Positive Orthogonal Code-based Cooperative Forwarding for VANETs

by

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Abstract

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Vehicular Ad hoc Networks (VANET) consist of radio-equipped vehicles and roadside units (RSU) and support many safety and commercial applications. Multi-hop forwarding can extend the communication range of both RSUs and vehicular broadcasts. Recently, the use of Positive Orthogonal Codes (POC) as transmission patterns of repetition-based broadcast medium access control (MAC) for safety messages has been proposed. This thesis proposes a cooperative forwarding protocol in which multiple relays at each forwarding hop form a virtual relay and coordinate their transmission times to correspond to a POC codeword. The protocol thereby exploits spatial diversity while conforming to the POC-based MAC, resulting in fewer collisions and mitigating the effect of hidden terminals. The design is validated through NS2 simulations, which show comparable performance with other forwarding schemes while producing significantly less performance degradation for safety message broadcasts on the same channel.
Dedication

To my mom Guiling, and my dad Yaolin.
Acknowledgements

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Chapter 1

Introduction

1.1 Motivation and Purpose

Vehicular accidents have claimed the lives of more Canadians over the past 50 years than the two world wars combined; each day eight Canadians on average die in vehicular collisions[3]. On a global scale, the social and economic impact of road accidents are staggering. The World Health Organization (WHO) and the World Bank estimate their direct economic cost at US$ 518 billion [4]. In terms of global burdens of disease and injury, traffic accidents are projected to become the third highest contributor of disability-adjusted life years (DALY) by 2020[4].

In response to the need for safer roads and vehicles, engineers have introduced many safety-enhancing technologies. Many are now standard in all vehicles, such as ABS brakes and air-bags, while other more recent technologies such as autonomous cruise control and pre-crash systems [5], are only offered in select vehicles. These last systems rely on vehicle-mounted cameras, radar or lasers to provide local information about the vehicle’s surroundings. The next step in safety-enhancing technologies will likely come in the form of active cooperative systems, in which vehicles communicate their Global Positioning System (GPS) locations and coordinate with each other to avoid collisions.
A roadmap for the next generation of vehicle safety-enhancing technology is defined under the banner of Intelligent Transportation Systems (ITS), which aim to improve road travel by preventing accidents, managing traffic volume, and streamlining toll collection, etc. A key component of the ITS framework is a vehicular communication network that provides low-latency and highly-reliable communication amongst vehicles and between vehicles and the roadside infrastructure. The ITS architecture as defined by the U.S. Department of Transportation is illustrated in Figure 1.1. It is evident that the many envisioned applications and services depend on the viability of the underlying communication platform. Therefore, ITS and safety-enhancing applications in particular have motivated the field of vehicular ad hoc networks (VANET) as a key enabling technology.

![Figure 1.1: U.S. Department of Transportation ITS architecture](image)

In 1999, to facilitate ITS communication, the U.S. Federal Communication Commission’s (FCC) allocated a 75MHz band at 5.9GHz for Dedicated Short Range Communication.
Chapter 1. Introduction

In 2003, ASTM and IEEE adopted the DSRC standard for wireless inter-vehicle communication [6]. DSRC divides the 75MHz band into seven 10MHz channels, of which one is the control channel (ch. 178) and the remaining six are service channels. Two types of communication are supported by DSRC: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.

Table 1.1: V2V/V2I applications [1]

<table>
<thead>
<tr>
<th>V2V applications</th>
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<td>Blind Merge Warning</td>
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<tr>
<td>Blind Spot Warning</td>
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<td>Cooperative Adaptive Cruise Control</td>
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<td>Cooperative Collision Warning</td>
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<td>Pre-Crash Sensing</td>
<td>Low Parking Structure Warning</td>
</tr>
<tr>
<td>Vehicle-Based Road Condition Warning</td>
<td>Pedestrian Crossing Information at Intersection</td>
</tr>
<tr>
<td>Vehicle-to-Vehicle Road Feature Notification</td>
<td>Road Condition Warning</td>
</tr>
<tr>
<td>Visibility Enhancer</td>
<td>Safety Recall Notice</td>
</tr>
<tr>
<td>Wrong Way Driver Warning</td>
<td>SOS Services</td>
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<td></td>
<td>Stop Sign Movement Assistance</td>
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<td></td>
<td>Stop Sign Violation Warning</td>
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<td>Traffic Signal Violation Warning</td>
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<td>Work Zone Warning</td>
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Reference [1] categorizes ITS applications under each of these two types of communi-
cation, which are shown in Table [I.1]. While V2V applications are mostly safety-related, V2I applications include both safety applications and commercial applications such as electronic toll collection and in-vehicle advertising. These V2I applications require a wireless connection between vehicles and stationary Road Side Units (RSU) deployed along the length of the road.

A significant obstacle to the deployment of ITS systems on today’s highways is the deployment and maintenance cost of the number of RSUs required to provide coverage over the length of the road. If the effective coverage range of an individual RSU could be extended through multi-hop V2V relaying as illustrated in Fig. [I.2] then the number of RSUs needed to cover a given stretch of highway could be reduced. This in turn would mean substantial savings for the governmental agency or service provider responsible for deploying and maintaining the roadside infrastructure for the vehicular network. This motivates the development of a robust forwarding protocol for multi-hop vehicular communication.

The goal of this thesis is to design a forwarding protocol for multi-hop communication between vehicles and the RSU. This scheme is expected to coexist with periodic broadcasts of high-priority safety messages.

![Figure 1.2: Use of multi-hop to extend the coverage of an RSU.](image-url)
Chapter 1. Introduction

1.2 Contributions

The main contribution of this work is the design of a novel cooperative forwarding protocol for multi-hop vehicular communication which extends the POC-based MAC. The proposed protocol makes use of spatial diversity by employing multiple relaying nodes at each forwarding hop. The multiple relays cooperate in a novel way by adhering their transmission times to that of a POC codeword. This enables the multi-hop traffic to be integrated into the POC-based MAC, allowing it to mitigate the effect of hidden terminals without the exchange of control packets. Furthermore, multi-hop traffic which adheres to the POC-based transmission patterns will also reduce their interference with periodic safety messages which are broadcast in the background.

The traditional way of designing networks focuses on the design of each of its abstraction layers in isolation from the others. In existing designs for vehicular routing, the nature of the background traffic is seldom considered in the design as it is usually regarded as a problem for the MAC layer. In multi-hop broadcasting, the focus is on mitigating the broadcast storm problem and achieving a high rate of message delivery while minimizing collisions or contention with packets generated by the same broadcast flow.

The protocol proposed in this thesis takes a cross-layered approach in adapting the POC-based MAC and extending it for multi-hop communications. The benefits of structured channel access times achieved by POC-based MAC are preserved and with minimal disruption to the broadcast of periodic safety messages using the same POC-based protocol. This design is validated through simulations performed using the NS2 packet simulator.
Chapter 2

Background

Since the proposed cooperative forwarding scheme takes a cross-layer approach in extending a vehicular broadcast MAC for multi-hop communication, a review of single-hop vehicular MACs for VANETs is needed. In this chapter, we will begin by reviewing how various vehicular MAC schemes address the issue of reliability in the vehicular environment, the challenges of which motivates repetition-based and finally POC-based MACs for broadcasting routine safety messages. Next, a discussion of routing and forwarding schemes for VANETs will be given.

2.1 Vehicular Broadcast MAC for Safety Messages

Many fundamental safety-related applications of VANETs, such as collision avoidance, require the on-board computer to maintain an accurate and up-to-date map of its local neighbourhood. To support such applications, broadcast communication should be highly reliable. In particular, broadcast safety messages should be delivered to the vehicles in the local neighbourhood within a maximum delay constraint with a high probability of success. Thus, the vehicular broadcast MAC mechanism should be able to ensure a guaranteed quality of service (QoS) for these periodic safety messages.

Since the message size is comparable to that of the control packets, the overhead
required for multiple handshakes for broadcast is prohibitive.

The current MAC layer of DSRC is based on the IEEE 802.11 Distributed Coordination Function (DCF). Broadcast communication with 802.11 DCF suffers from collisions due to the hidden terminal problem, which is exacerbated by the harsh nature of realistic radio propagation models [7]. Simulations of 802.11a in vehicular scenarios showed that although it was possible to meet the 100 ms latency requirement for vehicular collision warning applications with single-hop broadcast safety packets, a reliable QoS could not be guaranteed [8]. References [9] and [10] provide analytical studies of the DSRC MAC and show its deficiencies in providing reliable broadcast, and cite packet collisions from hidden terminals and packet loss due to the harsh fading channel as limiting factors. These two problems are handled in the unicast case with RTS/CTS/ACK handshaking control packets in 802.11’s unicast protocol, respectively, but are absent for the broadcast mode.

Naturally, CSMA-based MAC protocols developed for reliable broadcast have proposed various ways of adapting the RTS/CTS/ACK handshaking mechanism for broadcast transmissions, either by performing it with all receivers [11, 12, 13] or by selecting a single (farthest) neighbour with whom to perform the handshaking [14, 15]. However, the routine safety messages are short and are often comparable with those of the control packets themselves. Furthermore, each control packet consumes more network resources and adds a contention period and a probability of collision. For the latter schemes, the successful reception of a packet by the farthest neighbour does not guarantee the successful reception by all other neighbours.

2.1.1 Repetition-based Vehicular Broadcast MAC

Recently a family of repetition-based MAC protocols have been proposed for the one-hop broadcasting of safety messages in VANETs [16]. Built upon a time-slotted system, a transmission frame is set to a duration no more than the useful lifetime of a safety packet.
The transmission frame is then divided into \( L \) time slots, each of which corresponds to the transmission time of a single safety packet. In each time slot, a node is either broadcasting its packet or listening for transmission from other nodes. This is illustrated in Figure 2.1.

![Figure 2.1: A transmission frame composed of 9 time slots. Darkened timeslots represent transmission time slots.](image)

The safety packet is transmitted repeatedly during a time frame; the transmission time slots are selected in each frame using various random methods. For instance, in Synchronous Fixed Retransmission (SFR) each node randomly selects a fixed number \( w \) of the \( L \) time slots in a frame for transmitting, while in Synchronous p-Persistent Repetition (SPR) a node transmits its packet in each time slot with probability \( p \).

By repeating the transmission of a safety message multiple times during a time frame, the diversity in time helps mitigate the harsh vehicular channel. Each protocol relies on probabilistic means for distributing the transmission opportunities of users across the time frame, thereby reducing the chance of collisions with neighbours and hidden terminals without using extra control packets, which is well-suited for short, periodically-generated routine safety messages.
2.1.2 POC-based Vehicular Broadcast MAC

Farnoud et al. extend the repetition-based MAC by using structured transmission patterns based on Positive Orthogonal Codes (POCs)\[17, 18\]. POCs are families of constant-weight binary codes with constraints on the auto-correlation and/or the cross-correlation between codewords. There are two types of POCs: synchronous and asynchronous.

A *Synchronous POC* is a binary code wherein the cross-correlation between any pair of codewords is at most $\lambda$. That is, where $x$ and $y$ are two different codewords in a POC of length $L$ and weight $w$,

$$\sum_{i=1}^{L} x_i y_i \leq \lambda$$

(2.1)

In a synchronous POC MAC (POC-MAC), each user is assigned a synchronous POC codeword that dictates its transmission pattern in each time frame; a 1 represents a transmission time slot and a 0 indicates an idle time slot, as shown in Figure 2.2. As was the case with SFR, each user transmits $w$ times within a time frame of $L$ time slots. Thus, the POC codeword is of length $L$ and Hamming weight $w$. Since all nodes are assumed to be both frame-synchronous and time slot-synchronous, (2.1) ensures that at most $\lambda$ repetitions of any two interfering users can collide within a frame. The synchronization of the vehicular nodes may be achieved, for example, by assuming all vehicles are equipped with Global Position System (GPS) devices.

![Circular and linear representation of a synchronous POC codeword](image)

Figure 2.2: Circular and linear representation of a synchronous POC codeword where $L = 10$ and $w = 3$

*Asynchronous POCs*, also known as Optical Orthogonal Codes (OOC)\[19\], are defined by the following two properties: the *cross-correlation property* restricts the cross-
correlation between any pair of codewords to at most $\lambda_c$; the autocorrelation property limits the autocorrelation of each codeword to at most $\lambda_a$. In other words,

$$\max_j \sum_{i=1}^{L} x_i y_{i \oplus j} \leq \lambda_c \quad (2.2)$$

$$\max_j \sum_{i=1}^{L} x_i x_{i \oplus j} \leq \lambda_a \quad (2.3)$$

where $\oplus$ represents addition modulo $L$.

Although the more stringent conditions on Asynchronous POCs means they have lower cardinality for any given $w$, $L$, and $\lambda a = \lambda c = \lambda$, they free the repetition-based MAC from the frame synchronization requirement. This is because the orthogonality of a codeword and a circularly shifted version of itself is preserved due to the autocorrelation constraint.

Analytical studies and simulations of the synchronous version of the POC-MAC in [17, 18] have shown them to attain lower probabilities of reception failure than random repetition schemes such as SFR. These promising results for single-hop broadcast in the vehicular environment form the basis for the forwarding scheme presented in this thesis.

### 2.2 Multi-hop Communication in VANETs

Routing in mobile ad hoc networks (MANETs) is an extremely well-explored field of study. Over the years, researchers have produced a veritable taxonomy of routing protocols. However, the recent interest vehicular networks have sparked renewed vigour in the study of routing. The vehicular environment provides unique challenges and areas for exploitation for the routing scheme designer. On one hand, the vehicular nodes are highly mobile and wireless links may break frequently and unpredictably due to the harsh channel; on the other, the mobility of the cars are constrained to the geometry of the road and are thus predictable. Furthermore, VANETs do not suffer from the power constraints of many MANET realizations.
Routing protocols can be broadly divided into topology and position-based routing. Topology-based routing algorithms can be further categorized as reactive and proactive. Proactive routing maintains routing tables at each node to reflect the network topology, while reactive routing searches for routes on demand. The high mobility of the vehicular nodes create problems for both reactive and proactive protocols. The high overhead cost of maintaining the accuracy of the routing tables make proactive protocols difficult to apply to VANETs. Moreover, although reactive protocols such as AODV [20] only find routes on demand, high node mobility causes frequent route repairs as nodes move out of range. Hybrid protocols form clusters and perform proactive routing within each cluster while performing reactive routing for inter-cluster communication [21][22].

Due to the availability of onboard GPS devices and the restrictions on mobility imposed by roads, position-based routing protocols, which require no route maintenance, have been a favoured routing approach for VANETs. For dense vehicular networks with a linear topology, typically found on busy metropolitan highways during the rush hour, the position-based greedy forwarding of GPSR[23] is a popular approach for VANET routing because they scale well with large networks of fast-moving vehicles. These schemes take advantage of position information provided by Global Positioning System (GPS) devices; knowledge of the one-hop neighbourhood is maintained through periodic broadcasts of HELLO messages with a node’s position information. In addition, a location-service is assumed to obtain the position of the destination node, which is in turn placed in the packet header. In greedy mode, packets are transmitted via unicast at each hop to the neighbour which is closest to the destination.

GPSR and similar sender-based routing protocols have the sender at each hop select the next hop relay and forward the packet via unicast transmission. 802.11 RTS/CTS handshakes address the hidden terminal problem, although some studies suggest that this comes with a cost to throughput. Also, a hop-wise ACK and repeated transmissions ensure reliability at each hop. The performance of such protocols depend on the
accuracy of each node’s knowledge of the position of its neighbours. Outdated position information can result in sub-optimal choices which ignore newly arrived neighbours and fail to exclude recently departed ones. This imposes a trade-off between control packet overhead and routing accuracy.

Routing schemes have been developed to deal this problem in various ways. Some attempt to reduce the overhead requirement of the position information beacons and improve the accuracy of the local neighbourhood maps by including mobility information in the beacons. Some schemes use this mobility information in a heuristic way by including it in the routing metric in such a way to favour neighbours with similar directions and speeds. Others use the mobility information more directly to estimate the current position of the neighbours. It will then estimate whether each neighbour is still within radio range and select the one closest to the destination. Predictive variants of GPSR such as [24, 25, 26] are examples of these approaches.

Contention-based Forwarding (CBF)[27] and similar schemes in [28, 29, 30] eschews the broadcast of HELLO messages and knowledge of neighbours altogether. In CBF, instead of a single next-hop receiver, each data packet is broadcast with the positions of the last-hop sender and the destination embedded in its header. The nodes that successfully receive and decode the packet contend to relay the packet by setting a timer inversely proportional to the progress toward the destination from the previous hop’s sender. Nodes that overhear another node’s transmission of the packet before its timer has elapsed will suppress its own transmission and drop the packet. Only nodes that successfully received the packet contend to forward it, thereby eliminating the cases where a poor relay selection by a greedy algorithm would result in many retransmission attempts. Although packet duplication can result if the difference in the timers of the contending relays be insufficiently large to suppress the other relays, [27] notes that packet duplication is reduced due to the constrained geometry of highway scenarios. Since the decision of which node will perform the forwarding is made in a distributed manner
among the receivers instead of at the sender, we denote such protocols *receiver-based*.

Urban Multihop Broadcast (UMB) [15] is another example of a receiver-based protocol. Before transmitting a packet, the sender performs a request-to-broadcast/clear-to-broadcast (RTB/CTB) handshake. All neighbours who hear the RTB transmit black-bursts of length proportional to the distance from the sender so that only the farthest neighbour replies with a CTB packet.

Many multi-hop broadcast schemes have been developed for VANETs to cope with the broadcast storm problem. The latter is when flooding is used for multi-hop broadcast and packets are duplicated exponentially at each hop, heavily taxing network resources. Gossip-based routing [31] attempts to reduce this effect by probabilistically forwarding each newly received packet.

Reference [32] details several other forwarding schemes which aim to minimize packet duplication. Weighted p-Persistence broadcasting forwards a newly received packet with a probability proportional to the distance between the sender and the receiver. In Slotted 1-Persistence Broadcasting the distance covered by the last hop is used to calculate a number of time slots during which the node waits. If it overhears the same packet while waiting, it will cancel its own transmission. In this way, further nodes are given priority to become the forwarding nodes.
Chapter 3

POC-based Cooperative Forwarding

The previous chapter presented repetition-based MAC protocols for vehicular broadcast and in particular the POC-based scheme proposed by Farnoud et al [17, 18]. The repeated transmission of the same packet in the POC-MAC exploits diversity in time to avoid collisions as well as to mitigate the effects of fast-fading. However, repetitions within a time frame cannot account for the effects of slow-fading channels and nodes suffering from shadowing effects from obstacles.

One well-known method of dealing with these problems is by exploiting spatial diversity and the broadcast nature of wireless transmissions, that is, the independent channel conditions of antennas located at different points in space. We have seen a similar use of spatial diversity in opportunistic routing, CBF, and other “receiver-based” routing schemes. However, while these schemes take advantage of spatial diversity in the relay candidates, the transmission of the packet to the next hop is ultimately performed by a single relay determined through a distributed contention mechanism. In other schemes such as flooding and gossip-based relaying, the forwarding by multiple relays is done on a random access channel without coordination and often interfering with one another.

In this chapter, we propose a cooperative forwarding protocol for VANETs which extends the reliable POC-MAC protocol for multi-hop communication. The proposed
scheme is cooperative in the sense that forwarding is performed by multiple cooperating relays, thereby exploiting spatial diversity in both the sending and receiving nodes at each hop. An important difference to note is that whereas contention-based schemes like CBF gain from selection diversity by selecting a “most suitable” relay amongst successful receivers, in our proposed scheme, all successfully receiving nodes belonging to the set of relaying nodes contribute to the forwarding of the packet.

3.1 A Simple Multi-Relay Forwarding Scheme

To motivate many of the features of the proposed scheme described later in this chapter, let us first consider a naive design of a multi-relay multi-hop forwarding scheme. In designing the routing layer separately from the MAC layer, a naive approach would be to implement a position-based routing scheme such as GPSR or CBF on top of the POC-based MAC. For example, by taking CBF’s approach to opportunistic forwarding, we arrive at a multi-relay forwarding scheme in which a packet’s optimal forwarder is found through contention among the successful receivers of the transmission of the previous hop. We call this naive design Cooperative Receiver-based Forwarding (CRF).

Like CBF, CRF is a beacon-less scheme which does not require a one hop neighbourhood map to be maintained at each node. The scheme is built on top of the Synchronous POC-based MAC and assumes that all nodes begin their transmission frames at the same time. Each node in the network has a unique Synchronous POC, which dictates its $w$ transmission opportunities within each frame of $L$ time slots. In this scheme, those $w$ transmission opportunities are the only times a node may ever send any packets.

A node that has generated a new packet to send records the ID and position of the destination in the packet header, along with its own ID as the source and a sequence number. The sending node also attaches its position information as the ”previous hop relay” and initializes the hop count to zero. Next, the underlying POC-based MAC cre-
ates \( w \) repetitions of the packet and enqueues these for broadcast in a FIFO transmission queue. For each transmission opportunity dictated by the node’s POC, the packet at the head of the transmission queue is dequeued and broadcast, as shown in Fig. 3.1.

![FIFO Transmission Queue](image)

**Figure 3.1:** Transmission queue and Synchronous POC-MAC for \( w = 3 \) and \( L = 10 \).

Each node also maintains a list containing the packet ID of the packets it has received before. A node that successfully receives a packet will first search the list for its packet ID. If not found, the packet’s ID is added to the list. Next, the receiving node will determine its candidacy for becoming a relay using the position information of the destination and the previous hop sender located in the packet header and its own GPS location. Each relay will then place its ID and position information in the packet header, update the packet’s hop count, and add \( w \) copies of the received packet to its FIFO transmission queue.

However, if the packet’s ID was found in the list, meaning that it is a copy of a previously seen packet, the node will then search its transmission queue for a packet with the same ID in the header field. The search begins from the tail of the queue and the first such match is removed and dropped. The received packet is then dropped as well. This is to ensure that the number of successful retransmission of a packet at each hop is limited to \( w \).
This design is a direct adaptation of the principles of CBF’s operation to a repetition-based MAC like the POC-based one in this instance. While its operation is simple, there are significant flaws with such a design. First, if this scheme is applied for multi-hop traffic with a common POC-based MAC for one-hop safety message broadcasts, a simple FIFO scheduling would mean the expiration of those safety packets while waiting in the queue. Recall, that in the POC-based MAC, the number of time slots in a frame is set to correspond to the lifetime of a safety packet. Therefore, in order to guarantee the timely delivery of the safety packets, they must be scheduled immediately upon generation. This limitation may be accommodated by used a separate queue with higher priority to the MAC layer for safety messages.

However, in CRF, each node shares its $w$ transmission opportunities in each frame between its own traffic (and safety messages) and the relayed traffic. This obligation creates a scalability problem for CRF. We notice that in an infrastructure-based vehicular network, the multi-hop data traffic is not uniformly distributed in space and tends to become heavier near the RSU. This suggests that the last link is usually the bottleneck link.

We study the scalability of CRF by considering a network with vehicles uniformly distributed in the coverage area of an RSU, which can include multiple hops. We assume that the communication range of the RSU is 1 unit of space. Let $\mu$ be the number of vehicles in the communication range of the RSU. In practice $\mu$ is usually a function of velocity; in highways, lower velocities increases $\mu$. Let us also assume that the network has a table of $N$ nodes and each node creates a packet at each time slot with probability $P_a$. The total number of packets accumulated at the last link to be transmitted to the RSU is $NP_a$. In an ideal case where all POC codes at the last link are orthogonal, that is no collisions between transmission opportunities, and the channel is free of impediments such as fading, shadowing, or loss, the total number of available transmission opportunities is $\mu w$, which should be larger than the total number of packets, i.e. $NP_a < \mu w$. As
noticed, the total number of nodes in the network should be bounded.

In order to address this latter limitation, a cross-layer solution which also handles the scheduling the multi-hop relay traffic is needed. If we allow each node to transmit not only with its own POC pattern, but also in designated time slots for forwarding multi-hop traffic which have been assigned to it by the previous hop, each node will be able to transmit with a rate that is greater than that of its POC ($\frac{w}{T}$). Since transmission opportunities are thus allocated per data flow, nodes located at network bottlenecks will automatically obtain more access opportunities to the broadcast channel. Such an approach should be better suited for V2I communications and is the one taken by the proposed forwarding scheme.

### 3.2 The Proposed Cooperative Forwarding Protocol

While other multi-relay forwarding schemes exist in literature, the main novel ideas of the scheme proposed in the remainder of this chapter are a) to temporarily assign additional transmission opportunities to the transmission frame of relay nodes; and b) to coordinate the relaying nodes’ transmission times in a structured way, specifically, according to a POC codeword.

The latter feature allows a multi-relay multi-hop forwarding scheme to be integrated with the POC-based MAC, thereby benefiting from that scheme’s robustness to changes in network topology and the effect of hidden terminals. Furthermore, the proposed multi-hop scheme can perform well in an environment where each vehicle in the network is periodically broadcasting routine safety messages, which should also be received reliably by its one-hop neighbours.

The rest of this chapter continues by introducing the concept of a “virtual relay” to describe the coordination between the multiple relays at each hop in the proposed protocol. Next, the details of the distributed code-allocation method by which POC
codewords are assigned to vehicular nodes and virtual relays will be described. The metric and routing algorithm for the selection of the next hop relays will be discussed. Finally, the chapter will conclude with a summary of the protocol’s operation.

### 3.3 Virtual Relays

The advantage of structured transmission patterns for repetition-based MAC schemes has been shown for POC-based patterns in [33, 18, 34]. As a MAC scheme for vehicular broadcast, a POC codeword-based transmission pattern dictates the channel access opportunities of a single broadcasting node in the cluster. In a time-frame of $L$ time-slots, a node will transmit its packet $w$ times, in the time-slots specified by its POC codeword. Let $T = \{t_1, \ldots, t_w\}$ denote these $w$ transmission opportunities, which are also the indices of the 1 bits in the node’s POC codeword.

The proposed forwarding scheme aims to exploit spatial diversity and the broadcast nature of the wireless channel by using multiple relaying nodes at each hop. In order to retain the performance benefits of the POC-MAC in the multi-hop flows, the channel access times of the multiple relays at each hop should also adhere to a POC codeword.

For example, consider a set of $n$ relaying nodes denoted by $V = \{v_1, \ldots, v_n\}$ where $n \leq w$, and each of the transmission opportunities in $T$ is assigned to a relaying node in $V$. Let $v(t_i)$ represent the vehicle to which the $i$-th time slot has been assigned. One assignment is the simple modulo or round-robin scheme as in (3.1). An example is presented in Figure 3.2 for $n = 3$ and $w = 6$.

$$v(t_i) = v_k, \quad k = i \mod n \quad (3.1)$$

A virtual relay refers to such a set of cooperating relays in a multi-hop flow which share the transmission opportunities corresponding to a single POC codeword for relaying the packet to the next hop toward the destination. In terms of medium access control,
Figure 3.2: Round-robin time slot assignment for a 3-node virtual relay where $w = 6$

a virtual relay would appear to the other nodes in the network as if instead an extra 
“real” relay using the same POC codeword were added to the network. Thus, the spatial 
diversity of multiple relays can be exploited while preserving the orthogonal nature of 
their transmission pattern to retain the performance of the POC-based broadcast MAC.

Let us assume that the POC codewords used in the network have Hamming weight $w$. We can decompose a POC codeword of length $L$ and weight $w$ into $w$ codewords, each having a weight of 1, that is

$$x = \bigoplus_{i=1}^{w} x^i$$  \hspace{1cm} (3.2)

where $\bigoplus$ is the bitwise OR operator and $x^i$ is a vector of size $L$ with all elements set to zero except for one of the elements, which is set to 1. The non-zero element of $x^i$ is located at the position of the $i$-th non-zero element of $x$. For example, if $x = 1001011001$, 

POC= \{010010001001001001\}
then $\mathbf{x}^3 = 0000010000$. If we replace $\mathbf{x}$ with its decomposition in (3.2) we have

$$
\sum_{i=1}^{L} x_i y_i = \langle \mathbf{x}, \mathbf{y} \rangle
$$

$$
= \langle \bigcup_{i=1}^{w} \mathbf{x}^i, \mathbf{y} \rangle
$$

$$
= \sum_{i=1}^{w} \langle \mathbf{x}^i, \mathbf{y} \rangle
$$

$$
= \sum_{i=1}^{w} y_{t(i)}
$$

(3.3)

where $\langle \mathbf{x}, \mathbf{y} \rangle$ is the scalar product and $t(i)$ is the location index of the bit corresponding to the $i$-th 1 in $\mathbf{x}$. The equality (3.3) shows that the collective effect of $\bigcup_{i=1}^{w} \mathbf{x}^i$ is the same as that of the original generating POC codeword $\mathbf{x}$. A similar decomposition of $\mathbf{y}$ gives

$$
\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{i=1}^{w} \sum_{j=1}^{w} \langle \mathbf{x}^i, \mathbf{y}^j \rangle
$$

(3.4)

A virtual relay can now be realized by assigning each of the $w$ decomposed $\mathbf{x}^i$ to a different next hop forwarding node. Each member of the virtual relay will perform the forwarding transmission in the timeslot corresponding to the 1 bit in its unique $\mathbf{x}^i$. The transmissions of all virtual relay members collectively adheres to the transmission pattern specified by the original generating POC codeword $\mathbf{x}$.

To illustrate, consider the simple network shown in Figure 3.3, with a two-hop flow from the source node $S$ to the destination node $D$. Three nodes are available to forward the packet to the destination. Suppose that the POC-MAC allots three transmission opportunities ($w = 3$) per time frame of $L = 10$ time slots, and that the POC codeword assignments are as presented in Table 3.3.

A single-relay forwarding scheme would select one of the three relay candidates, as illustrated in Figure 3.3(a). The source node would then transmit the packet to the selected relay three times according to its POC codeword. If the chosen relay node successfully receives the packet, it will in turn transmit the packet three times according
to its POC-codeword to the next hop, or in this case, to the destination. However, the packet may be lost if the channel between the sending node and the next hop relays undergoes a period of slow fading which spans all three of the transmissions of the sender. Such prolonged periods of channel outage may be caused in the vehicular environment by shadowing effects of a large truck or an overhead sign.

<table>
<thead>
<tr>
<th>Node</th>
<th>POC Index</th>
<th>POC</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1</td>
<td>1000010010</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1010100000</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0101010000</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0000010101</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>1100000100</td>
</tr>
<tr>
<td>VR</td>
<td>6</td>
<td>0001001010</td>
</tr>
</tbody>
</table>

Table 3.1: POC codeword assignment

On the other hand, Figure 3.3(b) shows the forwarding being performed by all three
nodes between the source and the destination. These three nodes form a virtual relay and collectively forward the packet toward the destination. The member nodes of the virtual relay cooperate by sharing a common POC codeword which allows them to coordinate their transmission times. Each of the three transmission opportunities of that codeword is assigned to a different member of the virtual relay, and thus the scheme benefits from transmitter diversity. The multi-relay set is called a virtual relay because the total number of channel accesses as well as the times during which they are performed are identical to those of a relay in the single-relay case. Thus, in the ideal operation of the protocol, the cooperative diversity gains are unhindered by additional traffic load on the channel.

The transmission times of the virtual relay members are shown in Figure 3.4. The transmission time slots in red belong to each node’s own traffic and those in blue belong to the packet to be relayed. The bottom row represents the packets present on the wireless channel. Red packets are labelled with the ID of their sources, while the blue relayed packet is labelled ‘V’. Collisions occur in time slot where more than one node is transmitting and are coloured grey. Note the scheduling conflict in the fourth timeslot at Node 2. Node 2’s own packet and the packet to be relayed are both scheduled for the same time slot. In such cases, one of the packets is randomly selected to be transmitted and the others are dropped.

From this example, we see that the virtual relay scheme encompasses the routing and the scheduling of relayed packets. Virtual relays are essentially adding transmission opportunities to the selected nodes responsible for forwarding the multi-hop traffic. In terms of the MAC, channel resources are allocated per data flow rather than per user. This allows the members of the virtual relay to contribute to the propagation of multi-hop traffic, while at the same time not having to sacrifice the transmission opportunities for its own routine safety messages.
Chapter 3. POC-based Cooperative Forwarding

In a vehicular network using the POC-based MAC protocol, the performance of the MAC scheme in terms of avoiding packet collisions relies upon each vehicle in the cluster having a unique POC codeword [33, 18, 34]. The authors’ works on this single-hop broadcast MAC examined this scheme for a cluster of vehicles within one-hop communication of one another. However when considering a multi-hop network, a collision in the code space may occur between a vehicle and a hidden terminal both using the same POC codeword. This would mean a collision of all transmissions of both vehicles at all potential receivers located in between, and is a highly undesirable scenario. Hence, a code assignment scheme is needed which ensures that no two users within twice the nominal communication range \((2R)\) of each other have the same POC codeword.

Furthermore, each virtual relay also requires a POC codeword for transmission, al-
though only for a single transmission frame. The code allocation scheme must also pro-
vide a way to assign codewords to virtual relays while minimizing the probability that a
code is used by more than one virtual relay. Moreover, the distributed code allocation
scheme must account for the fact that virtual being logical entities consisting of many
real relaying nodes. Namely, all members of a virtual relay should be able to determine
a unique code assignment for its transmissions.

This section begins by reviewing the distributed POC code allocation scheme proposed
in [34] and follows by proposing some modifications to adapt that scheme for multi-hop
forwarding. Finally, the code allocation mechanism for virtual relays will be described in
detail.

3.4.1 Code Allocation Scheme for POC-MAC

A distributed code assignment scheme was proposed in [34] and will be summarized
briefly. The POC codebook is divided into a set of “permanent codewords” and a smaller
set of “temporary or tentative codewords” used strictly for network association. When
a vehicle joins the network, it randomly adopts a codewords from the pool of tentative
codewords and broadcasts a Code Information Request (CIQ) message. Neighbours who
received the CIQ message reply with a Code Information Response (CIR) message which
includes the node’s ID, the index of its POC codeword, and a list of their one-hop
neighbours and the indices of their POC codewords. In order to distribute the load on
the network created by CIR messages, the CIR messages are distributed over multiple
transmission frames known as the Code Information Response Window (CIRW). Each
responding vehicle will set an integer counter to a random number which is uniformly
distributed between zero and the CIRW value. The counter decrements by one after each
transmission frame and upon reaching zero triggers transmission of the CIR message.

CIR messages are also transmitted by each vehicle with a period of a few seconds so
that each vehicle’s knowledge of the two-hop neighbour is updated for topology changes.
When a vehicle discovers another vehicle within its two-hop neighbourhood is using the same codeword, it will drop its codeword and select a new one from the set of permanent codewords unused by any other vehicles in its two-hop neighbourhood. Thus, this scheme maintains each POC codeword’s assignment to a unique user within at most a $2R$ radius using a 2-hop neighbourhood map of code assignment at each node. We define the code contention area as the area within which vehicles must check for codeword assignment conflicts; for this scheme the code contention area consists of the two-hop neighbourhood and therefore can be as large as $4R$.

Therefore, the cardinality of the codebook is required to be large enough to accommodate all vehicles within a $4R$ length of road. We can express the degree of spatial reuse of this scheme by the maximum code density $\lambda_c$, which is the maximum number of codewords per unit length of the road. Given that there are $N$ codewords in the codebook, the code density is

$$\lambda_c = \frac{N}{4R} \tag{3.5}$$

### 3.4.2 Modified Location-based Code Allocation Scheme

Let us consider a vehicular network in a chain topology on a one-dimensional stretch of highway. We begin by dividing the POC codebook $C$ into three equal subsets which we denote by $C_a$, $C_b$, and $C_c$. The highway is then divided into equal segments or zones of length $R$, and each zone is associated with one of the three codeword subsets of POC codewords as shown in Figure 3.5.

![Figure 3.5: Three Zones](image-url)
Chapter 3. POC-based Cooperative Forwarding

Assuming that CIR messages are broadcast by all vehicles in the network periodically as a part of their periodic safety messages, each vehicle has a map of the codewords occupied by its two-hop neighbours and thus all neighbours located in the same zone. A vehicle entering a zone will use this knowledge to select a free codeword from the associated codeword subset. Once the vehicle leaves the zone, it releases its codeword and repeats the process for the new zone it has entered.

One advantage of this zone approach is the increased spatial reuse, observed through its maximum code density. Since at most $\frac{N}{3}$ codewords can co-exist in a zone of length $R$, the maximum code density of the modified scheme denoted by $\lambda'_C$ is

$$\lambda'_C = \frac{N}{3R} = \frac{N}{3R}$$

Comparing (3.5) with (3.6), we see an improvement in the maximum code density by a factor of $\frac{1}{3}$.

A further advantage over the original scheme comes from the reduction of the code contention area to a single zone. Since each zone is of length $R$, they are always within the one-hop neighbourhood of each vehicle. Since each vehicle’s information about its one-hop neighbourhood is more up-to-date than that of the two-hop neighbourhood, the unique assignment of each codeword is more easily maintained. Finally, further improvement to the scheme can be made by using mobility information of the two-hop neighbours to anticipate when they cross over from one zone to the next. Since the mobility of vehicles is constrained by the geometry of the road, the times at which each neighbouring vehicle crosses into a new zone can be predicted to further enhance the code allocation scheme.

3.4.3 Code Allocation for Virtual Relays

Virtual relays are temporary sets of cooperating nodes formed for the relaying of a data packet toward its destination. In the proposed protocol, a virtual relay’s transmission
pattern is dictated by a POC codeword in order to adhere to the POC-based MAC. Therefore, each virtual relay requires a POC-codeword to be allocated to it for the single transmission frame of its existence. However, a virtual relay is actually composed of multiple distributed nodes. Thus, for the second hop and beyond, the assignment of the POC codeword is performed in a distributed manner at each virtual relay member. Special provisions in the code allocation scheme are required to ensure that this distributed allocation is consistent for all members of the virtual relay.

Firstly, the position used to determine the associated zone of a virtual relay is defined by its centroid. Recall, that although a virtual relay will always transmit $w$ times in a time frame, it may consist of between one and $w$ real relaying nodes. Therefore, a virtual relay member may transmit more than once in a time frame. Thus, for a one-dimensional network, the centroid is simply the average of the positions of the virtual relay members weighted by its proportion of the transmission opportunities in a time frame. For instance, consider a virtual relay consisting of $n$ members, each located at $x_i$, $i \in 1, 2, \ldots n$ and transmitting $t_i$ times in the transmission frame. We note that $n \leq w$ and $\sum_{i=1}^{n} t_i = w$. The position of the virtual node is defined as

$$x_{VR} = \frac{1}{w} \sum_{i=1}^{n} t_i x_i$$  \hfill (3.7)

Let us assume that each virtual relay member has selected an identical sequence of relays for the next hop’s virtual relay. Since each node knows the positions of their two-hop neighbours, each node can calculate the next-hop virtual relay’s centroid location and find the zone to which the next hop virtual relay belongs. As before, the set of unused codewords in the sub-codebook associated with the zone is known to all nodes within a two-hop neighbourhood of the zone. Each sub-codebook is well-known to all vehicles in the network and the codewords in each zone are ordered by its index. In order to ensure all members of the current virtual relay select the same codeword for the next hop’s virtual relay, a quantity common to all its members is used to hash to an unused code. This common quantity can be the centroid position of the next-hop virtual relay, or
more simply the index of the current virtual relay’s POC codeword in its sub-codebook.

For example, at the $i$-th hop, the virtual relay is composed of three nodes $\{n(i,1), n(i,2), n(i,3)\}$ whose centroid is located in an A-zone. This virtual relay was assigned by the previous hop relays $c_k^A$, the POC codeword with the $k$-th index in A-zones’ sub-codebook $C^A$. Each member of the $i$-th hop virtual relay then computes a routing metric, the details of which will be explained in the following section, which yields a common list of vehicles for the $i+1$-th hop virtual relay, which are referred to here as $\{n(i+1,1), n(i+1,2), n(i+1,3)\}$.

Suppose these latter nodes of the $(i+1)$-st hop virtual relay have a centroid position located in a B-zone, with which the sub-codebook $C^B$ is associated. Let there be a subset $U^B \subseteq C^B$ of unused codewords in that B-zone sub-codebook, with cardinality $|U^B| = m$. We index the unused codes in $U^B = \{u_1, u_2, \ldots, u_m\}$ by preserving the order of their indices in $C^B$. Using the index of its own POC codeword, $k$, the virtual relay members calculate the index $j$ of the selected POC codeword in the set $U^B$ by a simple modulo operation as shown in (3.8).

\[
j = k \pmod{m} \tag{3.8}
\]

Since the quantities used to calculate the code assignment is available to each of $\{n(i,1), n(i,2), n(i,3)\}$, they can arrive at a consistent code assignment for the next hop’s virtual relay.

3.5 Distributed Next-Hop Relay Selection

As was the case for POC codeword assignment, the routing or relay-selection algorithm must account for the distributed nature of virtual relays. It should ensure that each virtual relay member makes a selection of the next hop relays which is consistent with those made by other members of its virtual relay. Furthermore, the ordered sequence in which the selected relays are assigned to the $w$ time slots should also be consistent for
all virtual relay members. Therefore, the routing metric by which candidate relays for the next hop are evaluated must be available to all members of a virtual relay.

In order for this to be possible, along with the POC code assignment information, each vehicle should periodically broadcast its own position information as well as the position information that it has heard from its one-hop neighbours. These beacons allow each vehicle to construct a map of its two-hop neighbourhood. In VANETs, nodes are highly mobile and so the overhead incurred from the required beacons frequency for an accurate neighbourhood map is substantial. Luckily, the position and mobility information of vehicular nodes are precisely the intended contents of the routine safety messages as they are needed for applications such as collision avoidance and warning.

We define a candidate relay as a one-hop neighbour of a forwarding node which is closer to the destination. The two-hop connectivity information and knowledge locations of the neighbours themselves means that each virtual relay member can find the candidate relays of all fellow members of its virtual relay. By taking the intersection of the candidate relay sets of each virtual relay member, and excluding the members of the current virtual relay, the distributed virtual relay members arrive at a common set of candidate relays for the next hop. This is depicted in Figure 3.6.

A routing metric is then calculated for each node in this candidate relay set. This routing metric must also yield identical values when evaluated at each distributed member of the current virtual relay. The best $w$ candidate relays are selected to form the virtual relay for the next hop. The selected vehicles are then assigned to each time slot in descending order of their routing metric. If there are fewer than $w$ nodes in the candidate relay set, the round-robin scheme depicted earlier in Figure 3.2 is used for timeslot assignment.

Note that unlike in contention-based forwarding schemes such as the Slotted 1-persistent forwarding scheme and CBF, all of the selected next hop relays are meant to retransmit the packet and there is no need for suppressing the transmissions of closer
relays. Therefore, once a common set of next-hop virtual relay members have been selected, they may be assigned to the timeslots in an arbitrary order, so long as the assignment is consistent among the distributed members of the current virtual relay. For example, we may use the ID of the vehicular nodes to provide a total order.

3.5.1 Realistic Wireless Channel Fading and Routing

Traditional position-based routing algorithms aim to maximize the length of each hop and in doing so minimize the total number of hops from the source to the destination. Source-based position-based routing protocols such as GPSR select the neighbour that is closest to the destination node, and thus the most distant of feasible next-hop relay candidates. We can express this greedy routing scheme as relay selection by maximizing
an “advancement toward the destination” metric as defined in (3.9). The routing metric of a candidate relay \( r \) evaluated at the sending node \( s \) is the difference between their distance to the destination node.

\[
ADV(s, r) = \text{dist}(\text{dest}, s) - \text{dist}(\text{dest}, r)
\] (3.9)

However, maximizing the distance of each hop assumes a unit disk graph model for the wireless links, in which the quality of wireless links between communicating nodes do not depend on the distance between them, provided that they are within a certain communication range. Realistic wireless channels with multipath fading do not behave in such a manner; the probability of reception over a wireless link decreases gradually with increasing distance between the end-points. Indeed, under a more realistic probabilistic wireless channel model, a specific communication range can only be defined as the maximum distance that maintains an arbitrarily specified minimal link quality.

For realistic wireless channels, using the advancement distance (or progress toward the destination) as a routing metric will result in the selection of relays with poor wireless links. The lower probability of success for each transmission means that more retransmissions are required per hop, more network resources being used and potentially higher end-to-end delays.

Receiver-based position-based routing schemes such as CBR address this issue by broadcasting the data packet and allowing the successful receivers contend to relay the message. However, our proposed relay scheme requires coordination between multiple receiving nodes whose identities need to be determined beforehand. In other words, a source-based routing approach is needed.

### 3.5.2 Distance-based blacklisting

A simple approach to this problem is to exclude certain faraway one-hop neighbours from consideration for the next hop relay selection. In effect, this approach reduces the
nominal radio range to exclude distant neighbours, which are likely to have poor links. However, the propagation distance of each hop will also be reduced, potentially increasing delay.

To illustrate, consider a $m$-Nakagami fading channel model with parameter $m = 3$. For a nominal radio range of $R$, the probability of packet reception varies with distance $d$ with the expression in (3.10) as derived in [35].

$$P_s(d) = e^{-3\left(\frac{d}{R}\right)^2} \left(1 + 3 \left(\frac{d}{R}\right)^2 + \frac{9}{2} \left(\frac{d}{R}\right)^4\right)$$  \hspace{1cm} (3.10)

Figure 3.7 shows the packet reception probability over 1000 meters for a nominal range of 500 metres. This nominal radio range corresponds to a probability of packet reception of around 0.4. We can exclude neighbours with bad links by only considering nodes within 250 metres.

Figure 3.7: Nakagami fading channel for $m = 3$ and $R = 500m$. 

3.5.3 Normalized Advance

Another metric which has been proposed is the product of the packet reception ratio of the wireless link and the progress toward the destination [36, 37, 38]. We shall refer to this routing metric which is defined in (3.11) as the Normalized Advance as in [36].

\[
NADV(s, r) = ADV(s, r) \times P_s(s, r) \tag{3.11}
\]

(3.11) expresses the NADV metric of a candidate relay \( r \) evaluated at the sending node \( s \), which consists of the ADV metric normalized by the probability of successful packet reception \( P_s \) over the wireless link from node \( s \) to node \( r \). Notably, the authors of [38] interpreted this same metric as an expected progress toward the destination.

Figure 3.8 plots the routing metric as it varies with progress toward the destination with the channel model from (3.10). The metric reaches a maximum value at a distance of around 350 metres from sender. The metric discounts the suitability of more distance candidate relays due to their lower probability of packet reception.

Since there are multiple relays performing the forwarding beyond the first hop, the metric value of a particular candidate relay for the next can be evaluated to a different value at each of the multiple senders of the current hop. Therefore, the routing metric should be a cumulative (or averaged) one over all the sending nodes of the current hop. Let the set \( VR \) represent the multiple sending nodes of the current hop, then the cumulative NADV routing metric of the candidate relay \( r \) will be as expressed in (3.12).

\[
NADV'(VR, r) = \sum_{s \in VR} ADV(s, r) \times P_s(s, r) \tag{3.12}
\]

3.6 Protocol Summary

The key features of the proposed cooperative forwarding algorithm have been described in this chapter. In this section, a brief summary of the operation of the protocol is
Figure 3.8: Normalized Advance routing metric.

presented. The required header fields are tabulated in Table 3.2. The packet handling algorithm of the cooperative forwarding protocol is summarized.
Table 3.2: The Cooperative Forwarding Packet Header

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ID_{src}$</td>
<td>ID of the packet’s originating node</td>
</tr>
<tr>
<td>$pid$</td>
<td>Packet ID</td>
</tr>
<tr>
<td>$ID_{dst}$</td>
<td>ID of the packet’s destination</td>
</tr>
<tr>
<td>$(x, y)_{dst}$</td>
<td>Position vector of destination</td>
</tr>
<tr>
<td>$ID_{VR}$</td>
<td>Array of $w$ IDs of virtual relay members</td>
</tr>
<tr>
<td>$indexPOC$</td>
<td>Index of virtual relay’s assigned POC codeword</td>
</tr>
</tbody>
</table>
Procedure 1 Cooperative Forwarding Packet Handling Algorithm

Upon reception of a packet, $p$:

if $currentNode$ is $ID_{dst}(p)$ then
    pass to upper layer
else if $currentNode$ is in $ID_{VR}(p)$ then
    Lookup POC codeword for $indexPOC(p)$
    Save transmission slot positions assigned to $currentNode$ from $ID_{VR}(p)$
    Find common candidate relay set (CCRS) of the virtual relay
    Evaluate routing metric for each node in CCRS
    Select best $w$ nodes from CCRS, write to $ID_{VR}(p)$
    Calculate centroid of selected nodes, find associated zone
    Get ordered list of the $m$ free POC codewords for that zone
    Use modulo scheme ($indexPOC(p) \mod m$) to select POC codeword, write to $indexPOC(p)$
    Duplicate (if necessary) and schedule for transmission in saved timeslot positions.
else
    drop $p$
end if
Chapter 4

Analytical Study

As we have seen from the previous chapter, the principal feature of our cooperative forwarding scheme is the use of coordinated multiple relays at each hop called virtual relays. In this chapter, through some simple analyses, we will demonstrate the advantages of using multiple relays for multi-hop forwarding.

4.1 Diversity Gains through Multiple Relays

Let us assume that the vehicular channel can be in the bad state with probability $P_f$ for the whole time frame and in the good state with probability $1 - P_f$. In the bad state, the channel drops all packets, while in the good state the channel operates with its nominal capacity and all packets are properly delivered to the receiver. This is a simple model which has been frequently used in the literature. We shall apply this model to analyse the probability of successful delivery of three different forwarding schemes, depicted in Figure 4.1 for a simple three-hop topology.

Using single relay routing, the probability of success is given by $P_{S,SR} = (1 - P_f)^M$ where $M$ is the number of hops between source and destination. As shown in Figure 4.1(a), at each hop, the packet is transmitted by a single relay $w$ times in a single frame. The analysis of the probability of success for packet delivery in virtual relay scheme is
more involved and is directly related to the forwarding algorithm used in virtual relaying.

Now assume that each virtual relay along the route has \( w \) distinct nodes, and that each node in a virtual relay transmits its packet once to a single peer node in the subsequent virtual relay. A total of \( w \) multiple parallel paths are formed between source and destination, as shown in Figure 4.1(b). The failure of this system is identical to all paths being simultaneously broken which has occurs with a probability of \( (1 - (1 - P_f)^M)^w \). This results in a probability of successful delivery at the destination of \( P_{S,VR} = 1 - (1 - (1 - P_f)^M)^w \approx w(1 - P_f)^M \).

A similar argument can be used to find the error rate where routes with a “butterfly” configuration are allowed. Assume that all \( w \) nodes in each virtual relay can communicate
with all $w$ nodes in the subsequent one, as shown in Figure 4.1(c). Each node in a virtual relay broadcasts the packet once to all $w$ nodes in the next hop’s virtual relay. We can represent this case using a Markov chain with the following $(w+1)$-state transition matrix $V$, whose elements are defined as

$$V_{i,j} = \binom{w}{j'} P_f^{i'} (w-j') (1 - P_f^{j'})^{j'} \quad i' = i - 1, j' = j - 1$$

(4.1)

where the number of participating nodes in a virtual relay, $i'$, determines the probabilities that the subsequent virtual relay would have $j'$ participating nodes. The transition probabilities follow a binomial distribution $B(w, 1 - P_f^{j'})$. An example Markov chain for $w = 3$ is shown in Fig. 4.2, where the number of active relays is labelled on each state and the transition probabilities are marked with the corresponding elements of the transition matrix.

For $M$ hops, there are $M - 1$ virtual relays and thus the $M - 1$ step transition matrix $V^{(M-1)}$ is used. An initial vector $s = (0, \ldots, 0, 1)$ represents the $w$ transmissions
made by the single originating sender and a vector \( t = (0, 1 - P_f, 1 - P_f^2, \ldots, 1 - P_f^w) \) is applied for the last hop to the single destination node. Thus, the probability of success is \( P_{S,VR} = sV^{(M-1)}t \).

Fig. 4.3 shows the different success probabilities for different values of \( P_f \) in a 4-hop network where each virtual relay has 4 nodes. From this simple example, the benefits of exploiting spatial diversity is apparent.

### 4.2 Multiple Relays for Nakagami Fading Channel

Another simple scenario is presented in this section in which the channel quality decreases with distance. The m-Nakagami channel model in (3.10) is used. Assume that the NADV routing metric described in the previous chapter is used for the selection of next hop relays. Now consider the following scenario for a linear network topology: a single source
node is located at the origin \((x = 0)\), with three candidate relays \(n_1, n_2\) and \(n_3\) located at x-positions of 250 metres, 350 metres and 450 metres, respectively.

For this simple example, let us assume that the number of repetitions in a frame is 2. Traditional single relay forwarding would select \(n_2\) to forward the packet as it has the highest \(NADV\) routing metric. The source transmits the packet twice and if \(n_2\) successfully receives the packet, it will transmit the packet twice in the next time frame. However, the cooperative forwarding scheme instead selects two nodes as relays giving each a single relaying transmission opportunity.

Considering slow-moving urban traffic, let us assume a relative velocity of 20 km/h. For 5.9 GHz DSRC, this corresponds to a maximum Doppler shift of \(f_m = 109.27 \text{Hz}\) and a coherence time of \(T_c = 3872 \mu s\). If we employ a POC-based MAC scheme with a frame size \(L=100\) time slots, data rate of 12 Mbps, and a packet size of 100B, then the frame duration \(T_f\) is approximately \(100 \times 800b \div 12\text{Mbps} = 6666\mu s\), which is roughly twice the coherence time.

To show the effect of channel coherence, we treat a frame of 100 time slots as 2 coherent blocks of timeslots. The channel will be either ON (meaning a packet can be successfully transmitted) in all the timeslots of a block or OFF (no communication) in all timeslots of the frame, and varies as a Bernoulli trial with probability of success of \(P_s(d)\) as shown above. For simplicity, we will assume that the ON/OFF blocks of time slot are synchronized with the frame so that there are always exactly two such blocks in each frame.

The probability of transmission failure for all \(w\) repetitions in a time frame of \(L\) time slots between nodes located \(d\) metres apart is

\[
P_{f-frame}(d, w, L) = (1 - P_s(d))^2 + 2P_s(d)(1 - P_s(d)) \left( \prod_{i=0}^{w-1} \left( \frac{0.5L - i}{L} \right) \right)
\]

Now we can express the two-hop probability of packet reception for the single relay case. For a destination node located at x-position \(x_d\) and a single relay located at \(x_r\), the
probability of packet reception is

\[ P_{\text{succ-single}} = (1 - P_{f-frame}(x_r, w, L)) (1 - P_{f-frame}(x_d - x_r, w, L)) \]

In the case of cooperative forwarding, we have independent channel realizations at each of the selected relays. The probability that an individual relay \( r \) located at \( x_r \) fails is

\[ P_{\text{relay-fail}}(r) = 1 - (1 - P_{f-frame}(x_r, w, L)) (1 - P_{f-frame}(x_d - x_r, 1, L)) \]

Therefore, the two-hop probability of packet reception for a multi-relay cooperative scheme that distribute the \( w \) transmission opportunities among the selected relay set \( R \) is

\[ P_{\text{succ-coop}} = 1 - \prod_{r \in R} P_{\text{relay-fail}}(r) \]

Numerical results for these probabilities are shown for the simple network scenario in Figure 4.4. The diversity gain of multiple relays provides clear advantages in handling fading channels that are highly correlated in time.
Figure 4.4: Two-hop reception probabilities for Single and Cooperative Forwarding
Chapter 5

Performance Evaluation

The previous chapter’s analytical study provided the motivation for the use of multiple relays which cooperate as a virtual relay. However, many simplifying assumptions were made. In particular, the analysis used packet loss probabilities which only considered the fading of the Nakagami channel and the effect of collisions at the MAC layer were not considered.

Since the main design feature of the proposed scheme is its robustness to periodic background traffic, which motivated the incorporation of the POC-MAC into its design, an evaluation of its performance must account for the effects of collisions at the MAC layer as well as the fading effects of wireless channel in the vehicular environment. We attempt to validate the design of our protocol through the simulations presented in this chapter, which compare the effectiveness of the proposed protocol against several other multi-hop vehicular forwarding schemes.

5.1 Simulation Setup

A stretch of highway is approximated in the simulation as a one-dimensional network topology. The vehicles are positioned at regular intervals with an inter-vehicle spacing of 10 metres. A roadside unit (RSU) is placed in the middle of the network. This network
topology is shown in Figure 5.1. For simplicity, the mobility of vehicular nodes is not represented in this simulation, nevertheless the simulations should illustrate the effects of collisions and MAC layer interactions of our cooperative forwarding scheme.

Figure 5.1: The simulation network topology

The NS-2 network simulator[39] was chosen as the simulation platform, for its versatility and its wide-use amongst researchers for packet-level wireless simulations. There are a large number of open-source modules for each level of the network stack, and their ready availability played a large role in the decision to choose the NS-2 simulator for this work.

The data rate was set to 6Mbps and both the periodic safety messages and the multi-hop messages are 300 bytes long. The length of each time slot should accommodate the transmission time of each 300B packet, and thus should be 400 $\mu s$ long. In our simulations, some guard time was added and the timeslot was set to 410 $\mu s$ to account for propagation delays. A transmission frame with $L = 80$, for instance, would then be $32.8ms$ in duration.

Our simulations use the VanetProp radio wave propagation module documented in [40]. VanetProp provides a realistic vehicle-to-vehicle wireless channel model which modulates the received signal power with a temporally-correlated Nakagami fading envelope.
Large-scale path loss is determined by a dual-slope piecewise linear model with empirically determined parameters from experiments detailed in [41] and [42].

The physical layer parameters were set so that a Two-Ray Ground propagation model would result in a communication range of 200 metres for our packets. However, the Nakagami fading channel reduces the probability of reception within this range gradually as the distance of the wireless link increases. The relationship between the packet reception probabilities and the length of the wireless link for different channel models is presented in Figure 5.2. Please note that the figure only considers packet losses due to the fading of the wireless channel in the absence of interfering transmissions.

Figure 5.2: The effect of the channel model on packet reception probabilities.

Our simulations use the *Highway* channel setting which, as can be seen in Figure 5.2, has significant packet reception probabilities beyond the nominal communication range of
the Two-Ray Ground model. In fact, there is a non-zero packet reception probability as far away from the sender as 300 metres. In the implementation of the proposed algorithm, distance-based blacklisting was used and only nodes within 150 metres were considered for relaying. It is assumed that the position information of each node is available to itself without any error or latency that would come from real-world GPS devices.

Except for the RSU, all other nodes broadcast a routing safety message with probability $\beta$ in each transmission frame using the Synchronous POC-MAC. It is assumed that all vehicles are time slot-synchronized and frame-synchronized. In each transmission frame, they also generate a packet to send to the RSU using the proposed cooperative forwarding protocol with probability $\alpha$. The RSU does not transmit any packets, only logging the packets it has successfully received. In order to account for border effects, the statistics of 5 nodes at either extreme of the network are excluded.

The parameters of the simulator are summarized in Table 5.1.

### 5.2 Protocols Used For Comparison

The proposed cooperative forwarding protocol is compared with four other multi-hop forwarding schemes presented in [32]. They are briefly summarized in this section.

A baseline for the performance of any forwarding scheme is simple flooding. In flooding, whenever a node receives a packet it has not handled before, it immediately re-transmits it. The number of copies of the original packet increases exponentially, resulting in the well-known broadcast storm and places heavy load on network resources. A position-based version called directional flooding was used for this performance study, in which a node only forwards a new received packet if the node is located closer to the destination than the last hop’s sender.

Gossip-based forwarding scheme can also be called p-persistent flooding, and was developed to mitigate the broadcast storm problem. A packet is forwarded with a certain
Table 5.1: Parameters of the simulation

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network simulator</td>
<td>ns-2</td>
</tr>
<tr>
<td>Simulation Area</td>
<td>1200m</td>
</tr>
<tr>
<td># Nodes</td>
<td>100</td>
</tr>
<tr>
<td>Inter-vehicle spacing</td>
<td>10m</td>
</tr>
<tr>
<td>Nominal transmission range</td>
<td>200m</td>
</tr>
<tr>
<td>Relay selection range</td>
<td>150m</td>
</tr>
<tr>
<td>Channel model</td>
<td>Nakagami (Highway)</td>
</tr>
<tr>
<td>Data rate</td>
<td>6Mbps</td>
</tr>
<tr>
<td>MAC</td>
<td>POC-MAC</td>
</tr>
<tr>
<td>Data packet size</td>
<td>300 bytes</td>
</tr>
<tr>
<td>Simulation repetitions</td>
<td>20</td>
</tr>
<tr>
<td>Simulation time</td>
<td>10 s</td>
</tr>
</tbody>
</table>

The version implemented in this work is also directional in restricting the forwarding nodes to those located closer to the destination than the last forwarder, the probability of forwarding was set to 0.5.

In weighted p-persistent forwarding, the probability of forwarding is calculated based on the distance from the last hop sender. If node $j$ received a packet from node $i$, and the two are $D_{ij}$ metres apart, then for a nominal transmission range denoted by $R$, the probability of forwarding is $p_{ij} = \frac{D_{ij}}{R}$.

In slotted 1-persistent forwarding, a node receiving a packet will wait a number of timeslots, determined by its distance from the last hop forwarder, before retransmitting the packet. If the node overhears another node transmitting that packet while it is waiting, it will cancel the retransmission. The farther a node from the last hop forwarder of the packet, the shorter its waiting time. The goal is so that ideally only furthest
receiving node retransmits it to the next hop. The number of timeslots to wait is

\[ S_{ij} = N_s - \left\lceil \frac{D_{ij} \times N_s}{R} \right\rceil \]  

(5.1)

where the maximum number of slots to wait \( N_s \) was set to 5.

For fairness, in each of the above schemes, the packet source will repeat the transmission of a packet \( w \) times within a time frame, just like the proposed protocol. A reception of a forwarded copy of any of the original \( w \) packet transmission is counted as a successful reception.

### 5.2.1 Simulation Results

In this section, the results of the simulations are presented and are organized by performance metric. The following results were obtained using a POC codebook with \( w = 7 \) and \( L = 80 \). The safety message generation probability \( \beta \) was set to 0.1 and two sets of results are shown here: low load of multi-hop traffic (\( \alpha = 0.1 \)), medium load (\( \alpha = 0.3 \)), and high load (\( \alpha = 0.5 \)).

**Multi-hop Packet Reception Ratio**

The packet reception ratio (PRR) is simply the ratio of the number of packets sent to the number of packets successfully delivered to the RSU. Note that each packet is transmitted \( w \) times by the original sender and, except for the proposed protocol, may be further duplicated at various forwarding nodes. The successful reception of any of the copies of a packet counts as a successful reception. However, reception of extra copies of an already received packet are not counted.

Figure 5.3 shows the PRR for a low level of multi-hop traffic plotted against the distance between the packet originator and RSU. The proposed cooperative forwarding protocol generally performs better than the other forwarding schemes. Although the weighted p-persistence scheme has similar performance for within 200 metres, it quickly
degrades beyond that distance. The opposite is true of the slotted 1-persistence scheme. It is the only scheme to match the PRR of the proposed protocol for distant sources, its performance is significantly worse for a large region within 200 metres.

Figure 5.3: Packet reception ratio vs. distance from RSU for low load, $w = 7, L = 80$

For medium traffic load shown in Figure 5.4, the PRR of all schemes diminish more rapidly with distance due to the increased amount of collisions. However, the proposed scheme still achieves the best performance overall, although there is little difference between it and the weighted p-persistence scheme.

The high traffic load scenario in Figure 5.5 shows a continuing trend. The PRR of all schemes drop off even more rapidly with distance. Again, the proposed scheme has the highest overall PRR.
Figure 5.4: Packet reception ratio vs. distance from RSU for medium load, $w = 7$, $L = 80$

**Overhead**

The overhead ratio metric is calculated by dividing the number of packets transmitted at the MAC layer in the simulation with the total number of distinct packets successfully received by the RSU. Figure 5.6 illustrates the broadcast storm problem, as flooding takes up the most network resources by far. The other forwarding schemes have less overhead, but are all outperformed by the proposed scheme. This is expected since the relays are explicitly selected at each hop and thus there can be no more than $w$ transmissions of the packet per hop. As we shall see, this difference in load placed on the channel greatly effects the quality of service of safety messages, which share the same network resources.
Normalized-Delay Metric

The normalized delay metric is a hybrid performance metric that ties the packet reception ratio to the end-to-end delay. It is calculated by summing up the total end-to-end delays for each packet received from a sender. Next, for each packet which failed to be delivered to the RSU, the duration of a time frame is added. Finally, the total is divided by the number of successfully received packets from that sender.

Figures 5.7, 5.8, and 5.9 show this metric for low, medium, and high multi-hop traffic loads respectively. While the proposed protocol performs on par or slightly worse for the low traffic scenario, for increasing amounts of traffic and interference, the benefits of POC-based transmissions begin to take effect. Please note that the latter two figures are
Figure 5.6: Overhead ratio for low, medium and high loads, $w = 7$, $L = 80$ plotted on a logarithmic y-axis. Only the weighted p-persistence scheme has performance on-par with the POC-based cooperative forwarding.

**Average hop count**

The average hop count of received packets are shown in Figures 5.10, 5.11, and 5.12. The average hop count does not vary much for the three different traffic levels, and the proposed scheme whose relays are selected explicitly always have the lowest hop count. One observation is that the weighted p-persistence scheme is more effective in reducing the average hop count than the slotted 1-persistence scheme.
Figure 5.7: Normalized delay vs. distance from RSU for low load, $w = 7$, $L = 80$

### 5.2.2 Effect on Safety Messages

A major design goal of our cooperative forwarding protocol was to minimize the effect of multi-hop traffic on the reliability and delay of periodically broadcast safety messages. In this section, the effect of multi-hop traffic using the different forwarding protocols on the reception ratio and latency of these safety messages.

**Safety Messages Reception Ratio**

The average reception ratio of the periodic broadcast safety messages can be seen in Figures 5.13, 5.14, and 5.15 for the three levels of multi-hop traffic load. They are plotted against the distance between the pair of one-hop neighbours. While the performance of
Figure 5.8: Normalized delay vs. distance from RSU for medium load, $w = 7, L = 80$

the proposed protocol was only marginally better than the other forwarding schemes for most performance metrics of the multi-hop packets, the proposed scheme has a clear advantage here. In each of the three cases, the proposed scheme resulted in the best reception ratio of the safety messages. This is expected as the proposed scheme generates much fewer duplicates of packets and thus places the least amount of load on the network. Furthermore, the POC coded transmission times further reduce the probability of collision between multi-hop traffic and the safety messages.

**Mean time between safety message reception**

The mean time between successful receptions of safety messages from one-hop neighbours depends on the safety message generation rate $\beta$ and the packet loss rate. Since the
Figure 5.9: Normalized delay vs. distance from RSU for high load, $w = 7$, $L = 80$

repetition-based MAC ensures that the delay for one-hop broadcasts cannot exceed one time frame, this mean inter-safety message time expresses the “oldness” of a vehicle’s map of its neighbourhood.

Figures 5.16, 5.17, and 5.18 show this performance metric plotted against distance for the three traffic load levels. It is important to note that for medium and high loads the safety message reception rate is so low for some forwarding schemes that their plots are invalid for distances over 100 metres.
Chapter 5. Performance Evaluation

5.3 Discussion

The simulations presented in this chapter showed that our proposed protocol design, through the use of multiple relays and POC-based transmission times, can achieve a performance level for multi-hop traffic on par with or better than receiver-based forwarding schemes that use up much more network resources. Furthermore, the proposed forwarding scheme has the least detrimental effect on the reception ratio and inter-safety message time of the one-hop safety broadcasts.

The simulations also show that the throughput of multi-hop forwarding without acknowledgements decreases rapidly with traffic load and distance. Thus it is unlikely that
such forwarding schemes will be able to support high-throughput applications and may be better suited to periodically generated low-throughput applications such as traffic monitoring.

One additional observation of note is that the implementation of the proposed protocol initially used the NADV routing metric. However, its performance was quite poor. In order to evaluate the routing metric in a distributed virtual relay, each node needed a two-hop neighbourhood map of the forward reception probabilities. However, since collisions and interfering transmissions were a significant source of packet loss, it was difficult to keep a consistent two-hop neighbourhood map of the reception probabilities. As a result, many virtual relays had inconsistent relay selection and/or relay ordering among its members.

Figure 5.11: Average hops vs. distance from RSU for medium load, $w = 7, L = 80$
Figure 5.12: Average hops vs. distance from RSU for high load, \( w = 7, L = 80 \)
Figure 5.13: Safety message reception ratio vs. distance of neighbour for low load, \( w = 7 \), \( L = 80 \).
Figure 5.14: Safety message Reception Ratio vs. distance of neighbour for medium load, $w = 7$, $L = 80$
Figure 5.15: Safety message Reception Ratio vs. distance of neighbour for high load, $w = 7, L = 80$
Figure 5.16: Mean time between safety message reception vs. distance of neighbour for low load, $w = 7$, $L = 80$
Figure 5.17: Mean time between safety message reception vs. distance of neighbour for medium load, $w = 7$, $L = 80$
Figure 5.18: Mean time between safety message reception vs. distance of neighbour for high load, $w = 7$, $L = 80$
Chapter 6

Conclusion

Although safety applications remain the driving force behind VANETs, many other applications and services have been envisioned for the communication platform that vehicular networks will provide. Many of these applications require not only reliable vehicle-to-vehicle (V2V) communication, but also wireless access to roadside infrastructure (V2I). The cost of infrastructure deployment, in the form of roadside units (RSU) may be a significant obstacle to providing coverage to long stretches of inter-city highway. If the coverage range of each RSU can be extended via multi-hop V2V communication, the overall deployment cost of RSU may be significantly reduced. However, the impact of forwarded V2I traffic on the quality of service of safety-related V2V messages cannot be neglected and must be considered in the design of the forwarding protocol.

In this work, we have proposed a novel cooperative forwarding scheme which takes a cross-layer approach to integrate with the POC-based MAC protocol. Packets are forwarded by multiple cooperating relays at each hop, thereby exploiting diversity gains and the broadcast nature of wireless transmissions. At each hop, the multiple relays coordinate by forming a virtual relay and ensure that their transmission times adhere to that of a POC codeword. In doing so, the scheme benefits from the POC-based MAC’s ability to reduce the probability of packet collisions and the effect of hidden terminals.
Following a simple analysis of some motivating examples, the protocol is validated through simulations. Its forwarding performance, in terms of probability of reception and delay, was found to be comparable to other forwarding schemes that consume much more network resources. The proposed scheme was superior in minimizing the detrimental effects on the quality of service of periodic safety messages broadcast in the background.

6.1 Future Work

The effects of mobility on the proposed scheme remain to studied. The constraint of the road on the mobility of the vehicles suggest that a predictive algorithm may be developed, both for relay selection and codeword allocation.

In adapting a forwarding scheme from a repetition-based broadcast MAC, the use of acknowledgements was not considered. If introduced, this would in turn have an impact on the appropriate routing metric. This remains an area for future study.

In this work, when more than one packet is scheduled for transmission in a single time slot by a node, one is chosen at random and the rest discarded. This situation appears to be one in which network coding seems a likely solution. The design of the coding scheme may prove to be a fruitful area for future research.
Bibliography


