A Predictive Cross-Layered Interference Management in a Multichannel MAC with Reactive Routing in VANET

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Abstract—Vehicular ad hoc networks (VANETs) represent a particular mobile technology that permits communication between vehicles, offering security and comfort. Nowadays, distributed mobile wireless computing is becoming a very important communication paradigm, due to its flexibility to adapt to different mobile applications. In this work, an interference aware metric is proposed in order to reduce the level of interference between each pair of nodes at the MAC and routing layer. In particular, this metric with a prediction algorithm is proposed to work in a cross-layered MAC and an on-demand routing scheme in multi-radio vehicular networks, wherein each node is equipped with two multi-channel radio interfaces. The proposed metric is based on the maximization of the average signal-to-interference ratio (SIR) level of the connection between source and destination. In order to relieve the effects of the co-channel interference perceived by mobile nodes, transmission channels are switched on a basis of a periodical SIR evaluation. Our solution has been integrated with an on-demand routing scheme but it can be applied to other routing strategies. Three on-demand interference aware routing schemes integrating IEEE 802.11p Multi-channel MAC have been tested to assess the benefits of the novel metric applied to a vehicular context. NS-3 has been used for implementing and testing the proposed idea, and significant performance improvements were obtained: in particular, the proposed policy has resulted in an enhancement of network performance in terms of throughput and packet delivery ratio.

Index Terms—802.11p, DSRC, interference aware routing, multi-channel routing, VANET, WAVE

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1 INTRODUCTION

NOWDAYS, we spend a significant amount of time in cars for work or leisure and this has led car manufacturers to design their vehicles as if they were living spaces. Efforts are geared toward making vehicles safer and more comfortable, thanks to the adoption of advanced technologies in different sectors of engineering. Cars have become more and more advanced from a technological point of view: in addition to the electronic control unit, it is not uncommon to find ESP-board computers and GPS navigation. In short, all these mechanisms could be controlled by a single processor, capable of displaying information on a display with a wireless interface for inter-vehicular communication (IVC). Many organizations, which also include the major car manufacturers, are working on devices that allow wireless communication between vehicles to prevent accidents and to provide support services.

In recent years the concept of vehicular ad-hoc network (VANET) has been introduced to refer to a network where nodes are represented by vehicles, which communicate without requiring the presence of infrastructure, but based on cooperation: a node may assume the role of intermediate router for forwarding packets to a destination that is not in the radio coverage of the sending node. Vehicular networks (VNs) can provide support for intelligent transportation system (ITS) applications, oriented to road safety and information services and entertainment. Vehicular communication systems represent one of the most desirable technologies when the safety, efficiency and comfort of everyday road travel needs to be improved. The main advantage is the absence of an infrastructure, typical of centralized networks, that makes them very scalable and adequate for highly-variable network topologies. On the other hand, communication protocols become very complex and, sometimes, signaling overhead may waste bandwidth availability. VANET are able to provide wireless networking capability in situations where no fixed infrastructure exists and the communication among nodes can be either direct or made via relaying nodes, as in classical ad-hoc networks. VANETs provide wireless communication between vehicles and vehicle to road side unit (RSU). RSU is a wireless transceivers and has the capability of data storage, computing power, and routing. Communication performance and quality of service (QoS) strongly depend on how the routing takes place in the network, on how protocol overhead affects the available bandwidth and on how different channels are selected in order to minimize interference levels. VANETs can provide support for ITS applications geared towards road safety and information or entertainment services. The term IVC is used to describe the transmission of information between vehicles, while VANETs and vehicular networks are equivalently used to mean a combination of vehicles that exchange network packets. If you want to distinguish between the vehicle-to-roadside (V2R) and vehicle-to-vehicle (V2V), the

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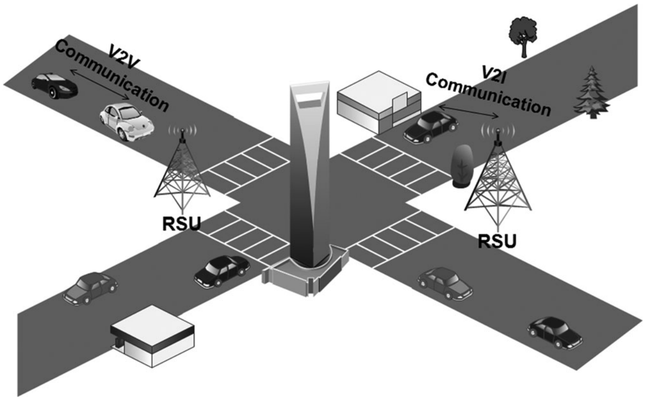

Fig. 1. A typical urban VANET scenario.

following terms should be used vehicle-to-roadside, or equivalently-vehicle-roadside communication (VRC), and Vehicle-to-Vehicle as shown in Fig. 1.

In this work, the availability of different communication channels is considered in order to improve system performance. In a distributed multi-hop architecture, a mobile node may potentially find multiple routes for all the destinations. When evaluating network topology through its routing table and, in the considered case, the availability of different available channels, a protocol may enhance communication quality. So, in this scenario, each node should select the best route in terms of QoS, not only considering a typical cost metric (bandwidth, delay, traffic load or a combination of them), as in the classical multi-hop architecture, but taking into account the benefits that can be obtained if different interference levels, i.e., different channels, are considered. QoS routing in multi-hop wireless networks is very challenging due to interferences among different transmissions, but VANETs offer the chance to reduce them since multiple simultaneous transmissions are possible. In this paper a new interference-aware routing protocol for VANET environments is proposed, taking the advantage of a dynamic allocation of the dedicated short range communications (DSRC) spectrum, in order to reduce interference level among mobile nodes. The proposed idea is mainly based on a cross layer approach to manage the interference in a MANET context. A new metric has been defined, based on the signal-to-interference (SIR) evaluation on the different available channels on a multichannel MAC. In addition, an algorithm to predict the SIR level on transmission channels over time is also introduced and used to select different routes if the SIR level degrades on a particular path. Finally an on demand routing scheme has been applied to take into account the chance of dynamically changing the channel used for data transmission. In particular, the proposed routing protocol aims to choose different channels, one for each hop on the path, in order to obtain a global SIR maximization for the connections between sources and destinations. This paper is organized as follows: Section 2 presents an in-depth overview on state-of-the-art routing in VANET; Section 3 gives an in-depth overview of the standards in VANET, then Section 4 introduces the considered scenario and the proposed protocol. Section 5 offers a detailed description of the obtained results. Finally, Section 6 concludes the paper.

2 RELATED WORK AND MAIN CONTRIBUTION

In this section we describe the state of the art related to routing protocols, MAC protocols used in vehicular networks and the description of the main contribution of this work.

2.1 Network Layer Protocols for VANETs

There are many studies in literature on routing over VANETs, investigating classical approaches, like AODV, DSR, GPSR, etc., and several routing protocols have been defined by many researchers.

In [1] distribution-adaptive distance with channel quality (DADCQ) protocol was proposed which utilizes the distance method to select forwarding nodes. In this work, the authors created a decision threshold function that is simultaneously adaptive to the number of neighbors, the node clustering factor, and the Rician fading parameter.

In [2], authors proposed an optimized version of OLSR based on Meta-heuristics techniques for VANETs context. Traditional ad-hoc routing protocols have also been investigated [3] through an in-depth performance analysis in highway scenarios; simulation results showed that the considered protocols increase the routing load on the network and decrease the packet delivery ratio and the end-to-end delay. In [4], authors propose a predictive technique based on sequential patterns and two mechanisms used to prepare data for this technique, as well as some performance evaluation for these mechanisms to determine the most feasible choice in terms of communication overhead. In [5], the authors designed a model to deal the context data dissemination in efficient manner and how to decrease the amounts of transferred and stored data in vehicular environment. In [6], the authors present a fault tolerant location based service discovery protocol for vehicular networks. The main advantages of this protocol is its ability to tolerate service provider failure, communication links failure and roadside routers failure. In [7] the authors addressed the problem of content discovery and provision in vehicular networks with infrastructure, when a publish/subscribe paradigm is applied. In this scenario, vehicular users can be providers and consumers of generic information content, which is available through the vehicular network itself. Special infrastructure nodes act as information brokers and aid vehicles in content retrieval and dissemination.

Another important issue in VANETs is the choice of an appropriate transmission channel, not only considering the type of traffic (emergency, security, platooning, etc.) but, mainly, focusing on the reduction of the inter-node interference. In [8] a contextual cooperative congestion control policy that exploits the traffic context information of each vehicle to reduce the channel load was proposed to reduce the load on the communications channel, while satisfying the strict application's reliability requirements. VANETs have been also considered for new applications [9], such as security and smart operations in vehicular environments or optimized data delivery [10].

In [11], the authors propose to evaluate the performance of a balanced load and introduce a new QoS gateway discovery protocol (Collaged) that permits the connection to heterogeneous wireless networks. The protocol guarantees balancing the load at gateways levels, as well as the routing paths between gateways and gateway requesters. In [12], authors proposed an algorithm that utilizes the prediction of vehicles position and navigation information to improve the routing protocol in VANETs with a cross-layer approach. In addition, they used the information about link layer quality in terms of SNIR and MAC frame error rate to further improve the efficiency of the proposed routing protocol. In [13], [14], [15], we proposed a novel preliminary interference-aware algorithm for VANET environments able to optimize the paths from sources to destinations in terms of interference, by introducing a new routing protocol; however, time variations of SIR are not taken into account. This work represents an extension of [13] and [14], since the metric used in routing decisions takes the way the SIR has to evolve in time into account and a prediction algorithm is also introduced.

2.2 Related Works to the VANETs MAC Layer

In [16] a novel multichannel TDMA MAC protocol (VeMAC) was proposed for a VANET scenario. The VeMAC supports efficient one-hop and multi-hop broadcast services on the control channel (CCH) by using implicit acknowledgments and eliminating the hidden terminal problem. The protocol reduces transmission collisions due to node mobility on the control channel by assigning disjoint sets of time slots to vehicles moving in opposite directions and to road side units. In [17], the authors proposed a new protocol, denoted as OFDMA based MAC protocol for VANETs, and compared it with other MAC protocols taken as benchmarks. They first proposed an analytical model in a simplified scenario, and then, developed exhaustive simulations in realistic scenarios, considering both urban and highway environments.

In [18] an adaptive medium access control (MAC) retransmission limit selection scheme is proposed to improve the performance of IEEE 802.11p standard MAC protocol for video streaming applications over vehicular ad-hoc networks. A multi-objective optimization framework, which jointly minimizes the probability of playback freezes and start-up delay of the streamed video at the destination vehicle by tuning the MAC retransmission limit with respect to channel statistics as well as packet transmission rate, is applied at the road side unit. The authors in [19] proposed novel analytical approach accounts for mutual influence among nodes, frequent periodic updates of broadcasted data, standard network advertisement procedures, and 802.11p prioritized channel access with multichannel-related phenomena under various link quality conditions.

2.3 Main Contribution of Our Work

The main contribution of this paper consists in the proposal of a new metric defined on the multi-channel WAVE protocol and applied on route discovery procedure in order to take neighbors' interference level into account. A prediction technique is also considered, in order to make decisions on channel selection based on future SIR values. The evaluation of the new metric is based on:

- Efficient management of the multi-channel capability of the WAVE standard at routing level, through a higher level channel selection, which is based on an interference-aware algorithm;
- Implementation of a channel model in order to take path-loss between transmitter and receiver nodes into account;
- Periodical signal-to-interference ratio estimation on the available transmission channels;
- Prediction of the future levels of SIR on different channels, in order to make an estimation of the best predicted available interference values;
- Definition of a SIR threshold value, in order to choose if a new transmission channel must be selected;

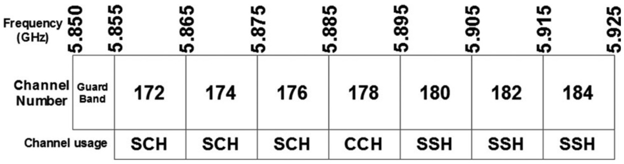

Fig. 2. Spectrum allocation in the DSRC standard.

Transmission of synchronization packets in order to advise the receiving node of a new channel selection.

3 MULTI-CHANNEL MAC STANDARD IN VANET

Now a brief overview on the main components of the VANET architecture is given.

The standard wireless access in vehicular environments (WAVE) [20] defines the way of operations for IEEE 802.11p in those situations where the properties of the physical layers are rapidly evolving and where the duration of the communication exchange is short. In other words, this standard is an extension of the IEEE 802.11 family for vehicular communications and it aims at providing the standard specifications to ensure the interoperability between wireless mobile nodes of a network with rapidly changing topology (that is to say, a set of vehicles in an urban or sub-urban environment). WAVE system supports both IP and non-IP based applications. Non-IP based applications are supported through the WAVE short message protocol (WSMP) defined in P1609.3. WSMP allows applications to directly control physical characteristics, e.g., channel number and transmitter power, etc., which is utilized for high priority safety message (emergency message).

Channel Sewering (or channelization as shown in Fig. 2) is an improvement of the IEEE802.11 MAC and interacts with the IEEE 802.2 LLC level. This function coordinates channel spacing depending on the channel synchronization operation of the MAC layer. In a WAVE system, there are two types of devices: Road-Side Units that is a WAVE device that operates in a fixed position and On-Board Units (OBU) that is a WAVE mobile device or laptop that supports information exchange with RSUs and other OBUs. WAVE devices need to manage a control channel and different service channels (SCHs). At startup, the device polls the control channel until a service WAVE advertisement is received, announcing a service that uses a service channel, or the device chooses to use the service channel based on WAVE messages it delivers. The IEEE 802.11p [20] is an amendment of IEEE 802.11–2007 for wireless network that focuses on improving the performance of CSMA/CA in highly mobile ad-hoc networks. It is considered as a core technology of WAVE, which includes a number of new classes of applications that pertain to roadway safety (such as

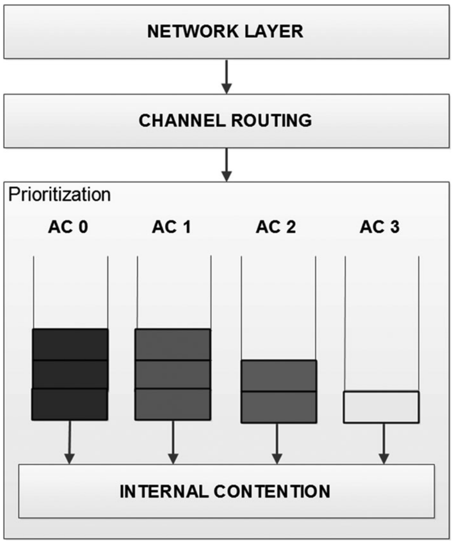

Fig. 3. Multi-channel EDCA extension for WAVE specifications.

collision avoidance) and emergency services (such as services by ambulance, police and vehicle rescue). These applications impact WAVE in a number of ways. Some critical applications require that the total time from first signal detection to completion of data exchange must be completed within the order of 100 millisecond.

The medium access control protocol in IEEE 802.11p uses the enhanced distributed channel access (EDCA) mechanism originally provided by IEEE 802.11e. Different arbitration inter frame space (AIFS) and contention window (CW) values are chosen for different application categories (ACs). There are four available data traffic categories with different priorities: background traffic (BK), best effort traffic (BE), voice traffic (VO) and video traffic (VI). IEEE 802.11p has the potential to become a single global standard for communications in ITS. The design requirements of the standard regards longer operating ranges, high relative speed between the nodes, extreme multi-path environment, multiple potentially overlapping ad-hoc networks, high quality of service, support for vehicular safety applications such as transmission-oriented messages. The implementation of IEEE 802.11p is understandable in view of other modifications of IEEE 802.11. The physical layer of IEEE 802.11p is based on the IEEE 802.11a: orthogonal frequency division multiplexing (OFDM) based modulation is used and the assignment of frequencies in the 5 GHz band [21]. medium access control is one of IEEE 802.11: carrier sense multiple access with collision avoidance (CSMA/CA). For the QoS, implementation has been adapted from the protocol IEEE 802.11e: with four access categories (ACs) (as shown in Fig. 3). Each AC has its transmission queue with built-in priority. IEEE 802.11p implements not only the characteristics of other IEEE 802.11, since the design requirements are unique in the family of protocols.

The Federal Communications Commission (FCC) of the United States approved 75 MHz of bandwidth 5.850 to 5.925 GHz to. The available bandwidth is divided into seven Channels of bandwidth 10 MHz (CH 172–184), of which 178 is designated as the CH Control channel. CCH has a limited use and is used to transmit data on the safety and transmission of control messages and management. The remaining channels are service channels available to non-secure transmission of data, including general Internet Services in case it is provided. Although the settings for the PHY configuration are not globally unique, the band has always used the same settings, making different assignments a challenge in terms of global distribution of devices and compatibility, but not critical in terms of research.

Possible modulation schemes are BPSK, QPSK, 16-QAM, 64-QAM, with coding rates equals to 1/2, 1/3, 3/4 1/2, 1/3 and $^{3}/_{4}$ and an OFDM symbol duration of 8 μs. The WAVE standard relies on a multi-channel concept which can be used for both safety-related and entertainment messages. The standard accounts for the priority of the packets using different access classes (ACs), having different channel access settings. This shall ensure that highly relevant safety packets can be exchanged timely and reliably even when operating in a dense urban scenario.

4 INTERFERENCE MANAGEMENT IN A CROSS-LAYERED VIEW

Our attention is focused on the interference management at routing and MAC layers on VANET in order to reduce packet dropping and improve communication quality. At MAC layer each node (CAR) estimates the local interference on its channels whereas the routing layer is able to estimate a path interference. It is assumed that the channel router of the WAVE MAC layer (as illustrated in Fig. 3) is able to analyze the LLC data unit in order to choose the right priority queue. As introduced and explained in [2], we considered that each VANET node has two interfaces (transceivers): the first (transceiver1), which is always tuned to the control channel and the second one (transceiver2), which can be tuned to any of the six service channels [2]. Using the information carried out in the messages sent and received on CCH, in each time slot a node can switch on a selected service channel, as will demonstrate in Section 4.5.

4.1 Proposal Summary

The basic idea consists in the evaluation of the SIR level on each available channel for each node of the network and each path from a source to a destination is built-up maximizing the obtained level of SIR on each point-to-point link. In addition, a SIR prediction algorithm is introduced in order to take into account how the SIR values change in time, having the possibility to know a-priori which link will be the best in terms of SIR level. The MAC layer is able to perform a dynamic channel switching in order to balance interference among the available channels. Moreover, the interference estimation algorithm is able to compute a smoothed interference value in order to offer a stable measure to select the best path among source-destination pairs. In the following, the math formulation, the problem statement and the modification at MAC and routing layer are proposed in order to obtain advantage from a cross-layered view in interference management.

4.2 List of Symbols Adopted in the Math Formulation and Metric Definition

See Table 1 for a detailed list of symbols adopted in the math formulation and metric definition.

TABLE 1
Symbols Adopted for Metric Definition

$G = < V, E >$	*The graph associated with the considered VANET topology*
$V = \{n_1, \ldots, n_W\}$	*The set of vertexes, cardinality W*
$E = \{(n_0, n_1), \ldots, (n_{M1}, n_M)\}$	*The set of edges, cardinality M*
$n_S \in V, n_D \in V$	*Source node and Destination node*
$P_k(n_S, n_D)$	*The k-th route from node n_S to node n_D*
$N(n_j) = \{n_{j1}, \ldots, n_{jT}\}$	*The set of n_{jl} nodes that are neighbors of node n_j, with $\|\|N(n_j)\|\| = T$ and $l = 1,\ldots,T$*
r	*Coverage radius*
$P(n_S, n_D)$	*The set of all the possible Paths from node n_S to node n_D, cardinality K*
$n_{p,k}$	*p-th node on the k-th path from a generic couple of source/destination n_S, n_D*
CH	*The set of available transmission channels, cardinality C*
$ch_c \in CH$	*The generic transmission channel*
$MAX_SIR_{nm,k}$	*The best available SIR value available on node n_m belonging to k-th path*
$P_{opt}(n_S, n_D)$	*The best path in terms of interference (eq. (2)) from node n_S to node n_D*
$SIR_{nm,chc}$	*The SIR value on channel ch_c for node n_m (eq. (3))*
P_t	*Transmission power (assumed to be the same for each node)*
$P_r(ch_c, n_j)$	*The received power on generic node n_m on channel ch_c due to the transmission of node $n_j \in Neigh(n_m)$ (eq. (5))*
$d(n_m, n_j)$	*The distance between node n_m and node n_j*
η	*Reflection coefficient*
h	*Antenna height*
$\lambda(ch_c)$	*The wavelength related to the carrier frequency of channel ch_c*
γ	*Path-loss factor*
T_r	*Periodical refresh time*
T_p	*Periodical probes-sending time*
δ	*The minimum SIR level that must be granted on each selected channel*
$SIR_{nm,chc}(n)$	*The sequence of SIR values observed on a given channel ch_c (eq. (6))*
$\vec{\theta}^*$	*Optimal coefficient vector for RLS algorithm (eq. (7))*
$\vec{u}(n)$	*The input vector for eq.(6) of the RLS algorithm (eq. (8))*
$\hat{\vec{\theta}}(n)$	*Estimated parameters vector for the RLS algorithm (eq. (9), eq. (11))*
λ	*Forgetting factor for the RLS algorithm*
$\vec{k}(n)$	*The gain vector for the RLS algorithm (eq. (10))*
$P(n)$	*The input inverse correlation matrix of the RLS algorithm (eq. (12))*
$d(n)$	*The desired output for the RLS algorithm*
SIR_PROBES_h	*The average instantaneous SIR on $Path_{opt}(n_S, n_D)$ at the h-th step (eq. (13))*
SIR_PROBE_k	*The value of SIR contained in the k-th received PREP packet*
D	*The input threshold used to consider a degradation of SIR*
$SIR_{nm,chc}(n+1)$	*Predicted (n+1)-th SIR value (eq.(15))*
α	*Smoothing factor*

4.3 Problem Statement in Interference Management at Routing Layer

Let $G = < V, E >$ be the graph G associated with the considered VANET topology, $V = \{n_0, \ldots, n_W\}$ the set of vertexes with $|V| = W$, *let* $E = \{(n_0, n_1)_1, (n_1, n_m)_2, \ldots, (n_j, n_D)_M\}$ be the set of edges with $|E| = M$. Let $n_S \in V$ be a source node that has to transmit a certain amount of packets to a destination $n_D \in V$ and $P_k(n_S, n_D)$ the *k*th route from n_S to n_D, composed by a sequence of edges $(n_S, n_1), \ldots, (n_r, n_D)$. Let $N(n_S) = \{n_1, \ldots, n_I\}$ be the set of neighbor nodes of n_S so that $\overline{(n_S, n_i)} < r$, $\forall n_{\underline{j}} \in N(n_S)$, r radio coverage radius of each node $n_j \in V$) and $\|N(n_S)\| = I$. let *CH* be the set of available transmission channels for each node in the considered scenario, so *CH = {172, 174, 176, 180, 182, 184}* and $\|CH\| = C = 6$ (channel 178 is disregarded because it is used only for signaling purposes).

To provide a specific scheme where interference aware procedures and metrics are introduced, let us refer to a generic on-demand scheme where two messages are used: *RREQ* (broadcast) to request a path from source to destination, and *RREP* (unicast) to answer on the reverse path forwarding from destination to source. In this view, before formulating the path optimization problem, we explain the path discovery (PD) strategy. The proposal can be applied also to other routing schemes using the mechanisms that we will explain in the next paragraphs.

During the *Path Discovery*procedure of the proposed interference-aware reactive (IAR) scheme, the source node n_S, unaware of the best path toward n_D in terms of SIR, broadcasts *RREQ* packets to its neighbors $N(n_S)$ in order to know the set of all the possible paths to $n_D : P(n_S, n_D) = \{P_1(n_S, n_D), \ldots, P_K(n_S, n_D)\}$, with $\|P(n_S, n_D)\| = K$. Without loss of generality we hypothesize that G is a connected graph, so $K \geq 1$ for each couple n_S, $n_D \in V$. Each neighbor node $n_i \in N(n_S)$ will forward the *RREQ* packet to its neighbors $N(n_i)$, until the RREQ packet reaches the destination node n_D. After receiving the RREQ packet the destination will forward towards the source on the reverse path forwarding the RREP packet. In this case, the previous hop of the destination node $n_{p,k}$ (it represents the *p*th node on the *k*th path) $P_k(n_S, n_D)$ with $p = \|P_k(n_S, n_D)\| - 1$will compute the maximum local SIR perceived on its channels such as shown in Fig. 4. In particular, the node $n_{p,k}$ scans all the available channels ch_i with $i = 1, \ldots, 6$ to find the one that guarantees the best local SIR (see the Section 4.4). Then, the node inserts this pre-computed SIR inside RREP packet. At this point, the RREP packet is sent back to the previous hop on the *reverse path forwarding* such as on-demand routing schemes for MANET; each previous hop receives the RREP, evaluates its *maximum local SIR* and modifies the SIR field of the *RREP* packet with the *min value*; the local min SIR is executed by each intermediate node $n_{m,k}$ on $P_k(n_S, n_D)$, computing the minimum value between the local SIR perceived and the SIR value carried by the *RREP* packet such as shown in Fig. 4.

If at source node n_s arrives *k* RREP packets meaning that *k* routes have been discovered, the best path in terms of interference by the following relation:

$$P_{opt} = \left\{ P_i(n_S, n_D)/i = index\left\{ \max_j \left(MIN\_SIR_j \right) \right\}, j = 1, \ldots, k \right\} \tag{1}$$

s.t.

$$MAX\_SIR_K\left(n_j\right) \geq \delta \quad \text{with} \quad j = 1, \ldots, \|P_k(n_S, n_D)\| - 1, \tag{2}$$

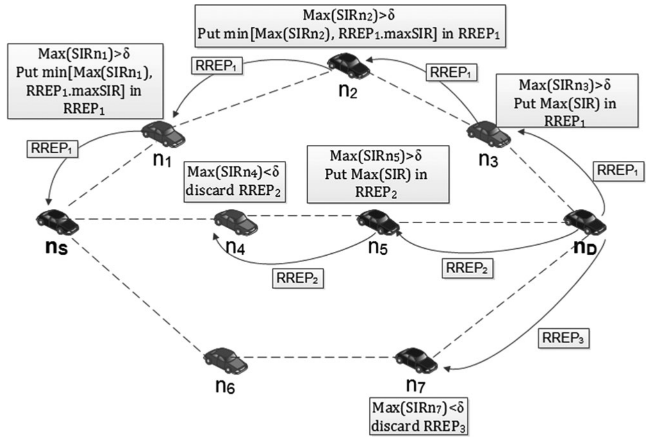

Fig. 4. Path discovery procedure in IAR protocol and SIR computation.

where δ is the minimum SIR threshold that should be guaranteed. The k term, is the number of discovered paths from source n_S to destination n_D, MIN_SIR_j is the minimum SIR registered on a link of a path jth between $\mathrm{n_s}$ and $\mathrm{n_D}$.

Fig. 5 shows an example of IAR PD procedure for node n_S, which needs to communicate with node n_D: in this case $K = 3$, $P(n_S, n_D) = \{P_1(n_S, n_D), P_2(n_S, n_D), P_3(n_S, n_D)\}$,

$$
\begin{aligned}
P_1(n_S, n_D) &== \{(n_S, n_A), (n_A, n_D)\},\\
P_2(n_S, n_D) &= \{(n_S, n_B), (n_B, n_E), (n_E, n_D)\},\\
P_3(n_S, n_D) &= \{(n_S, n_C), (n_C, n_D)\}.
\end{aligned}
$$

At the end of the *PD* procedure, the node n_S will receive three *RREP* packets, containing the $MIN_S IR_1 = 9$, $MIN_S IR_2 = 16$ and $\mathrm{MIN}_S IR_3 = 8$ values respectively. From Eq. (2), the optimal path P_{opt} is $P_2(n_S, n_D)$ because it is the path that maximize the min SIR value. In the case in which more paths have the same best SIR value, the algorithm will select among these best paths the shortest one.

4.4 SIR Evaluation on Multi-Channel MAC

As seen in the previous section, each intermediate node n_m on the kth path, $n_{m,k}$, needs to estimate the current value of SIR on the generic channel $ch_c \in CH$. This operation can be executed by defining the SIR as a function of the transmitted and received signal power, subject to radio propagation conditions. In particular, the SIR value on channel ch_c, for node n_m is:

$$SIR_{n_m,ch_c} = \frac{P_t}{\sum_{j=0}^{\|N(n_m)\|-1} P_r(ch_c, n_j)}, \tag{3}$$

where P_t is the transmission power (without loss of generality it is assumed that P_t is the same for each user and for each channel as defined by the standard, so $P_t(ch_c, n_m) = P_t \forall n_m \in V$ and $\forall ch_c \in CH$) and $P_r(ch_c, n_j)$ is the received signal power of node n_m on channel ch_c due to the transmission of node $n_j \in N(n_m)$. At this point, it can be written that:

$$
\begin{aligned}
&MAX\_SIR_K(n_m)\\
&= \left\{ SIR_{Ch_j} / j = index\left\{ \max_j \left(SIR_{n_m,ch_j} \right) \right\} \right\}
\end{aligned} \tag{4}
$$

with $j = 1, \ldots, 6$.

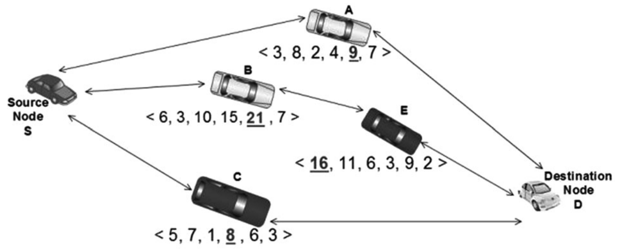

Fig. 5. Path Discovery procedure in IAR protocol.

So, the value of *SIR* obtained by Eq. (4) is the one that each intermediary node n_m will use to fill the *SIR* field of *RREP* packets.

Nowadays, each vehicular node has the possibility to evaluate the received power via hardware, but for our simulation purposes an analytical expression for $P_r(ch_c, n_j)$ in Eq. (3) is mandatory. With this aim, we based the propagation modeling on the two-ray model for vehicular environment [22], so for a node n_m it can be written that:

$$P_r(ch_c, n_j) = \frac{P_t}{(4\pi)^2 \left(\frac{d(n_m, n_j)}{\lambda(ch_c)}\right)^{\gamma}} \left[1 + \eta^2 + 2\cos\left(\frac{4\pi h^2}{d(n_m, n_j) \cdot \lambda(ch_c)} \right) \right], \tag{5}$$

where P_t is the transmitted power, $d(n_m, n_j)$ is the distance between n_m and the neighbor n_j, η is the reflection coefficient (related to the road surface), h is the height of the antenna, $\lambda(ch_c)$ is the wavelength related to the carrier frequency of channel ch_c and n_j is the path-loss factor [22].

4.5 Dynamic Channel Switching Procedure

In order to ensure a good quality on the transmission path from n_S to $n_{D,}$ a channel refreshing mechanism is also provided. Once a generic node $n_m \in V$ has chosen the optimal channel in terms of interference, the associated SIR value has to be periodically refreshed (let us indicate the refresh time as T_r) in order to know if it can be still considered as the best *SIR* value for the transmission: if the refreshed SIR value falls below a lower-bound, then the node has to start a dynamic channel switching procedure for the selection of a new transmission channel with a better SIR value. The transmitter node will advertise the receiving neighbor node $n_n \in V$ with a Change-REQuest (*CREQ*) packet about the switching on a new channel: the *CREQ* packet is similar to the *RREQ* packet and contains the *CHAN* and *SIR* fields, which indicate the new transmission channel and the associated SIR value respectively. The receiving node n_n will reply with a Change-REPly message (*CREP*), in order to send to the transmitting node the acknowledgement of the *CREQ* packet.

Fig. 6 shows the structure of *CREQ* and *CREP* packets on the right side. Fig. 7 contains the flow diagram of the updating procedure, executed every T_r seconds by the generic node n_m that is currently transmitting on channel ch_c to the receiving node n_n: Let $N(n_m)$ denote the number of neighbor nodes of n_m and δ is an input threshold that represents the minimum SIR level that must be granted on each selected channel. The value of SIR on the current channel

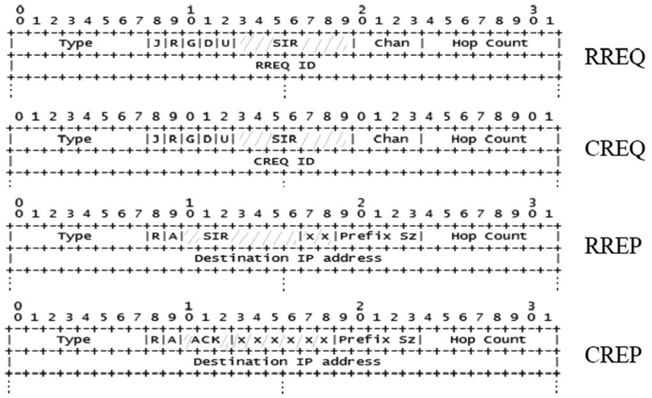

Fig. 6. Signaling packets in IAR Protocol.

chch_c must be greater than *δ*; if this is not satisfied, the channel has to be updated, so for each available channel the SIR value has to be evaluated, in order to find the new one, let us indicate it with ch_b, associated with an acceptable SIR level.

At this point the transmitting node n_m can send to n_n the *CREQ* packet containing the information about channel ch_b and its associated SIR value. Node n_n will reply with a *CREP* packet as acknowledgement.

4.6 Predictive Interference Metric

IAR is based on the instantaneous evaluation of *SIR* levels on different available transmission channels. Since the degradation conditions on the channels change quickly on the basis of nodes mobility and propagation conditions (fading, shadowing, Doppler-shift, etc.). In this way, the choice of a path is not made only considering instantaneous values of *SIR*, but considering the future evolution of channel conditions in a particular time period. So, a predictive version of the IAR protocol is proposed.

In Section 5 the enhancements due to the introduction of a predictive algorithm are shown. The Predictive IAR protocol (PIAR) chooses a path from a source n_S to a destination n_D on the basis of the best predicted average *SIR* value, and not on the basis of instantaneous evaluations (IAR).

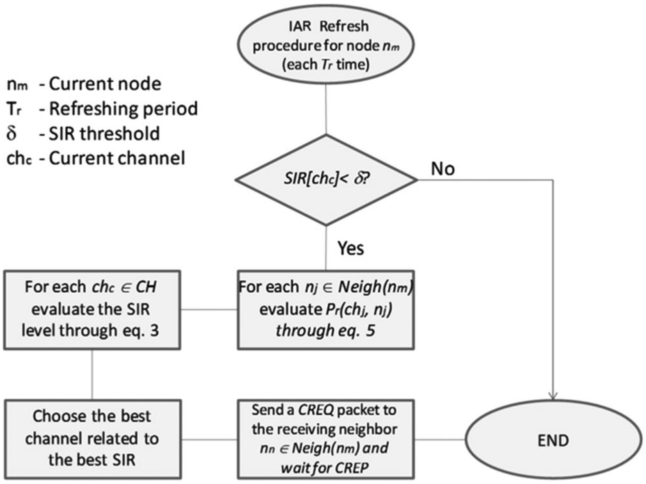

Fig. 7. Threshold-based dynamic channel refresh procedure.

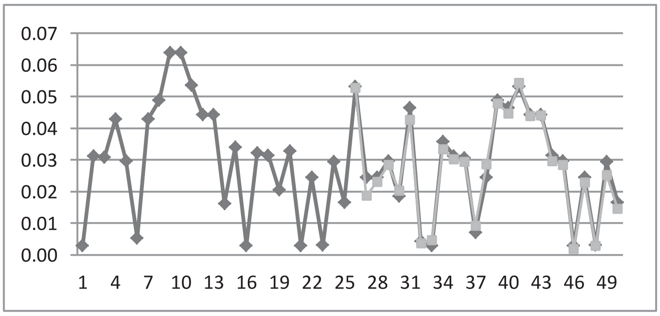

Fig. 8. Predicted SIR values with N = 25 and M = 10.

The equations and mechanisms used in IAR are still effective, but instantaneous *SIR* values are replaced by predicted ones. In order to make the prediction, the adaptive filter theory has been employed [23]: the sequence of *SIR* values observed on a given channel ch_c has been considered to be an *N*th order auto regressive (*AR*) process (a time series in particular) $SIR_{nm,chc}(n)$, defined as:

$$SIR_{n_m,ch_c}(n) = \theta_1^* SIR_{n_m,ch_c}(n-1) + \theta_2^* SIR_{n_m,ch_c}(n-2) + \cdots + \theta_N^* SIR_{n_m,ch_c}(n-N) \tag{6}$$

and it is based on the general assumption that the value of the process at time unit *n* is a linear function of previous *N* values. Basing our treatment on the theory of [23], it can be written that the unknown optimal coefficients vector is:

$$\vec{\theta}^* = [\theta_1^*, \theta_2^*, \ldots, \theta_N^*]^T \tag{7}$$

and in the *n*th time unit an input vector $\vec{u}(n)$is defined as:

$$\vec{u}(n) = [SIR_{n_m,ch_c}(n-1), SIR_{n_m,ch_c}(n-2), \ldots, SIR_{n_m,ch_c}(n-N)]^T. \tag{8}$$

If the estimated parameters vector is indicated with:

$$\hat{\vec{\theta}}(n) = [\hat{\vec{\theta}}_1(n), \hat{\vec{\theta}}_2(n), \ldots, \hat{\vec{\theta}}_N(n)]^T \tag{9}$$

then the estimation of the optimal $\vec{\theta}^*$vector can be made through the recursive least squares (*RLS*) algorithm [24], in the following way:

$$\vec{k}(n) = \frac{\lambda^{-1} P(n-1)\vec{u}(n)}{1 + \lambda^{-1}\vec{u}^T(n)P(n-1)\vec{u}(n)} \tag{10}$$

$$\hat{\vec{\theta}}(n) = \hat{\vec{\theta}}(n-1) + \vec{k}(n)(d(n) - \hat{\vec{\theta}}^T(n-1)\vec{u}(n)) \tag{11}$$

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}\vec{k}(n)\vec{u}^T(n)P(n-1), \tag{12}$$

where λ is the forgetting factor, *P(n)*represents the input inverse correlation matrix, $\vec{k}(n)$ is the gain vector, *d(n)*is the desired output ($d(n) = SIR_{nm,chc}(n)$); as initial condition $n = 0$, $\hat{\vec{\theta}}(0) = 0$ and $P(0) = \varepsilon^{-1}I$, where I is the identity matrix and ε is an arbitrary, positive and tending to zero constant. Fig. 8 illustrates an example of the effectiveness of the *RLS* prediction of the *SIR* process for $N = 25$ and $M = 10$ (*M* is the number of future values predicted on the basis of the previous *N* ones). As indicated in the next section, for our purposes, *N* has been fixed to 25 and the obtained values of SIR are normalized respect to 10^{10} in order to offer a better visibility of curves. Moreover, further graphics with different *N* and *M* values are not shown due to space limitations.

In the PIAR protocol, a source node $n_S \in V$ that is transmitting data packets to a destination $n_S \in V$ along $P_{opt}(n_S, n_D)$ periodically (each T_p seconds) sends a control packet called Probe-REQuest (*PREQ*) to its neighbor $n_{St} \in N(n_S)$ that belongs to $P_{opt}(n_S, n_D)$ in order to test the SIR value on the link toward the destination; node n_{St} will forward the *PREQ* packet to its neighbor, and so on, until the *PREQ* reaches the previous hop of n_D.

At this point, each node on $P_{opt}(n_S, n_D)$ will answer to n_S with a Probe-REPly packet (PREP), containing the SIR value related to the active transmission channel, so node n_S can evaluate the average level of instantaneous SIR on $P_{opt}(n_S, n_D)$ at the *h*th step as follows:

$$SIR\_PROBES_h = \frac{1}{||P_{opt}(n_S, n_D)|| - 1} \cdot \sum_{k=1}^{||P_{opt}(n_S,n_D)||-1} SIR\_PROBE_k, \qquad (13)$$

where $SIR_P ROBE_k$ is the value of *SIR* contained in the *k*th received *PREP* packet. At this point node n_S will evaluate the following relation:

$$SIR\_PROBES_h \cdot (1 - D) \leq SIR\_PROBES_{h-1}, \qquad (14)$$

where *D* is an input threshold (discussed in the next section) and *SIR_PROBES*$_{h\text{-}1}$ is the value of the average *SIR* on $P_{opt}(n_S, n_D)$ evaluated at the *(h-1)*th step (the previous step). If the relation in (14) is verified, then the route from n_S to n_D has to be updated and node n_S starts the *PD* procedure as in IAR (exchange of *RREQ* and *RREP* packets), but the expression of the instantaneous $SIR_{nm,chc}$ of Eq. (3), is substituted with the one of Eq. (6) $SIR_{nm,chc}(n)$ that considers a predicted value of *SIR*.

4.7 Smoothed Metric

In order to consider more stable interference values in the route selection procedure, a smoothed metric of interference is defined. This metric is included in PIAR protocol and this new protocol variant is called Smoothed PIAR (SPIAR). This variant is not based on the RLS algorithm for the prediction but it considers a smoothed evaluation of the SIR, based on past and current values of SIR. In particular, given *(n-1) SIR* samples, and the current one, then the (n+1)th predicted value of SIR will be:

$$\mathrm{SIR}_{\mathrm{n_m,ch_c}}(\mathrm{n}+1) = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}-1} \mathrm{SIR}_{\mathrm{n_m,ch_c}}(\mathrm{i})}{\mathrm{n}-1}(1-\alpha) + \mathrm{SIR}_{\mathrm{n_m,ch_c}}(n)(\alpha), \qquad (15)$$

where $\alpha \in (0, 1)$ is the smoothing factor and acts as weight between past and current values of SIR. In Section 5 the performance evaluation of the IAR, PIAR and SPIAR is considered.

4.8 Interference Aware on Demand Routing Scheme

The novelty of the proposal consists in the adopted metric for the choice of the optimal route from source to destination, and in the route maintenance procedure: it is based on the interference concept, as explained before. The IAR is based on the following assumptions:

- Data packets can be delivered on six service channels (SCH - 172,174,176,180,182 and 184), while signaling ones are transmitted only on the control channel (CCH - 178);
- Each node can transmit/receive on one channel, so no simultaneous transmissions per node are allowed;
- Each node is equipped with two interfaces radio (with multiple channels); one of these is always tuned to the control channel and the other one is tuned to any of the six service channels.
- Channels are essentially time synchronized using coordinated universal time (UTC), commonly provided by global positioning system (GPS) equipped on board the vehicles.
- The time needed for channel switching is negligible (in terms of the 802.11p MAC implementation, the channel router only has to forward data units to a different queue).

For the IAR, PIAR and SPIAR it is also supposed that a node knows exactly the SIR level on the available channels for each neighbor and packet transmission over the final optimum path from a source node n_S to a destination node n_D will be made using a set of channels that minimizes the inter-node interference, achieving better signal quality during the considered session.

5 PERFORMANCE EVALUATION

The idea proposed in previous sections has been implemented in the Network Simulator 3 (NS-3). Different classes were created or modified in the NS3 source code. The SUMO mobility generator [25] was introduced in order to obtain a more realistic scenario. Simulation parameters are listed below:

- **Simulation Map dimension**: 1,500 meters x 1,500 meters;
- **Transmitting coverage radius**: 300 meters;
- **Streets width**: 10 meters;
- **Simulation time for a single run**: 1,000 seconds;

The considered protocols are four:

- SPIAR protocol
- PIAR protocol
- IAR protocol
- CLWPR protocol

We designed the first three protocols. CLWPR [12] is a Cross-Layer protocol that utilizes the prediction of the node's position and the information about the link layer quality in term of SNIR (Signal to Noise Interference Ratio).

5.1 How to Choose Protocol Parameters in PIAR Protocol

PIAR protocol uses some critical parameters: *N* and *M* (for the prediction of *SIR* values associated to the different channels), the timer T_p (for the periodical sending of Probes packets), the threshold value *D* (used to consider a degradation of *SIR*, due to mobility of nodes). Simulation campaigns were carried out in order to set these parameters to the

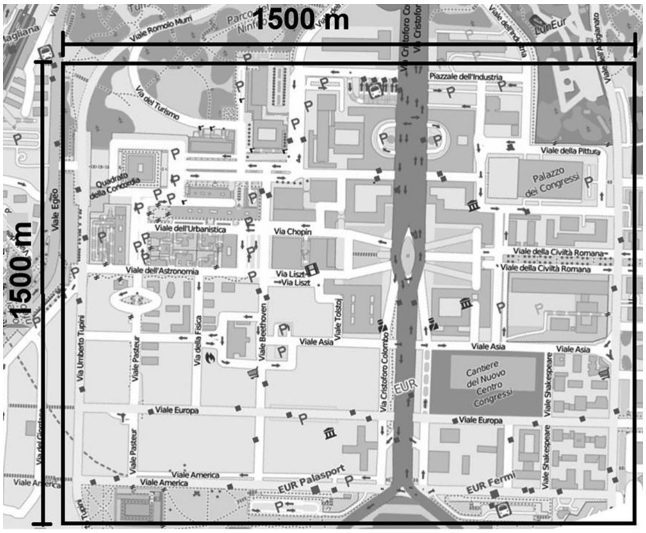

Fig. 9. Map of the Rome city.

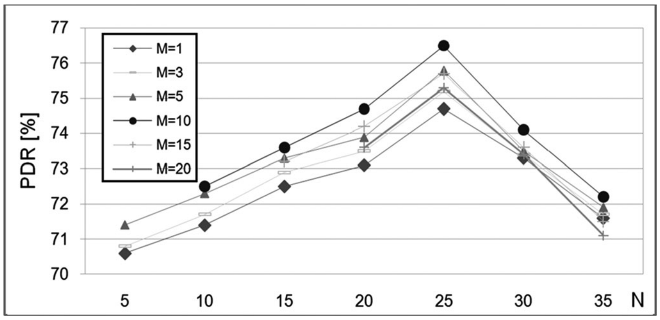

Fig. 10. Packet delivery ratio for different values of N and M.

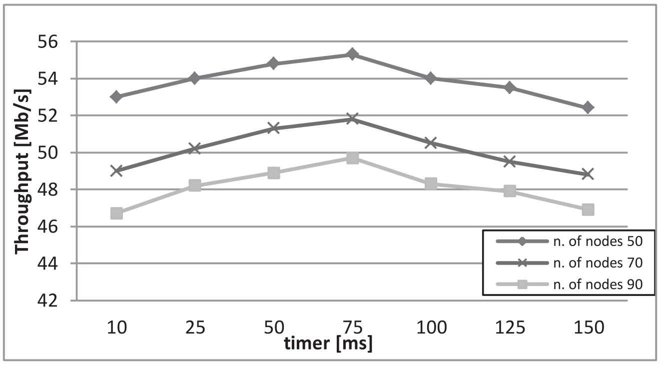

Fig. 11. System throughput versus probes-timer Tp.

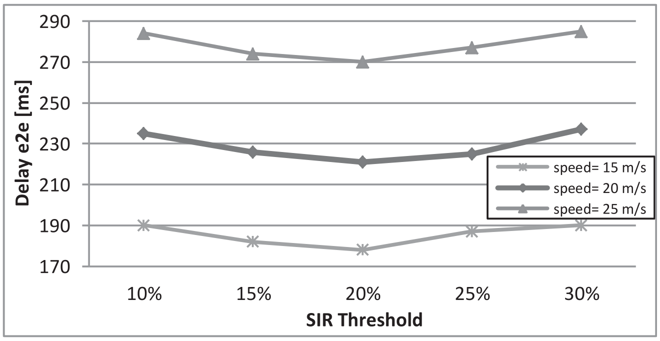

Fig. 12. Delay e2e versus threshold D.

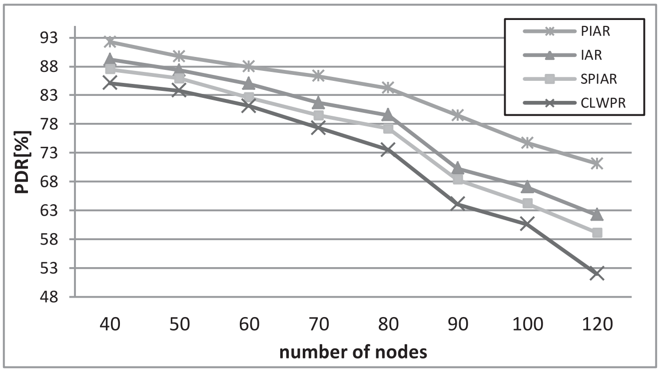

Fig. 13. Network packet delivery ratio for 20 active connections.

values that lead the protocol to obtain the best results, in terms of Packet Delivery Ratio (*PDR*), Throughput, Overhead, etc. Fig. 10 shows that for $N = 25$ and $M = 10$ the best results are obtained in terms of *PDR*. The use of Probes packets for PIAR is of crucial importance for the monitoring of *SIR* values on different paths; the right choice of T_p can improve protocol performance; also in this case, due to space limitations, only the Throughput trend is illustrated in Fig. 11. It can be noticed that for $T_p = 75$ ms the network offers the best performance independently from the number of nodes.

Another parameter that has to be tuned for PIAR is the *SIR* threshold *D*, used to decide if the transmission route has to be updated. The choice of the value of *D* influences the end-to-end (e2e) delay (every time a path is changed an additional amount of time is requested to establish the new route) and the overhead (the updating of a new path triggers new overhead in the network). Also in this case, only one figure is shown, but also for the other results the chosen value of *D* leads to the best performance.

Observing Figs. 10, 11 and 12, it can be concluded that if *D* is set to 0.2 (20 percent of SIR degradation on the path), for different average node velocity, the system performs better in terms of *end to end* delay, *PDR*, Throughput and *SIR* on the link of the followed path. In the next section it will be shown that the additional overhead is acceptable.

5.2 Protocols Performance Evaluation

It is possible to note in Fig. 13 that *PDR* is inversely proportional to the number of nodes of the considered network. The best performing protocol in terms of *PDR* is PIAR because it is able to execute, under a SIR level degradation on the transmission channels used for data forwarding, a strategy to select a novel path with a higher SIR. IAR reaches values lower than PIAR, because it re-computes the overall path when a *SIR* degradation occurs on the transmission channels (it executes just one channel switching on the channel that maximizes the *SIR* value).

The SPIAR protocol, on the other hand, obtains *PDR* values lower than IAR because it does not use a dynamic prediction scheme and it bases its channel switching strategy only on the previous *SIR* values. This approach can lead to some prediction errors. Concerning the CLWPR, it obtains lower performance in comparison with the other protocols because it considers a metric without exploiting the potential of multi-channel MAC for vehicular networks. For

TABLE 2
Values of PDR [%] versus Number of Nodes

N. of nodes	IAR	SPIAR	PIAR	CLWPR
40	89,16	87,5	92,2	85,1
50	87,32	85,9	89,7	83,8
60	84,96	82,6	87,9	81,1
70	81,67	79,5	86,3	77,3
80	79,52	77,2	84,2	73,5
90	70,3	68,3	79,5	64,1
100	67	64,2	74,7	60,6
120	62,2	59,1	71,1	52

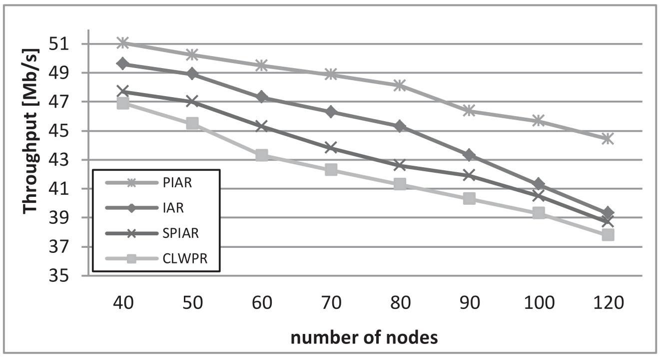

Fig. 14. Network throughput with 20 active connections.

TABLE 3
Values of Network Throughput [Mbit/s] versus Number of Nodes

N. of nodes	IAR	SPIAR	PIAR	CLWPR
40	49,6	47,7	51,05	46,9
50	48,9	47	50,22	45,5
60	47,4	45,3	49,49	43,2
70	46,2	43,8	48,87	42,3
80	45,7	42,6	48,1	41,4
90	43,2	41,9	46,36	40,6
100	41,1	40,5	45,67	39,3
120	39,3	38,7	44,43	37,8

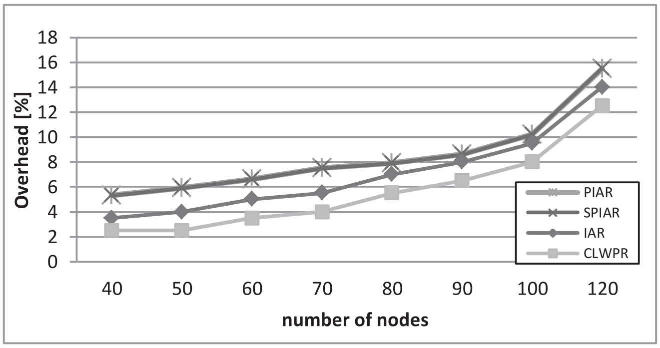

Fig. 15. Network overhead with 20 active connections.

TABLE 4
Values of the Overhead [%] versus Number of Nodes

N. of nodes	IAR	SPIAR	PIAR	CLWPR
40	3,5	5,3	5,3	2,5
50	4	5,9	5,9	2,5
60	5	6,6	6,6	3,5
70	5,5	7,5	7,5	4
80	7	7,9	7,9	5,5
90	8	8,6	8,6	6,5
100	9,5	10,2	10,2	8
120	14	15,5	15,5	12,5

different mobility speed of network nodes (these graphs are not shown for space limitations), the routing protocols obtain similar performance in comparison with the previous simulation scenario.

PIAR protocol performs better than other routing schemes for higher speeds scenario because it is able to better adapt and switch to minimum interference paths. From Fig. 14 it can be noticed that throughput values are higher for PIAR protocol, because it is able to recompute, in a more efficient way, the entire path with higher *SIR* after a SIR level degradation due to nodes mobility.

IAR protocol presents lower *Throughput* values in comparison with PIAR, because it does not re-compute the overall path after a *SIR* level degradation but, instead, makes just a local channel switching to the best channel (in terms of *SIR*) on the nodes belonging to the already used path. The SPIAR protocol, instead, offers lower throughput values than IAR, because it uses a "not dynamic" prediction scheme based just on previously computed *SIR* values and, for this reason, it can commit errors in SIR prediction. With regards to the CLWPR protocol, it continues to present lower performance than other protocols due to the different metric. The throughput presents a decreasing trend for increasing number of nodes. For very high-density network, PIAR protocol presents higher throughout values due to its capacity to select lower interference paths.

As explained previously, simulation campaigns proved that performance evaluation of the considered protocols under increasing mobility speeds presented similar trends in comparison to the shown curves. From Fig. 15, it is possible to note how the control overhead (evaluated as the ratio between signaling transmitted packets and all the packets) is directly proportional to number of network nodes and number of connections (source-destination pairs). PIAR and SPIAR obtain higher control overhead due to the additional signaling packets (such as periodical probes). In this specific case, the two protocols present the same overhead because the same timer for probes forwarding is applied.

However, for the same control overhead, PIAR presents a higher PDR and throughput in comparison with SPIAR. On the contrary, CLWPR protocol presents lower overhead values in comparison with PIAR and IAR, because they do not need to update the state information about interference between neighbor nodes. Moreover, the overhead increases in a constant way for higher network density or higher mobility condition. Also in this case, due to space limitations, the curves are not shown. Observing Fig. 16, it is possible to see how the SIR value related to the transmission channels is inversely proportional to the number of network nodes.

The protocol that presents the best performance is PIAR, which has as its primary purpose the selection of the maximum-SIR path on the available channels for data transmission. The IAR protocol has lower values in comparison with PIAR because, when SIR values of the transmission channels degrades due to mobility, it tries to maximize the SIR

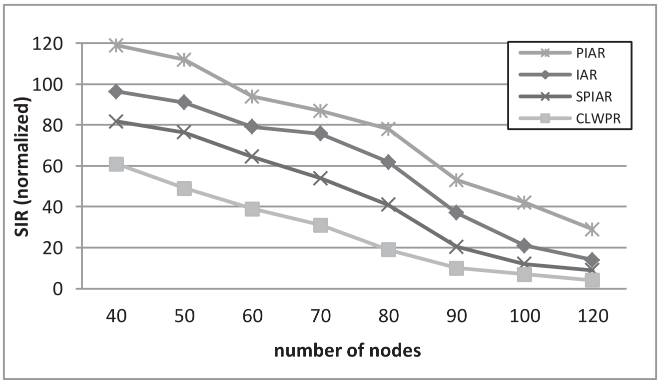

Fig. 16. Average normalized SIR value for 20 active connections.

TABLE 5
Values of Avg. Normalized Sir versus Number of Nodes

N. of nodes	IAR	SPIAR	PIAR	CLWPR
40	96,36	81,68	119,18	61,2
50	91,06	76,38	112,2	49,11
60	79,19	64,42	94,37	39,18
70	75,75	54,12	87,21	31,21
80	61,83	41,5	78,43	19,15
90	37,20	20,44	53,27	10,11
100	21,07	12,19	42,26	7,23
120	14,46	9,14	29,31	4,41

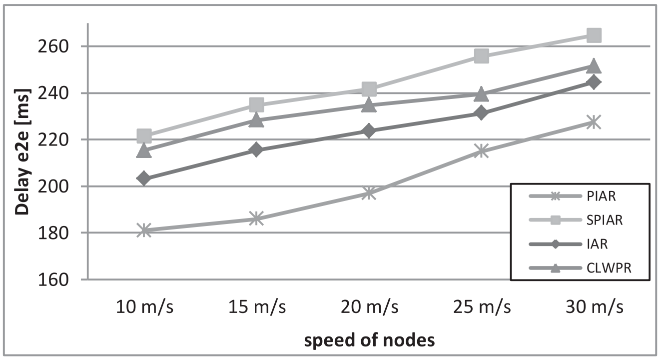

Fig. 17. E2e delay for 20 active connections and 60 mobile nodes.

value, changing the channel (differently, PIAR re-builds the overall path).

TABLE 6
Values of Delay End-to-end versus Number of Nodes

speed of nodes	IAR	SPIAR	PIAR	CLWPR
10 m/s	203,13	221,43	181,19	215,46
15 m/s	215,61	234,67	186,55	228,32
20 m/s	223,59	241,56	196,87	234,67
25 m/s	231,26	255,64	214,89	239,43
30 m/s	244,63	264,65	227,32	251,51

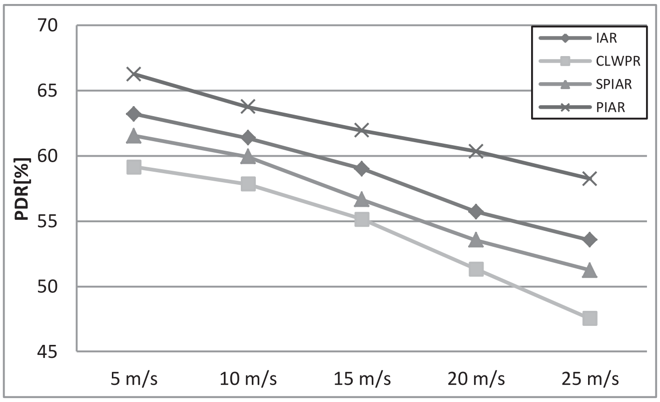

Fig. 18. Network packet delivery ratio versus speed of nodes.

TABLE 7
Values of PDR [%] versus Speed of Nodes

speed of nodes	IAR	SPIAR	PIAR	CLWPR
5 m/s	63,2	61,5	66,23	59,1
10 m/s	61,3	59,9	63,73	57,8
15 m/s	58,9	56,6	61,93	55,2
20 m/s	55,7	53,5	60,33	51,3
25 m/s	53,5	51,2	58,23	47,6

SIR values obtained by the SPIAR protocol are slightly lower than PIAR and IAR values, because the smoothed metric is based only on historical and current SIR values, differently from the PIAR scheme, that is based on RLS algorithm. It is also possible to observe how low dense network interference-aware routing schemes present more visible improvements in terms of SIR on the different channels. This is due to the possibility to better distribute the data traffic on the different channels and on the lower length paths that can be discovered. The CLWPR protocol presents lower SIR values in comparison with other protocols, because it is mainly based on the construction of paths using the position of the nodes and the problem of interference is not crucial in it. In Fig. 17 it is possible to observe how the end-to-end delay is directly proportional to the speed of nodes. Protocols that obtain better results in terms of end-to-end delay are respectively PIAR, IAR and SPIAR because they use a robust metric that minimizes the number of retransmissions that take into account the values of interference due to transmission data. Some reasons for the slightly higher delays of IAR routing schemes are listed below:

- SPIAR protocol presents higher delay because, after a SIR degradation, it applies a procedure to re-compute the overall path from source to destination. This means that he packet forwarding needs longer times;
- PIAR obtains delays slightly lower than SPIAR, because it makes use of a more accurate prediction algorithm;
- IAR obtains delays which are lower than PIAR and SPIAR because it does not use a procedure to re-compute the path, but it makes use of a local channel switching on the nodes where the SIR is degraded.

CLWPR obtains a value that is slightly lower than SPIAR in terms of end-to-end delay because it employs a procedure to build paths considering the location of vehicles.

Regarding Fig. 18, we set the number of nodes to 30 and the transmitting coverage radius to 100 meters, in order to considerate a low density scenario. In this case, it is possible to see how the PDR decreases compared to the previous scenarios (see Fig. 13). By reducing the coverage radius, it is easy to obtain many network disconnections and, consequently, the PDR decreases. Therefore, the PIAR protocol outperforms others routing protocols, reacting better to the rapid changes of the network topology, due to the nature of the VANETs.

6 CONCLUSIONS

In this manuscript, the VANET routing strategies in condition of a multi-channel MAC such as DSRC and IEEE WAVE protocol have been addressed. In particular, in situations where a higher number of vehicles in urban areas needs to communicate in an efficient manner, traditional routing protocol such as minimum hop metric, are not suitable. For this purpose, a novel metric based on the interference levels on the data channels at MAC layer has been described, and this metric has been adopted at routing layers to offer more efficient path discovery procedures. This work proposed novel metrics to account the interference levels of nodes in a condition of multi-channel MAC and reactive routing protocols for MANET. Some routing strategies such as PIAR, SPIAR and IAR with some variants in route maintenance procedures or metric computation have been proposed and evaluated. In particular, PIAR builds minimum interference paths on a hop-by-hop basis through the prediction by a time-series of the *SIR* on the available data channels of each single node. SPIAR protocol applies a *SIR* prediction based on the average SIR value estimated through the smoothed moving average inherited by TCP protocols. IAR protocol does not make use of predictive schemes to compute the *SIR* value, but it uses the instantaneous *SIR* values computed in the previous instant on a hop-by-hop basis. The protocols proposed in this work presented better results in terms of *PDR*, throughput, interference level and end-to-end delay in comparison with the CLWPR protocol. However, interference-aware routing strategies present slightly lower performance in terms of control overhead. This is due to the computation and maintenance of state info associated to the channel interference levels among nodes. The most performing protocol was the PIAR protocol.

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