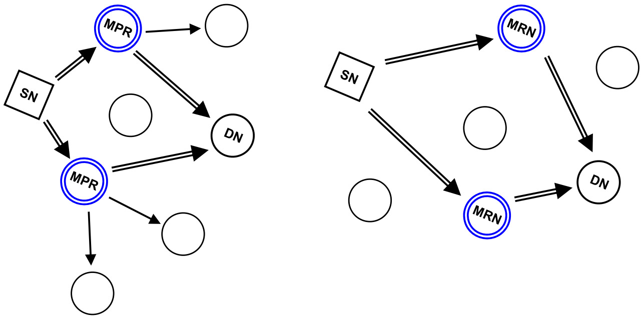

Fig. 4.5 Common aspect of the MPR selection heuristic and the VAA technology

RNs to specific VAAs [15], [19]. Let us just recall that the sets $N(x)$ and $N^{(2)}(x)$ are formed by one-hop neighbours and two-hop neighbours of node x, respectively. It is also assumed that both these sets contain symmetric nodes only reachable via bi-directional links. Moreover, the degree of a symmetric one-hop neighbour is defined as the number of its symmetric neighbours, excluding all the members of $N(x)$ and node x itself [5]. Analysing Algorithm 2, first, each neighbour n characterised

Algorithm 2 REACT

for all $n \in N(x)$ **do**
  if $degree(n) = 0$ **then**
    $N(x) \leftarrow N(x) \setminus \{n\}$
  end if
end for
$i \leftarrow 1$
while $N(x) \neq \emptyset$ **do**
  $MPR^i(x) \leftarrow$ OLSR_MPR_HEURISTIC($N(x)$)
  for all $n \in MPR^i(x)$ **do**
    for all $n^{(2)} \in N^{(2)}(x)$ **do**
      if $n = neighbour(n^{(2)})$ **then**
        $VAA(x, n^{(2)}) \leftarrow VAA(x, n^{(2)}) \cup \{n\}$
      end if
    end for
  end for
  $N(x) \leftarrow N(x) \setminus MPR^i(x)$
  $i \leftarrow i + 1$
end while

by zero degree ($degree(n) = 0$) is removed by node x from set $N(x)$. Then the classic MPR selection heuristic is executed iteratively over set $N(x)$, until all the potential MPR nodes have been assigned to distinct $MPR^i(x)$ sets. Consequently, each iteration results in an additional MPR set, i.e. secondary, ternary and so on, and then all nodes it contains, are allocated to the most relevant Virtual Antenna Arrays. These VAAs are denoted as $VAA(x, n^{(2)})$ and are capable of providing cooperative connectivity between the source node x and the destination node $n^{(2)}$, where $n^{(2)}$ belongs to the two-hop symmetric neighbourhood of node x. As a result, any intermediate node n can be included in more than one VAA. In this way not only all the intermediate nodes are pre-selected, but also additional redundancy is introduced to the MPR selection mechanism, as it was signalled previously. Such redundancy can be utilised in case there appear very sudden changes in the network topology so these additional $MPR^i(x)$ can be taken into account autonomically to provide better coverage [17], [18].

In the case of the Optimised Link State Routing protocol, all the one-hop neighbours are notified about having been chosen as MPRs with the aid of Hello messages. The same pattern is followed in the case of informing them about having been assigned to the specific VAAs. In this way additional information is conveyed upon which a node n can learn, firstly, that it is supposed to take part in space-time coded cooperative transmission and, secondly, according to which column of the relevant space-time block code it should process the received signal. Evaluation of

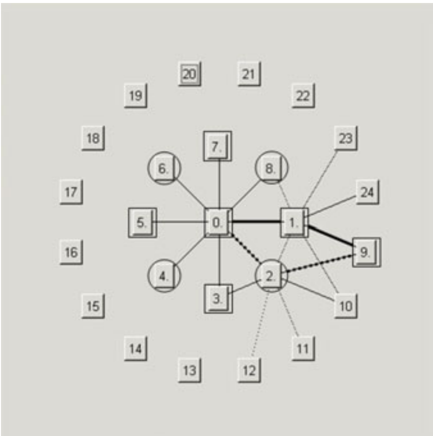

Fig. 4.6 REACT scenario

the performance of the proposed approach is carried out in the scenario depicted in Figure 4.6 [15], [19]. The wireless network is formed by the nodes of the following types: SN (0), RN (1-8) and DN (9-24). Relay nodes in squares are the ones that would be selected by the classic Multi-Point Relay selection heuristic, whereas the ones in circles belong to the redundant, secondary MPR set, selected additionally by the REACT algorithm. For the purposes of reducing the complexity of the simulated system, the maximum size of VAA is limited to 2, so the unity rate, G_2 space-time block code, is applicable [3], [13]. Consequently, once the REACT mode is active, the following primary $MPR^1(0) = \{1,3,5,7\}$ and secondary $MPR^{(2)}(0) = \{2,4,6,8\}$ sets are created, respectively. Actually, this is where the readiness of the proposed solution for the incorporation into autonomic system design [21], [4] is clearly visible, as the latter set may be used autonomically, if an increase in the control overhead is required. Based on both these sets and on the initial assumption that the test data stream would be originated from the SN and destined to the DN number 9, the $VAA(0,9) = \{1,2\}$ is set up at the beginning of the simulation, as shown in Figure 4.6. However, since the RNs and the DN are assumed mobile and moving at the speed of 5 km/h, the assignment of RNs to $VAA(0,9)$ needs to be dynamic during the course of the simulation time. Although the simulator supports switching between the conventional two-hop and the REACT mode, it is guaranteed that at least two RNs are available in the region of interest, so that the space-time coded cooperative transmission is continuous. The simulation investigations are carried out on the downlink and the block SIMO (at the first hop) and MISO (at the second hop) Rayleigh channels are used [15], [19]. The channel coefficients for the links between distinct pairs of nodes are generated according to formulas proposed in [22], as already introduced in Section 3.6. Similarly to all previous simulations, the total transmitted power, either by a single node or a VAA, is always normalised to unity. Additionally, the signal is perturbed by the additive white Gaussian noise with zero mean and $N_0/2$ variance per dimension. Always 100 million bits are transmitted and the QPSK modulation scheme is used. Under these

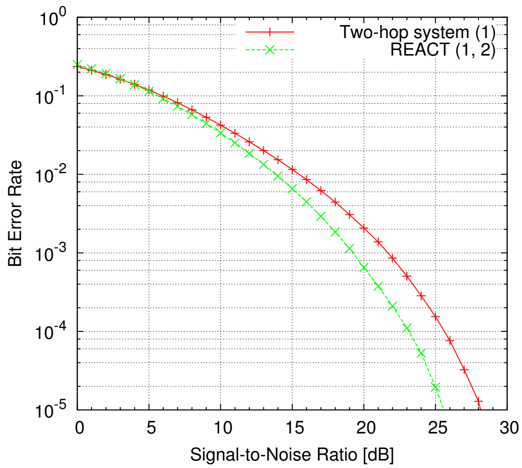

Fig. 4.7 Comparison of the performance for both the REACT and the conventional two-hop system

simulation assumptions, both the conventional two-hop mode without cooperative relaying, where the transmission is assisted by one RN only, and the REACT mode, exploiting two RNs, are analysed. The corresponding results are presented in Figure 4.7, where the numbers placed in the legend next to the names of the specific system configurations denote the next hop neighbour(s).

Looking at the presented results, one might notice that the Bit Error Rate (BER) curves almost overlap in the region of low SNR values. This is undoubtedly related to the problem of the propagation of the first hop errors during the second hop, as analysed in [15]. Namely, the first hop transmission, where the SN feeds the selected

RNs over the SISO radio links, is less robust to the radio channel impairments when compared to the space-time coded cooperative transmission at the second hop (see also Section 2.4 and Section 3.6). Usually, however, the SN is represented by a Base Station or an Access Point. It means that higher transmission power and better antenna gains are available compared to battery powered Mobile Relay Nodes (see additionally Section 4.7). To quantify the influence of the first-hop transmissions,

Algorithm 3 Pre-selection of first hop neighbours

for all $n \in N(x)$ **do**
  while $j \geq 0$ **and** $P_x^{VAA(x,n^{(2)})[j]} < P_x^n$ **do**
    $VAA(x,n^{(2)})[j+1] \leftarrow VAA(x,n^{(2)})[j]$
    $j \leftarrow j-1$
  end while
end for
$VAA(x,n^{(2)})[j+1] \leftarrow n$

Algorithm 3 is validated. This algorithm goes through the entire set $N(x)$ and promotes these potential RNs which are characterised by the highest received power P_x^n. In particular, two cases are evaluated, where the first-hop SNR value is maintained either at the level of 10 or 20 dB. The obtained results are depicted in Figure 4.8

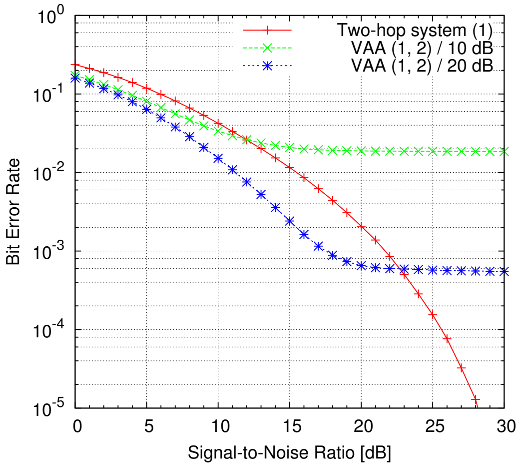

Fig. 4.8 Performance for first-hop SNR maintained at the level of 10 and 20 dB

where the numbers placed in the legend next to the names of the specific system configurations denote the next hop neighbour(s). This analysis aims to answer the question of what BER one could expect in the case of an equivalent dynamic system, if the SN would be able to pre-select RNs observing the received power level P_0^n being respectively 10 and 20 dB higher than the mean noise power N. Consequently, the performance of the investigated system would be not worse than what is indicated by the curves in Figure 4.8. Indeed, a gain in BER is observed, becoming the higher the higher the guaranteed SNR is. What is important is that such a system starts saturating at the values close to the assumed 10 and 20 dB, which additionally shows that the first hop is critical here.

4.6 Modifications to OLSR Protocol

The proposed concept requires certain extensions and modifications to the Optimised Link State Routing protocol [15], [19]. Special attention has been paid to make any changes compliant with the OLSR specification [5]. This assumption is fully met in the case of the first of them, related to the introduction of a new Neighbour Type, where an unallocated Neighbour Type value is exploited. This modification is required for the purposes of VAAs configuration, and more specifically, once the VAA pre-selection phase has been completed, each of the chosen RNs must be informed about its assignment to the specific $VAA(x,n^{(2)})$ set. In this way the RNs can conclude the way they are supposed to process the signals received from the SN. To this end, the list of Neighbour Types, originally specified by the OLSR protocol and given in Table 4.2, is extended by the introduction of a new VAA_NEIGH type, as described in Table 4.4. Consequently, Hello messages are able to convey Link messages of a new class, determined by this Neighbour Type. This information will have to be stored in an additional information repository, however, the details will be given after the Modified Hello message format has been discussed first. The introduction of a Modified Hello message format is inevitable, especially

Table 4.4 New neighbour type

Neighbour Type	Value	Description
VAA_NEIGH	3	Indicates that there exists at least one symmetric link between this node and each of the listed neighbours, additionally selected as VAAs.

for the purposes of extending the proposed REACT algorithm as outlined in Section 4.7. The Extended REACT [16] makes use of a more detailed information regarding the parameters of the specific radio links. Unfortunately, since the OLSR protocol was developed for Mobile Ad-hoc Networks [2], it collects merely very rough information about the links to the discovered neighbours (see Section 4.2). As a result, the parameters it provides would not be accurate enough to make the aforementioned extension feasible. Specifically, only four different Link Types are available, i.e. UNSPEC_LINK, ASYM_LINK, SYM_LINK and LOST_LINK, as previously summarised in Table 4.1.

Such an approach would sound reasonable, taking into account solely the characteristics of MANETs, where the knowledge whether a link is symmetric or not, suffices for setting up the communications. However, further optimisation of REACT demands a more detailed information pertaining to the power level of the received signal. In the case of the classic OLSR protocol, the Link Type is specified in the Link Code field of Hello message (see Figure 4.2). Consequently, each node groups in one Link Message these Neighbour Interface Addresses which are characterised by the same Neighbour Type and the same Link Type (see also Figure 4.3). Since information about link types is not very precise, such an approach guarantees that a number of Neighbour Interface Addresses are likely to fall into the same Link Message and it is why this kind of grouping seems rather effective, at least when the size of Hello messages is concerned [19]. Introducing any additional data regarding the link parameters might, on the one hand, spoil this effectiveness, because the more precise information is included, the smaller gets the number of nodes to be assigned to the same group. Eventually, each Link Message may contain one Neighbour Interface Addresses only. On the other hand, if the initial assumption regarding backward compatibility with the OLSR protocol specification is to be fulfilled, this might be the only reasonable solution to this issue. Therefore, a modified Hello message format is proposed in this section, which is depicted in Figure 4.9. This modified format contains a new 16 bit Extended Link Code field, compris-

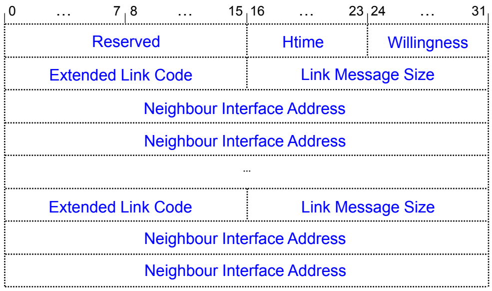

Fig. 4.9 Modified Hello message format

ing both the classic Link Code and Reserved fields. The structure of this Extended Link Code is outlined in Figure 4.10. The idea is to utilise the four Most Signifi-

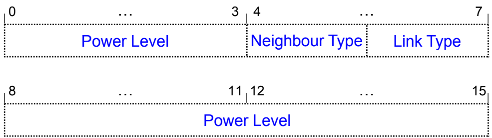

Fig. 4.10 Extended Link Code format

cant Bits (MSBs) of the Link Code field together with the eight additional bits of the Reserved field. It makes twelve bits in total which form together a new Power Level field, and are now available to convey additional information about the power level of the radio signal. As a result, the node x will be able not only to find out, whether its one-hop neighbour n can hear the transmitted signal coming from this node, but it may also learn what is the precise power level of this signal. Moreover, as Hello message sent by a node n usually contains similar information pertaining also to other one-hop neighbours of this node, which in turn may by the two-hop neighbours of the aforementioned node x, this node x can have far more concrete overview of the link parameters in its entire one-hop and two-hop neighbourhoods, especially if radio channel reciprocity could be assumed.

However, this very modification to the Hello message format is not completely transparent to the internal mechanisms of the Optimised Link State Routing protocol. Namely, unlike it was the case for the first modification, where it was sufficient to make the protocol aware of the new VAA_NEIGH type, here situation seems somewhat more complicated. The main problem is that the Reserved field is utilised which, according to the specification, should remain unchanged [5]. Moreover, the aforementioned four MSBs are exploited which are meant for future extensions, however, are not straightforwardly applicable in the case of the proposed modification. Therefore, for the purposes of overcoming this problem, a simplified attempt to guarantee backward compatibility is outlined below. Namely, when a Hello message is processed for the purposes of performing the classic protocol operations, the new Extended Link Code field should be masked with the Extended Link Code Mask, depicted in Figure 4.11. In particular, any specific implementation of such a

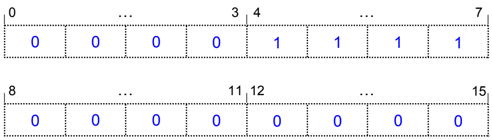

Fig. 4.11 Extended Link Code Mask format

modified OLSR protocol would have to utilise the defined mask for the purposes of performing a logical AND operation over all the Extended Link Codes, included in a specific Modified Hello message. The only exception to this rule is when the Power Level data need to be accessed for the needs of the Extended REACT algorithm. Such an approach seems to be the safest way from the backward compatibility perspective. However, one could also consider the introduction of a new Hello message format [15], [19]. Such an example Generalised Hello message is presented in Figure 4.12. Its format differs from both the classic and modified ones because it lacks the Link Message Size field. This solution is dictated by the fact that, as mentioned earlier, it is very likely that, in most of the cases, solely one Neighbour Interface Address will be included in one Link Message. Therefore, the size of the

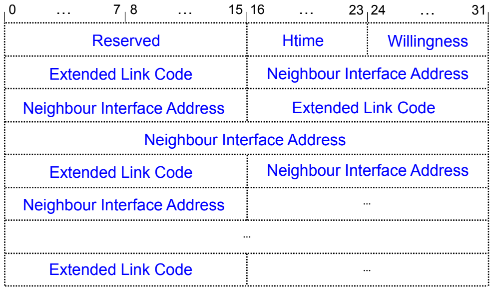

Fig. 4.12 Generalised Hello message format

entire Hello message could be reduced by skipping the Link Message Size field and always including only one Neighbour Interface Address in a Link Message[2].

Now, going back to the new VAA_NEIGH neighbour type, the initial idea, straightforwardly applicable to the original REACT, was to exploit the order in which the Neighbour Interface Addresses of VAA_NEIGH type are located on the list of the Neighbour Interface Addresses. This was meant for the purposes of notifying these neighbours about the way they are supposed to cooperate during the retransmission phase. More specifically, the position on the list would determine the identification number of the column, in the relevant space-time block code matrix, according to which each of the nodes belonging to $VAA(x,n^{(2)})$ should cooperatively process the retransmitted signal. The reciprocal of the number of addresses on such a list would originally specify the power scaling factor. One should note that in the Extended REACT the power will be not scaled in this sense anymore (Section 4.7). This way or another, since Modified Hello messages carry more detailed information about the parameters of distinct links, it is rather unlikely that two Neighbour Interface Addresses would fall into one Link Message. Therefore, it should be rather guaranteed that the order of the one-element Link messages would correspond to the identification numbers of the columns in the relevant space-time block code matrix. One should also take into account that, although unlikely, it might happen that two Neighbour Interface Addresses of VAA_NEIGH type fall into the same Link message after all. For this reason, once again, the optimum solution would be to include one Neighbour Interface Addresses of a VAA_NEIGH type in a Link Message only and, what is more, to place all such messages in Hello message in the first order to avoid fragmentation. This additionally proves, however, that the Generalised Hello message would be more applicable here.

Last but not least, after having processed such a Modified Hello message, each node VAA_NEIGH must store the acquired data [15], [19]. To this end, an additional VAA Selector Set is proposed to be maintained in the Neighbour Information Base[3]. This new VAA Selector Set is then formed by VAA-Selector Tuples of the

[2] Another issue is if such a structure could be still named a Link Message.

[3] For further information regarding the OLSR protocol repositories the reader is referred directly to the specification [5].

format presented in Table 4.5. As a result, each node can easily determine if it is

Table 4.5 VAA-Selector Tuple

Item	Description
VS_main_addr	The main address of a node which has selected this node as the element of a VAA.
VS_elem_id	The VAA element identification number specifying the column of the relevant space-time block code, according to which the retransmitted signals should be processed.
VS_time	The time at which this tuple expires and must be removed.

to cooperate after receiving a user data packet from a neighbour by simply comparing its address with VS_main_addr. If so, then it will use the relevant column of the space-time block code, as specified by VS_elem_id.

4.7 Algorithm Extension and Protocol Overhead

In this section, a low-mobility and high-density hot-spot scenario is investigated [15], [16]. In particular, Mobile Relay Nodes are taken into account but either the fixed or movable ones are of course conceptually not excluded. The velocity of mobile terminals is in-between 0 - 5 km/h which is equivalent to 0 - 1.4 m/s. A Line of Sight (LOS) channel model is assumed, characterised by the path-loss parameter $L(d)$, given by the formula (4.4) [8], [15]:

$$L(d) = 13.4\log_{10}(d) + 36.9 \quad [\mathrm{dB}], \tag{4.4}$$

where d represents the distance, in meters, and is limited in the following way: 5 m $< d <$ 29 m. The shadow fading standard deviation σ is equal to 1.3 dB. Additionally, the SN, being a Base Station in this case, is assumed to transmit with the average power equal to 200 mW. The BS is equipped with an antenna characterised by the gain of 8 dBi. The DNs, here UTs, which also act as mobile relays, are characterised by the corresponding parameters equal to 200 mW and 0 dBi. The downlink is investigated and the Quadrature Phase Shift Keying (QPSK) modulation scheme is assumed. Moreover, the noise figure introduced by the radio frequency chain of the mobile station is equal to 7 dB.

The analysed network topology, limited to one sector, is presented in Figure 4.13. The destination UT (18) is located 29 meters away from BS (0). The distance between BS and each UT belonging to the first (1 - 6) and to the second group (7 - 17) is equal to 10 and 24 meters, respectively. One should remember that BS and UTs

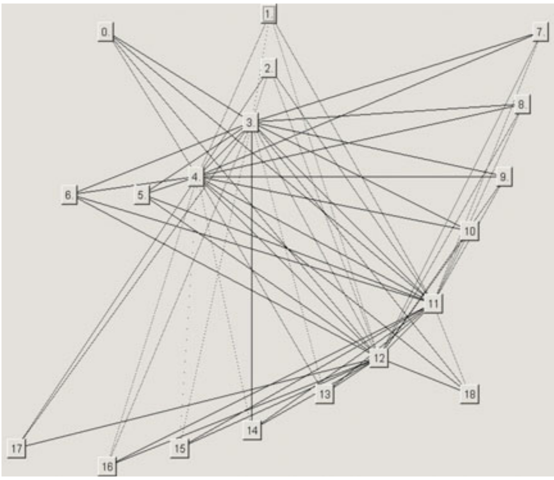

Fig. 4.13 Extended REACT scenario

are equipped with antennas offering different gains. Consequently, even if the power level of the signal received from BS by the destination UT (18) is acceptable, it does not necessarily hold true in the opposite direction. This is to some extent in contrast with MANETs, for which the OLSR protocol was originally designed [20]. More precisely, in the case of OLSR, if two nodes hear each other, a symmetric link can be established without any additional considerations regarding the power levels, because in general, these nodes are perceived homogeneous [7]. For the needs of the following analysis, it is assumed, however, that in the case of the considered scenario, a power threshold must be satisfied by the specific UT, if, using the OLSR terminology, it is to be recognised as a neighbour of BS. As UT (18) does not meet this requirement, it is assigned to the $N^{(2)}(x)$ set, whereas all the intermediate UTs form the $N(x)$ set.

Similarly to Algorithm 2, also in the case of the Extended REACT, first each node n having zero degree ($degree(n) = 0$) is removed by node x from the one-hop neighbour set $N(x)$, as outlined in Algorithm 4. Then the classic MPR selection heuristic, described in Section 4.3, is carried out iteratively over the set $N(x)$, until all the nodes it contains have been assigned to the redundant $MPR^i(x)$ sets and pre-selected into the most relevant Virtual Antenna Arrays $VAA(x,n^{(2)})$. After each iteration, all the elements of set $MPR^i(x)$ are removed from set $N(x)$. However, the pre-selection itself is performed in a different way. In the case of the original REACT, the order of potential relays in the specific $VAA(x,n^{(2)})$ sets was strongly correlated with the MPR heuristic selection criteria, and therefore, not necessarily optimum. In the proposed extension, additional information about the power levels of the signals received by distinct nodes from their one-hop neighbours, collected by the modified OLSR protocol, is exploited. This information is stored in the Power Level field of the Extended Link Code (see Section 4.6). Based on it, a node is placed in $VAA(x,n^{(2)})$ at this position which corresponds to the power level at which it is

Algorithm 4 Extended REACT

for all $n \in N(x)$ **do**
    if $degree(n) = 0$ **then**
        $N(x) \leftarrow N(x) \setminus \{n\}$
    end if
end for
$i \leftarrow 1$
while $N(x) \neq \emptyset$ **do**
    $MPR^i(x) \leftarrow$ OLSR_MPR_HEURISTIC($N(x)$)
    for all $n \in MPR^i(x)$ **do**
        for all $n^{(2)} \in N^{(2)}(x)$ **do**
            if $n = neighbour(n^{(2)})$ **then**
                $j \leftarrow size(VAA(x, n^{(2)})) - 1$
                while $j \geq 0$ **and** $P^{n^{(2)}}_{VAA(x,n^{(2)})[j]} < P^{n^{(2)}}_{n}$ **do**
                    $VAA(x, n^{(2)})[j+1] \leftarrow VAA(x, n^{(2)})[j]$
                    $j \leftarrow j - 1$
                end while
                $VAA(x, n^{(2)})[j+1] \leftarrow n$
            end if
        end for
    end for
    $N(x) \leftarrow N(x) \setminus MPR^i(x)$
    $i \leftarrow i + 1$
end while

heard by the destination node. It means that the first relay nodes in a VAA set provide the best connectivity to the target UT. In this way the process of pre-selection is additionally optimised which is validated by simulations, as presented below.

A dedicated simulation environment is used [15] and the situation presented in Figure 4.13 is evaluated, where all the recognised neighbours of nodes 3, 4, 11 and 12 are depicted. The simulations are performed in the presence of a zero mean additive white Gaussian noise characterised by the power level N expressed in dBW. Always 100 million bits are transmitted. The noise power level is given in Figure 4.14 instead of SNR because the effective SNR in the system would vary from point to point, depending on the power level of the received signal modelled according to (4.4). The transmission is originated by BS (0) and destined to UT (18). Five distinct cases are considered. First, although it has been assumed that the destination UT is conceptually not a neighbour of BS, the performance of the one-hop link towards the destination UT is evaluated as the worst, reference case. Then two different configurations of a two-hop system are tested, where the transmission is assisted by UT (3) and UT (12), respectively. An advantage is observable, especially in the latter case, when the relaying UT is situated closer to the destination and the antenna gain of BS may be more efficiently exploited. Finally, REACT and its extended version are validated. In the case of the original REACT, where UT (3) and UT (4) are selected and consequently the $VAA(0,18) = \{3,4\}$ is configured, a significant improvement in the performance may be observed. What is even more important, the Extended REACT, featuring the modified pre-selection method, provides the ex-

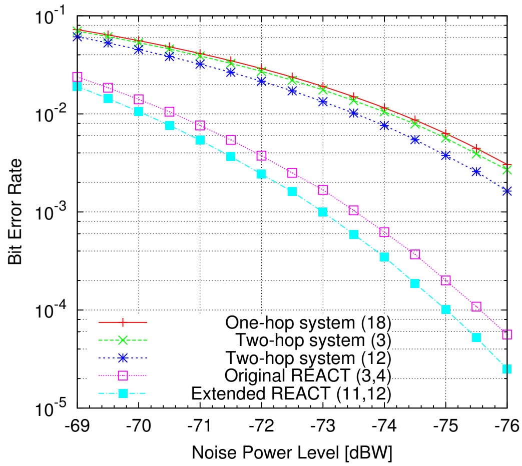

Fig. 4.14 Simulation results comparison for extended REACT

pected, additional performance gain. In its case, these MRNs (UTs) are pre-selected which are closer to the destination UT, and as a result the $VAA(0,18) = \{11,12\}$ is created. The detailed comparison of the results can be found in Figure 4.14, where the numbers placed in the legend next to the names of the specific system configurations denote the next hop neighbour(s).

Given the continually progressing convergence between the cellular systems and routing [20], especially in part related to the relay enhanced radio access network [7], it is also crucial to provide additional details about the process of routing when two-hop cooperative transmission is concerned. In general, when the Network layer sends a packet to a Destination Node denoted by an IP address of value R_dest_addr, it uses the IP address of value R_next_addr and requests the Link layer routines to send this packet, in a Medium Access Control (MAC) layer frame, to a MAC address corresponding to this R_next_addr IP address. Obviously, the MAC address is resolved with the aid of the Address Resolution Protocol (ARP) [10]. However, in the case of REACT a packet must be transmitted concurrently via all the RNs belonging to a given VAA. This issue may be addressed by associating an additional routing table with each column of the space-time block code matrix [15], which leads to a multidimensional routing table as depicted in Figure 4.15. For the sake of providing an example, let us follow the assumption that the size of the VAA is limited to two RNs, so that only two routing tables need to be maintained. Bearing in mind the Extended REACT configuration, RNs 11 and 12 are chosen to constitute the VAA serving the destination UT (18). According to the information stored in the VAA Selector Set, one entry will be included in the first routing table, whereas the other entry will go to the second routing table. In other words, when the Network layer routine at BS (0) is going to send a user data packet to UT (18) it should check both routing tables. As a result it would find out that cooperative transmission is possible, because two intermediate RNs are available: 11 and 12. It would then

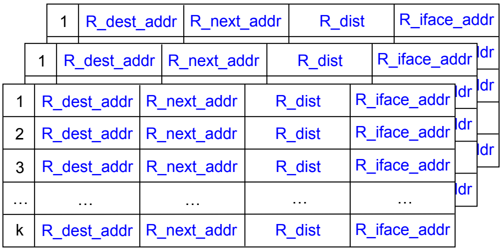

Fig. 4.15 REACT routing table

request the underlying Link layer to send one packet to UT (18) via nodes 11 and 12, i.e. $VAA(0,18) = \{11,12\}$. The obvious requirement here is that this Link layer must be able to transmit frames to a group of MAC addresses.

As already indicated, the proposed solution integrates well with the routines of the Optimised Link State Routing protocol, so the instantiation of cooperative transmission does not require any additional messages to be transmitted. However, the format of the Hello Message is slightly modified in such a way that the normal operation of the OLSR should be not disturbed. This comes at a price in terms of an increase in the size of the Modified Hello Message, as mentioned in Section 4.6 [19]. It means that one may expect some overhead induced by the additional data that needs to be distributed (see Figure 4.16). The reason for that increase is mainly the

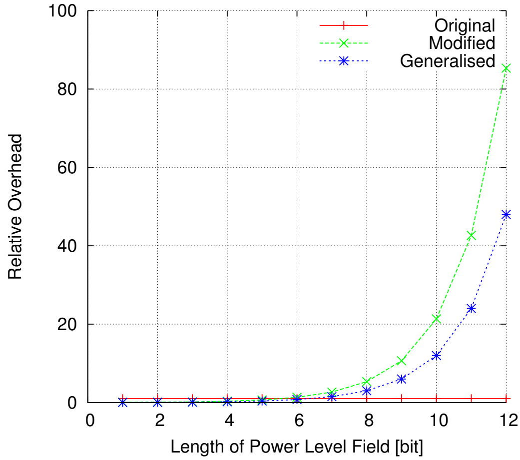

Fig. 4.16 Overhead introduced by the Modified and Generalised Hello Message format

Extended Link Code. Typically, the OLSR protocol distinguishes among 4 different link types and 3 different neighbour types. This gives 12 combinations which means that all the Neighbour Interface Addresses can be qualified to 12 groups, i.e. Link Messages, at most. For the proposed modification it suffices, when only some of these Link Messages are separated into smaller sets by including extra information about the power level. In particular, due to the type of the data required by the MPR selection heuristic and by the algorithms presented in this chapter, it is sufficient to focus on the SYM_LINK, as well as on the SYM_NEIGH and MPR_NEIGH. This limits the number of theoretically possible 16 combinations, in fact enlarged as a result of the introduction of the VAA_NEIGH, to just 2. The main factor influencing the overhead is then the size of the Power Level field [19]. This field is 12 bits long so there are theoretically 4096 values allowed which multiplied by the aforementioned 2 combinations gives 8192 possibilities. Taking into account that there are only singular interfaces characterised by a given power level, in the worst case, one would end up with 8192 Link Messages, each accompanied by a header of the length of 32 bits. This is of course the worst possibility and Figure 4.16 presents the expected overhead for different number of bits used. One can see that for 6 bits the overhead is almost diminishable.

4.8 Conclusion

In this chapter, the Routing information Enhanced Algorithm for Cooperative Transmission was presented as a solution for enabling Virtual Antenna Array aided cooperative relaying on the basis of Distributed Space-Time Block Coding and with the aid of the Optimised Link State Routing Protocol. Especially, the Multi-Point Relay station selection heuristic was employed and integrated with Virtual Antenna Arrays. To this end, certain modifications to the OLSR protocol were proposed keeping in mind backward compatibility. The introduced concept will be further integrated into the autonomic cooperative system design in the following chapter.

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