Mobility Prediction Progressive Routing (MP2R), a Cross-Layer Design for Inter-Vehicle Communication

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SUMMARY In this paper we analyze the characteristics of vehicle mobility and propose a novel Mobility Prediction Progressive Routing (MP2R) protocol for Inter-Vehicle Communication (IVC) that is based on cross-layer design. MP2R utilizes the additional gain provided by the directional antennas to improve link quality and connectivity; interference is reduced by the directional transmission. Each node learns its own position and speed and that of other nodes, and performs position prediction. (i) With the predicted progress and link quality, the forwarding decision of a packet is locally made, just before the packet is actually transmitted. In addition the load at the forwarder is considered in order to avoid congestion. (ii) The predicted geographic direction is used to control the beam of the directional antenna. The proposed MP2R protocol is especially suitable for forwarding burst traffic in highly mobile environments. Simulation results show that MP2R effectively reduces Packet Error Ratio (PER) compared with both topology-based routing (AODV [1], FSR [2]) and normal progressive routing (NADV [18]) in the IVC scenarios.

key words: mobility prediction, position-based routing, cross-layer design, directional antenna, inter-vehicle communication

1. Introduction

Mobile Ad hoc Networks (MANET) consist of mobile nodes cooperating to support multi-hop communications. They are easy to deploy and may be used in many fields such as Inter-Vehicle Communication (IVC). IVC brings about new applications. One is extension of the Internet to the road, letting a vehicle access the Internet through the road-side Access Points (AP). This is characterized by the burst traffic. Another application may be the continuous communication such as Voice over IP (VoIP) between two vehicles moving along the same trace. This may occur in the travel group of cars or the marching troop of tanks. When the distance between a vehicle and an AP, or the distance between two vehicles, is beyond direct access, multi-hop communication is necessary. In this paper the communication with up to 10 wireless hops is considered.

Most of multi-hop routing protocols in MANETs are based on the global topology, where route calculation depends on either proactive topology distribution or on-demand route discovery. Typical proactive routing protocols include distance vector protocols (e.g. DSDV) and link state protocols (e.g. FSR [2], OLSR). AODV [1] and DSR are known as on-demand routing protocols, where a route is discovered when necessary. Some recent protocols also considered link quality in the route calculation, either preferring strong links in the route discovery stage [3]-[5], or making the initial route converge to the local optimum by gradually optimizing the active route [6]. When the topology varies too fast without converging, performance of the topology-based protocols may be greatly degraded.

On the other hand, in geographical routing protocols [8]-[13], with the position of the destination learned in advance [14]-[15], each node can make the forwarding decision locally. The greedy forwarding mode usually selects the longest link towards the destination. As a result, the chosen link may have poor quality, and cause frequent retransmissions and packet loss. This is especially obvious when gray zones [7] come into being in times of fading. Then tradeoff should be made between link quality and progress in selecting the forwarding node [16]-[18].

Some researchers also introduced directional antennas [20]-[21] into MANET to improve Signal to Noise Ratio (SNR) at the receiver and increase system capacity by space-division multiple access. Then one problem is to effectively determine the antenna beam ahead of actual transmission.

In this paper we analyze the characteristics of vehicle mobility and show that neither conventional routing protocols nor directional antenna work well in the IVC scenarios. Then we propose a Mobility-Prediction Progressive Routing (MP2R) protocol. With the cross-layer design, we try to jointly optimize routing, MAC, and beam control of directional antenna based on mobility prediction. In MP2R, the forwarder of a packet is selected according to link quality, load and progress. The local relative mobility is also taken into account to opportunistically salvage a packet. And the actual transmission is directional. Compared with the existing MANET routing protocols, MP2R is more suitable for the highly mobile IVC scenario.

In the rest of the paper section 2 reviews the related work. In section 3 we analyze the special characteristics of the IVC scenario and point out the research
problem. Then in section 4 we present the system architecture and the details of MP2R protocol. Section 5 shows the evaluation results and the performance analysis. Finally section 6 concludes the paper.

2. Related Work

2.1 Link Quality-aware Routing

Toh reported the ABR protocol in [3], where each node learns the associativity of its neighbors by the periodic beacon and utilizes it as the metric in route calculation. In this way a route is discovered, preferring the nodes with less relative mobility. Dube et al. proposed in [4] the SSA protocol, which utilizes the signal stability as the metric in the route discovery and prefers links with high signal strength. Both protocols depend on the whole topology and can not well adapt to fast mobility in the IVC scenarios.

De Couto et al. suggested the Expected Transmission Count (ETX) metric [5], optimizing the routes by reflecting the real cost of each link in the route calculation. However, it usually takes much time for ETX to converge, which limits its application in the mobile scenarios. In [6], the link metric is inversely associated with Received Signal Strength Indication (RSSI). A route is maintained by the local route update scheme. It tracks link quality and topology variations in the presence of low/moderate mobility.

2.2 Position-based Routing

Ko et al. proposed the LAR protocol [8] for the efficient route discovery, where the route request is only flooded in the specific zone estimated by the position and moving speed of the destination. A typical geographical routing protocol (GFG [9], GPSR [10]) utilizes the position information to forward data packets instead. When a packet is ready, a node chooses in a greedy way from its neighbors as the forwarder the one that is closest to the destination. This greedy forwarding mode may fail in the presence of local void areas. Then the packet enters the perimeter mode and is forwarded by the right-hand rule in the planar graph [10]. Blazevic et al. proposed a more efficient scheme for routing around the void area in a large network, where packets are forwarded along a rough geographical path specified by the anchors [13]. When a packet gets within two hops of the destination, its forwarding falls back on the local link-state in order to compensate for the position inaccuracy.

The main demerit of position-based routing is neglect of link quality. The greedy forwarding mode tends to result in transmission over long links with poor quality. To solve this problem, Lee et al. proposed the Normalized ADVance (NADV) [18] metric, a combination of the link quality aware routing and the geographical routing. The link quality is reflected in the link cost, which focused on Packet Error Ratio (PER). The greedy forwarding rule is embodied in the progress. Then the tradeoff is done by maximizing the progress normalized by 1-PER. NADV is mainly proposed for dense networks where the nodes move at moderate speeds and the greedy forwarding seldom fails. Similar to most of the local routing schemes, congestion may occur at a node when many packets go through it.

2.3 Utilization of Directional Antenna

Utilization of a switch-beam antenna usually consists of two steps. (i) Determining the beam forming direction to each neighbor. Bandyopadhyay et al. suggested building the Angle SNR Table (AST) for the Electronically Steerable Parasitic Array Radiator (ESPAR) antenna [21]. In AST scheme each node periodically scans its neighbors as follows: An initiator broadcasts a SETUP frame by the omni-beam if the carrier is sensed idle; this frame reserves the channel. Then the initiator broadcasts REQUEST frames with each sector beam respectively, carrying the corresponding beam number. Finally the initiator transmits an END frame by the omni-beam, releasing the channel. Then the neighbors of the initiator send back unicast REPLY frames indicating the heard beam numbers and the associated RSSI, based on which the initiator learns the best transmission beam. (ii) Transmitting a data frame with a suitable sector beam. If a valid cache of the direction to the peer node is found from the AST table, the DATA (or RTS) frame is transmitted with the cached sector beam; otherwise the omni-beam is used instead. The ACK (or CTS) frame is transmitted with the omni-beam. The antenna is immediately returned to omni-beam mode for the following reception or carrier sense once the transmission is finished. The reception is always under the omni-beam mode.

Several problems exist in the AST scheme: (1) The overhead makes it not scalable to node density since each node periodically performs beam scanning, which involves a sequence of frame transmission at a relatively low rate (one of the basic rates). (2) The instantaneous unstable RSSI due to fading degrades the beam stability. (3) The topology variation under high mobility invalidates the cached beam-forming direction quickly.

2.4 Our MP2R Scheme

Compared with most of the link quality aware routing protocols (ABR [3], SSA [4], ETX [5], LHAOR [6]), MP2R takes the special characteristics of IVC into account, where the forwarder selection is based on the local topology and adapts better to relative mobility. MP2R reflects link quality in the forwarder selection, distinct from the position-based routing protocols (LAR [8], GFG [9], GPSR [10]). Mobility pre-
diction is adopted in MP2R to mitigate the position inaccuracy, in contrast with the mixed routing scheme in TRR/TLR [13]. The progressive routing policy in MP2R is partially similar to NADV [18] with several significant distinctions: (1) MP2R utilizes directional antenna and calculates antenna beam by the position information. (2) MP2R benefits from the relative mobility. When an intermediate node finds no forwarders for a packet, it holds the packet and opportunistically forwards it later if a passing node comes near soon and reestablishes the connectivity. (3) The forwarding decision of a packet in MP2R is made just before the packet is to be actually transmitted so as to reflect the potential topology variation during its stay in the queue. (4) The load at the forwarding node is also considered in MP2R to distribute potential heavy traffic over multiple forwarders.

3. Characteristics of an IVC Scenario

In this section we analyze the characteristics of the IVC scenarios and define the research problem. An IVC scenario is quite different from a general ad hoc network. It mainly consists of three components: the roads, the intersections connecting roads, and the Mobile Nodes (MN). A road is usually bidirectional. MNs may run on either side of a road and MNs on the opposite sides move in the reverse directions. An MN may change its lane when overtaking others. Generally an MN only changes its moving direction at an intersection, where it may be temporarily stopped by the signal.

3.1 Characteristics of Vehicle Communication

Specifically, an IVC scenario has its special characteristics as follows.

**Propagation model.** Since the obstructions seldom exist on the road and the Line-of-Sight (LOS) path usually exists, the radio signal generally propagates in terms of the two-ray model, which depends on the distance between two MNs. The LOS propagation means that the transmission direction to a neighbor matches the geographic direction.

**Regular speed.** Each MN in its normal state almost runs at a constant speed on a lane with a relatively stable direction. Therefore the position of an MN in the near future is predictable.

**Node density.** To guarantee the safety, vehicles moving on the same lane should be separated far enough so that an urgent brake will not make them collide with each other. Then among the MNs along the same direction sometimes only few nodes are within the communication range. To improving the connectivity MNs in the opposite direction can be used. Meanwhile the directional antenna can also be applied. It increases the connectivity and reduces interferences by the directional transmission.

**Topology and route variation.** Several reasons result in quick topology variations. Firstly, among the MNs in the same direction an MN may overtake the others and the high relative speed between two MNs in the reverse directions results in short-term links which break soon. The transmission direction changes greatly when two MNs cross each other, which makes it difficult to control the antenna beam. Secondly, the forwarding path tends to vary greatly near an intersection. When a group of MNs gets near to the intersection they may decrease the speeds. Their distance gets short and the route shortens. The route stretches again as the group of MNs leaves the intersection. Sometimes a sudden change of the signal at an intersection may even split a group of MNs into two disconnected parts.

**Potential variation of routes.** A packet may wait in the queue due to congestion or in the presence of burst traffic. In the highly mobile environment, as the packet is actually transmitted the best route may already changed and differ from the one that was decided when the packet entered the queue.

3.2 Problem Definition

Figure 1 shows a typical IVC scenario where each MN is equipped with a directional antenna. MNs S, E, D moves in the same direction and S is communicating with D. If there is an MN at P1, S can use it to forward packets to E, which further forwards to D. When this MN does not exist, the route may temporarily breaks. Instead S may opportunistically use the passing MN B as the instantaneous forwarder. Then two problems occur: (1) How does S detect the link to B quickly at the high relative speed? (2) How does B control its antenna beam to E? When B moves from P3 to P1 and E moves from P1 to P2, the transmission direction from B to E changes over 90 degree.

The special characteristics of the IVC scenario require a new routing protocol to forward packets under the high mobility and an efficient beam control scheme for the directional antenna. With the cross-layer design and mobility prediction, all MNs, including those with a high relative speed in the opposite direction, are used to forward packets. The forwarding decision made at the time a packet is to be actually transmitted further avoids the potential route variation when the packet stays in the queue. And the position-based beam control scheme effectively controls the directional antenna.
4. System Architecture and Protocol Description

We assume that each MN is equipped with a single wireless LAN card, a switch beam antenna and a GPS (Global Positioning System) / INS (Inertial Navigation System) module. Each MN builds a Position Table (PT) storing the position of all MNs and a Neighbor Table (NT) recording the link quality to and the load at a neighbor. The outgoing packets wait in the output queue. When a packet is dequeued, the accurate forwarding decision is made based on the predicted progress and the associated link cost. In case no forwarder is found, this packet is temporarily held in the queue if an MN is predicted to come near and re-establish the connectivity within a short time.

Figure 2 shows the framework of the cross-layer design inside a single MN. In the following sections we will address it in detail.

4.1 Information Collection and Sharing

As shown in Figure 2 three kinds of information are used in the system: (i) position (including speed and moving direction), (ii) link quality (RSSI), (iii) load associated with the output queue of the wireless interface. Each MN collects information as follows: ① obtains its own position information by the GPS/INS module and synchronizes itself with Universal Time Coordinated (UTC) clock; ② detects RSSI of a link when receiving a packet over it; ③ treats the queue length as the load; ④ learns the position of all MNs and load at its neighbors by the newly defined Information Distribution Message (IDM).

The collected information is managed by a PT table and a NT table, where each position entry consists of ID, \( t_ID \), \( <x_{1t}^{ID}, y_{1t}^{ID}> \), \( V_{1t}^{ID} \), \( \alpha_{1t}^{ID} \), and each neighbor entry consists of ID, RSSI_ID, load_ID. The meanings of these fields are explained below.

\( ID \) unique identifier of a MN.

\( t_ID \) timestamp of a position entry.

\( <x_{1t}^{ID}, y_{1t}^{ID}> \) position of a MN at time \( t \).

\( V_{1t}^{ID} \) speed of a MN at time \( t \).

\( \alpha_{1t}^{ID} \) moving direction of a MN at time \( t \).

\( RSSI_ID \) signal strength of the link to a neighbor MN.

\( load_ID \) queue length of the wireless interface.

The PT table is accompanied by the position prediction module. In step ⑤ link quality, load and the predicted positions of MNs are used in route calculation; in step ⑧ antenna beam is calculated from the predicted position.

The IDM message is defined as a UDP packet, as shown in Figure 3. It consists of four fields with the first field being the normal IP and UDP header. By the specific UDP port an IDM message can be distinguished from other types of messages. The following three fields of IDM are encapsulated in the payload part. The second field contains the load and position entry of the sender. The third field contains the position entries in the PT table with a distance less than \( th\text{\_distribute} \). The fourth field is optional and it contains the position entries with a distance greater than \( th\text{\_distribute} \). The position distribution is like the fish-eye link state distribution in [2]. An IDM is transmitted at a regular interval \( t_{IDM} \). However the fourth field is only contained every \( N \) intervals (\( N \ast t_{IDM} \)) to reduce the overhead. An IDM message is exchanged between adjacent MNs and is never forwarded. When an MN receives an IDM message, it detects the instantaneous RSSI to the sender and records it in the NT table together with the load of the sender. Then it updates the position entry of the sender. For each of the following position entries in the IDM message, its timestamp also acts as the sequence number. Only the entries with a fresh timestamp are processed and used to update the corresponding entries in the PT table.

4.2 Mobility Prediction

For each of the position entry in the PT table, its instantaneous position is predicted. Assume an MN A's position information at time \( t_1 \), \( <x_{11}^{A}, y_{11}^{A}> \), \( V_{11}^{A} \), \( \alpha_{11}^{A} \) is already known. Its position at time \( t \), the immediate future, is calculated as follows.

\[
x_{1t}^{A} = x_{11}^{A} + V_{11}^{A} \cos(\alpha_{11}^{A})(t - t_1)
\]

\[
y_{1t}^{A} = y_{11}^{A} + V_{11}^{A} \sin(\alpha_{11}^{A})(t - t_1)
\] (1)

In MP2R the predicted position is utilized in two aspects: (i) for progress calculation in the forwarding de-

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**Fig. 2** Packet forwarding framework.

**Fig. 3** IDM message format.

- IP & UDP header
- self load & self position
- position entries of near nodes
- position entries of far nodes

- necessary
- optional
cission, (ii) for antenna beam control. Mobility prediction is effective only when MNs move at nearly constant speeds in the fixed direction. This is not always true in the IVC scenarios. Then prediction errors occur. When the distance between two nodes are far enough, the prediction error is relatively small and seldom affects the forwarding decision and the antenna beam. Big errors may occur when two MNs cross each other at high speeds with big accelerations. However, at such situations the distance between two MNs is short, which makes them less preferred by each other in forwarding packets.

4.3 Packet Forwarding Decision

When a packet is to be actually transmitted, the routing module performs the following procedure to find the best forwarder at that time.

4.3.1 Find the Candidate Forwarders

From the PT table the position of the destination is found, with which the neighbors in the direction of the destination are obtained and their progresses towards the destination are calculated. These neighbors compose a candidate list. When the destination is also a neighbor with a distance \( d_{\text{dist}} \), only the neighbors with a distance no longer than \( d_{\text{dist}} \) are considered.

4.3.2 Link Cost Estimation

RSSI to a neighbor is a rough estimation of the link quality and it is detected every time a packet is received from a peer MN. Instantaneous RSSI may vary with time due to fading. Therefore we choose to use the expectation of the instantaneous RSSI. Consider RSSI between two MNs \( A \) and \( B \). Ignoring small-scale fading, their RSSI can be expressed as \( P(d) = k_1 - k_2 \cdot \log(d) \) where \( d \) is the predicted distance between \( A \) and \( B \), \( k_1 \) follows the Gaussian distribution to allow for the shadowing effect due to obstruction, and \( k_2 \) is the path loss factor. When \( d \) varies within \([d/\varepsilon, d \cdot \varepsilon]\) (\( \varepsilon > 1 \)) RSSI falls into \([P(d) - k_2 \cdot \log(\varepsilon), P(d) + k_2 \cdot \log(\varepsilon)]\). In this distance range RSSI almost has the same expectation value as \( \varepsilon \) approaches 1. Then all instantaneous RSSI with its distance falling in the range \([d/\varepsilon, d \cdot \varepsilon]\) can be averaged to calculate the RSSI expectation. The distance range varies as \( d \) does and RSSI expectation is made adaptive to mobility.

The average transmission count [5] reflects the actual cost of a link. We measured the relation between link cost and RSSI. The result is shown in Figure 4. On this basis the link cost is directly calculated from the RSSI expectation and does not require the long convergence time.

4.3.3 Forwarder Selection

If the candidate forwarder list is not empty, for each of the candidate \( k \) in the list, its metric \( \text{metric}_k \) is calculated from its link cost \( \text{cost}_k \), its progress \( \text{prog}_k \), and its load \( \text{load}_k \) as shown in Figure 5. When a candidate MN is exactly the destination, its load has no effect on this packet and the metric is the ratio of link cost to progress. When a candidate MN is not the destination, it has to further forward the packet after transmitting all waiting packets in the queue. Therefore its load is involved in the forwarding decision, which plays a load-balance role to alleviate the congestion. Finally the MN with the least metric is selected from the candidate list as the forwarder.

If the candidate list is empty, the network is temporarily partitioned and the progressive forwarding fails. Instead of face routing [10] where the packets goes back in the IVC scenarios, we suggest the opportunistic forwarding policy benefiting from the mobility. If another MN is predicted to come within the communication range in a short time \( t_{\text{wait}} \), the packet is held in the queue and a timer is set to this waiting time, after which this packet is supposed to be forwarded. However, if \( t_{\text{wait}} \) is too long, exceeding the predefined time limit \( t_{\text{wait}} \), this packet will be dropped silently.

4.4 Delayed Forwarding Decision

In general the routing protocol determines the next hop node for an outgoing packet and puts it in the output queue, from which the MAC module will get the packet and transmit it later. As we have analyzed in section 3, the packets may have to wait in the queue when congestion occurs or in times of burst traffic. During the waiting period the topology may have already changed. To exploit the instantaneous topology, in MP2R an out-

![Fig. 4](image-url) Relation between link cost and RSSI.

```latex
\text{if the candidate MN } k \text{ is the destination}
\quad \text{metric}_k = \text{cost}_k / \text{prog}_k
\text{else}
\quad \text{metric}_k = (\text{cost}_k + \alpha \cdot \text{load}_k) / \text{prog}_k
```

![Fig. 5](image-url) Metric calculation.
4.5 Position-based Beam Control

Figure 6 shows the position variations of two MNs A and B. Both A and B know A’s position \((x_1^A, y_1^A)\), speed \(V_1^A\) and moving direction \(α_{11}^A\) at \(t_1\), and B’s position \((x_2^B, y_2^B)\), speed \(V_2^B\) and moving direction \(α_{12}^B\) at \(t_2\). Then A estimates their positions \((x_1^A, y_1^A)\), \((x_2^B, y_2^B)\) at a near future time \(t\) by Eq. 1. With the instantaneous positions, the geographic direction from A to B, \(θ_{1→B}^A\), is calculated according to Eq. 2.

\[
θ_{1→B}^A = \tan^{-1}\left(\frac{y_1^B - y_1^A}{x_1^B - x_1^A}\right) \tag{2}
\]

\[
θ_{1→B}^A = \text{mod}(θ_{1→B}^A - α_{11}^A, 360°) \tag{3}
\]

Assume the directional antenna is fixed on an MN and its first beam matches the moving direction. As A changes its moving direction \(α_{11}^A\), the reference direction of the beams is also changed. Subtracting \(α_{11}^A\) from \(θ_{1→B}^A\) in Eq. 3 leads to the correct beam direction for the antenna. This Position-based Beam Control (PBC) procedure is done for each unicast outgoing frame (step 8 in Figure 2).

5. Evaluation and Analysis

In this part we first confirm the effectiveness of the PBC scheme. Then we evaluate the routing performance of MP2R with the IVC scenarios.

5.1 Testbed Evaluation of the PBC Scheme

In our testbed the ESPAR antenna [21] is used. Each ESPAR antenna has 12 equally spaced beams and is mounted on top of a car. The extra gain of a sector beam compared with the omni-directional beam is about 6dB. The 3dB beam bandwidth is about 90°.

Figure 7 shows the experiment layout. Three cars, 2, 3 and 4, are stationary, spaced in a line. The source MN 1 moves along the line at the speed 1m/s and communicates with the destination MN 2. In the experiment, instead of MP2R the route is directly calculated from the positions. At first MN 1 communicates directly with MN 2. When MN 1 passes MN 3, it uses MN 3 as the forwarder and the route becomes 1-3-2. The final route is 1-4-3-2 when MN 1 passes MN 4.

The whole process takes about 300s. Figure 8 is the instantaneous beam direction from MN 1 to MN 3. From 100s to 120s MN 1 passes MN 3, during which the antenna beam variation is nearly 180°. Antenna direction of the PBC scheme changes very smoothly, as was expected. In contrast, antenna direction of the AST scheme varies frequently. The AST track at a single node can be finished within about 20ms. Therefore its latency has little effect on antenna directions in the experiment since only MN1 moves and the speed is relatively low (1m/s). On the other hand, the AST module in each MN updates the antenna directions to its neighbors every 1s. Due to multi-path fading, the direction with the maximum RSSI varies each time. As a result, beam stability of the AST scheme is degraded. It results in high packet loss, as reflected by PER in Figure 9.

As MN 1 moves the route stretches and PER in Figure 9 gradually increases. The PBC scheme experiences burst errors at 90s due to deep fading between MN 1 and MN 2. At 250s MN 1 goes around the curved road and some obstruction exists between MN 1 and MN 3. As a result, the LOS path has a weak RSSI and causes burst error. In MP2R these weak links are less preferred by involving the actual RSSI in the forwarder selection. In consequence the burst PER can be
5.2 Evaluation of Routing Performance

5.2.1 Simulation Setup

The simulation is done with network simulator QualNet [22]. IEEE 802.11 distributed coordination function (DCF) [23] is used as the MAC protocol. The erroneous wireless channel is emulated according to IEEE 802.11b specification. The detailed simulation conditions are listed in Table 1.

Table 1 Simulation conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position distribution</td>
<td>$d_{\text{distribute}} = 500, \text{m}$, $N=3$, $t_{\text{IDM}} = 1, \text{s}$</td>
</tr>
<tr>
<td>Opportunistic wait</td>
<td>$t_{\text{wait}} = 1, \text{s}$</td>
</tr>
<tr>
<td>CBR flow</td>
<td>interval $= 0.1, \text{s}$, size $= 512, \text{Byte}$</td>
</tr>
<tr>
<td>MAC rate</td>
<td>constant, 2Mbps</td>
</tr>
<tr>
<td>Path loss</td>
<td>communication range $= 220, \text{m}$</td>
</tr>
<tr>
<td>Shadowing</td>
<td>average $= 2, \text{dB}$</td>
</tr>
<tr>
<td>Rician fading</td>
<td>fading parameter $= 2.0$</td>
</tr>
</tbody>
</table>

In the evaluation we mainly use two metrics: PER and Packet Transmission Count (PTC). All nonduplicate packets arriving at the destination, whether in order or not, are regarded as successful receptions. PTC is defined as the sum of the transmission count of a packet over all links from the source to the destination. The results of 10 runs with different random seeds are averaged.

In the simulation, we compare four routing protocols, AODV [1], FSR [2], NADV [18] and MP2R. The same position distribution is adopted in NADV and MP2R. AODV is enhanced with the local update function [6]. In AODV and FSR, RSSI in Figure 4 is divided into non-overlapped ranges, each mapping to one metric corresponding to the typical cost in that range, as shown in Figure 10. Then the link cost is calculated from RSSI.

Figure 11 is a simple IVC topology. Altogether there are 30 MNs divided into two groups. The communication group consists of 6 MNs ($S, A, B, C, E, D$) moving along the same trace. The rest 24 MNs ($F$ etc.) form the background group of traffic. A CBR flow is established from $S$ to $D$ and the normal forwarding path is $S$-$A$-$B$-$C$-$E$-$D$. However, due to the long distances of $A$-$B$ and $C$-$E$, their RSSI is weak and the two links are the bottlenecks of the route. Without extra MNs the route from $S$ to $D$ has a low performance.

By mobility prediction $A$ learns when a passing MN $F$ lies between $A$ and $B$. Then $A$ may opportunistically use $F$ as its forwarder. The absolute speeds of the communication group (Comm.) and the background group (Bg.) and their relative speeds (Rel.) are listed in Table 2. The minus speed means that the communication group is moving in the reverse direction as the background group.

5.2.2 Effect of Mobility Prediction

Figure 12 shows the PER under different relative speeds. The performance difference among the four protocols is very obvious, especially at high speeds. AODV and FSR have high PER because they rely on a relatively stable topology and can hardly utilize the passing MNs. At high speeds sometimes they suffer when a passing MN on the active route leaves quickly and results in route breaks. The superiority of MP2R over NADV is obvious when the relative speed is high, reflecting the effect of mobility prediction.

In Figure 13 MP2R has very low PTC compared with AODV/FSR. It also has obvious superiority over NADV at moderate or high speeds since it can effectively avoid the misuse of weak links and opportunistically forward packet.

In the following we give an explanation for the performance degradation in NADV and stress the distinction between NADV and MP2R. Two factors may af-
flect the performance of the progressive routing protocols. (i) The accuracy of progress and link cost under the mobile environment. The obsolete position may be used in NADV while in MP2R the local topology is predicted and the calculation of RSSI expectation depends on the predicted distance. As a result the progress and link cost in MP2R are more accurate. (ii) The potential topology variation and the routing timing. In Figure 11 assume $F$ receives a packet from $A$ at $P_1$, chooses $B$ as the next forwarder and puts the packet in its queue. There are two typical cases for the topology variations. In the first case $F$ moves in the same direction as $A$. At a faster speed $F$ overtakes $B$ and $C$ and arrives at $P_2$ quickly. In MP2R at $P_2$ the packet is sent to $E$, an MN nearer to $D$, or it may even be directly sent to $D$ if the distance of $F-D$ is short enough. In consequence MP2R can benefit from the mobility to opportunistically reduce the transmission count. In NADV this packet is still forwarded to $B$, as is predetermined. In the second case $F$ moves in the reverse direction as $A$. $F$ may forward the packet to $B$ immediately if it has no waiting packets in the queue. Otherwise $F$ takes the packet away from $B$ and transmits it later at $P_3$, where the link $F-B$ may have poor quality due to the increased distance. In MP2R $F$ chooses a suitable forwarder according to the mobility prediction just before transmitting the packet, taking the topology variation into account, while in NADV the link $F-B$ is insisted, which may cause extra retransmissions or even packet drop.

To see the effect of mobility prediction and opportunistic forwarding more clearly under the mobile environment, we simulate the burst traffic with the topology shown in Figure 11. The burst traffic is a modification of the CBR traffic. Define $N$ as the burst length. Then each time $N$ packets are generated and over a long term a burst flow transmits the same number of packets as a CBR flow does. These packets stay in the output queue and wait for their turn. Figure 14 shows the PER under different burst length $N$. PER increases as $N$ does. When the relative speed is 20m/s, PER of NADV is nearly twice of MP2R. As the relative speed increases to 40m/s, PER of MP2R only increases a little while PER of NADV nearly doubles, even at the moderate burst length. It infers that the potential congestion also adds to the performance degradation of NADV. In times of burst traffic packets accumulate in the queue. In NADV forwarders are selected regardless of its load. When a single forwarder is insisted, congestion may occur and increase the average waiting time, during which the topology may vary greatly. In MP2R packets are distributed over different forwarders as packets begin to accumulate, which reduces the average waiting time.

5.2.3 Effect of Antenna Control

In the evaluation of antenna beam control, the topology in Figure 11 and CBR flow in Table 1 are used. Figure 15 shows PER of MP2R with an omni-directional antenna, a switch-beam antenna at the AST mode (MP2R-AST), and a switch-beam antenna at the PBC mode (MP2R-PBC). At the AST mode each MN refreshes the beam every 4 seconds. It is a little strange that utilization of the directional antenna in the AST mode actually have lower performance than the omnidi-
rectional antenna, even when the relative speed is very low. The factors that degrade performance are mainly overhead and inadaptability to mobility. The high overhead makes frequent beam scanning impossible. Even at a moderate period, 4s, the overhead degrades the routing performance greatly. In addition, the cached beams in the AST mode become invalid quickly at a high relative speed. In the PBC mode, the estimation of beam control based on the predicted position removes this overhead meanwhile the exact beam control reduces PER over each link. As a result the end-to-end PER is also reduced.

Figure 16 shows the PTC of MP2R and MP2R-PBC. PTC of MP2R-AST is always over 40 and is not drawn in the Figure. The forward path is almost the same in either antenna mode. However the directional antenna can provide extra gain to improve the link quality. Therefore MP2R-PBC has fewer retransmissions over each link and thus a lower PTC compared with MP2R.

5.2.4 Delay and Jitter

With the topology in Figure 11 and CBR flow in Table 1, the end-to-end delay and delay jitter are evaluated. Figure 17 shows the end-to-end delay under different relative speeds. MP2R-PBC always has a lower delay than MP2R, revealing the effectiveness of the PBC scheme in antenna beam control. Its delay is larger than that of NADV at low speeds due to the following fact: a packet is dropped in NADV by an intermediate MN when its retransmission limit is reached, and dropped packets are not included in delay calculation; while in MP2R and MP2R-PBC packets are salvaged by adjusting the forwarders according to the instantaneous topology. When these salvaged packets arrive at the destination, they are involved in the delay calculation and contribute to a larger delay. However, at the high speeds MP2R-PBC still has the lowest delay by reducing the number of retransmissions over all the links, as revealed by PTC in Figure 13 and Figure 16.

Figure 18 reflects that MP2R-PBC always has the lowest delay jitter, and MP2R has a similar performance. Here jitter is mainly affected by two factors: PER and delay. Though NADV has a relatively low delay in Figure 17, its frequent packet loss results in gaps between packet arrivals at the destination. In consequence it has a much bigger delay jitter than that of MP2R and MP2R-PBC.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection</td>
<td>30s pass duration / 30s stop duration</td>
</tr>
<tr>
<td>Road width</td>
<td>16m / two parallel lanes in each side</td>
</tr>
<tr>
<td>Road length</td>
<td>1000m</td>
</tr>
<tr>
<td>Group MNs</td>
<td>10 nodes, average speed=10m/s</td>
</tr>
<tr>
<td>Background MNs</td>
<td>40 nodes, average speed is in [7.5, 12.5]</td>
</tr>
</tbody>
</table>

5.3 A More Realistic IVC Scenario

5.3.1 Design of the Realistic IVC Scenarios

Next we consider a more realistic IVC scenario, which follows Japan traffic rule. It consists of MNs, roads and intersections, as shown in Figure 19. A group of 10 MNs (1-10) move along the same trace with an average speed of 10m/s. The rest of 40 MNs (11-50) are the background traffic and move along random traces with a randomly chosen average speed falling in [7.5, 12.5] m/s. Each side of the road has two lanes. On the same lane, when the distance between two adjacent nodes gets very short, the node behind may randomly choose either to overtake the ahead node or reduce its own speed to keep the safe distance. Each intersection independently controls its signal. Both the pass duration and stop duration are 30s. A node at an intersection facing the red signal has to wait until the signal becomes green. Some of the parameters of the scenario are listed in Table 3.

A CBR flow is established from MN 1 to MN 10. Figure 19 shows an instance of the topology at 312s, where MN 1 is moving upwards, followed by MNs 2, 3, 4, 5. MNs 6-9 are waiting at an intersection, while MN 10 is approaching it. The group is split into two disjoint parts. Fortunately two passing MNs, 27 and 45, approach the same intersection in the reverse direction and provide temporary connectivity.

5.3.2 Time-Series PER

Figure 20 shows part of the time-series PER of AODV, FSR, NADV, MP2R and MP2R-PBC, where the group of MNs is around the intersection marked in Figure 19. AODV and FSR, the topology based routing protocols, have relatively high PER. NADV and MP2R have lower PER by the local forwarding decision. MP2R further reduces the PER by always relying on the fresh local topology. The differences in PER are especially obvious around 295s and 330s, where the route break occurs. The extra antenna gain in MP2R-PBC improves link quality. Therefore PER in MP2R-PBC is almost zero when the group is not separated by an intersection. Near the intersection the long transmission distance of the directional antenna extends the link lifetime and reduces the duration when no valid route exists.

5.3.3 Average Performance

The average performance is listed in Table 4. It is obvious that AODV/FSR is not suitable for the IVC scenario with high mobility. Compared with NADV which has a PER of 11.73%, MP2R has a PER of 9.61% with an obvious superiority. Its PER is further reduced to 7.19% by MP2R-PBC. It should be noted that most of the packet loss in NADV and MP2R (MP2R-PBC) occurs when the communication group is partitioned around the intersections. If we focus on the first 200s, where such cases do not happen, then NADV has a PER of 2.23%, MP2R has a PER of 0.76% while MP2R-PBC has a PER of 0.21%. The PER is low enough to support real time applications such as VoIP. If some infrastructures are to be installed near the intersections to improve the connectivity, the total PER can be reduced too.

6. Conclusion

We have analyzed the characteristics of Inter-Vehicle Communication and proposed the Mobility Prediction Progressive Routing (MP2R) protocol for it. MP2R makes use of the relative mobility of the nodes to increase the connectivity. It makes forwarding decision for each packet based on the predicted progress, link quality and load at the time when the packet is to be transmitted over the channel. The simulation results show that at high mobility the frequent topology variations greatly degrade the performance of both the topology based routing protocols (AODV, FSR) and the normal progressive routing protocol NADV. In comparison, MP2R adapts well to high mobility and retains low PER. Especially, MP2R with the directional an-
tenna exhibits very obvious superiority over other protocols in the IVC scenarios.

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References


Fig. 19 A general IVC scenario (coordinate unit: meter).
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