

On Power-Aware Greedy Forwarding in Highway Scenarios

Andreas Festag¹, Roberto Baldessari², Hao Wang¹

¹ NEC Deutschland GmbH, festag@netlab.nec.de

² NEC Europe Ltd., Network Laboratories, Germany, baldessari@netlab.nec.de

Abstract—Position-based routing (PBR) provides efficient and scalable routing in ad hoc networks with frequent topology changes and is a strong candidate for vehicular ad hoc networks (VANETs). Like all other routing protocols, simple PBR does not specify a value of power for transmission to the next hop and most commonly a high value is chosen in order to assure correct reception, which results in unnecessary harmful interference to other nodes. Based on a model for wireless communication, we designed a cross-layer approach combining routing scheme and transmit power control, called power-aware PBR for VANETs, that improves overall sharing of bandwidth. We implemented the scheme in a software prototype, set up an experimental testbed and conducted experiments with vehicles on German highways. By comparison with simple PBR, we conclude that power-aware PBR achieves considerable saving of power without impairing the probability of reception.¹

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are a specific type of self-organizing mobile ad hoc networks. VANETs applications are road safety, road traffic efficiency, and infotainment. VANETs provide communication among nearby vehicles and roadside access points by means of wireless multi-hop communication. The availability of short-range wireless technology IEEE 802.11, GPS positioning system, and almost unlimited energy resources of vehicles have led to the development of *position-based-forwarding* [1] and its application to vehicular environments (e.g. [2], [3]).

Position-based routing (PBR) assumes that (i) every node is aware of its own geographical position using GPS, and (ii) every node knows the position of its neighbors, which is obtained by means of *beacon*

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messages that are periodically broadcasted by each node. Before two nodes can communicate, the source node determines the current position of the destination node. This is accomplished by a location service, which maps an arbitrary node identifier to its current position if multi-hop connectivity to the node exists. The main principle of PBR is as follows (Fig. 1): On reception of a data packet that needs to be forwarded, the node calculates the distance between all neighbors and the destination and determines which neighbors are geometrically closer to the destination. This algorithm is commonly known as *greedy forwarding*. The *most-forward within radius* policy [4] selects the node with the minimum remaining distance to the destination’s position. Transmission to the selected next hop, irrespectively of its position, occurs with a predefined power level, which is commonly chosen as high as possible in order to assure optimal reception.

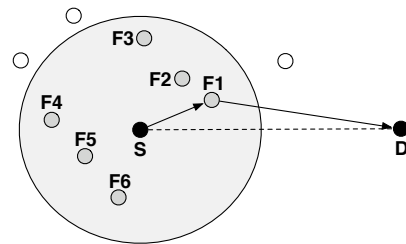


Fig. 1. Principle of greedy forwarding: Source node S selects neighbor node F1 as next forwarder towards destination D.

VANETs have scarce resources in terms of bandwidth which is shared among potentially many vehicles. Transmit power control, well-known from cellular networks, is a technique to better exploit the resources in wireless environments by increasing the spectral re-use of channels. In contrast with cellular networks, VANET do not have a centralized control, links are semi-duplex, data are sent on shared channels (single or multiple in parallel), and nodes contend for channel access. These aspects do not allow to reuse traditional transmit power control algorithms.

This paper presents an improvement of PBR for unicast communication that utilizes transmit power-control on a per-packet basis. The so called 'power-aware' greedy routing reduces the harmful interference to other nodes, the spatial coverage achieved by data packets and, hence, the occupied bandwidth. As a result, the overall available bandwidth increases. Previously proposed power control approaches target connectivity ('topology control'), network capacity, and energy efficiency [4], [5], [6], [7], [8]. However, these approaches do not address VANET-specific requirements, in particular high nodes velocity and frequent topology changes. Recently, power control has been investigated in VANETs in order to control wireless bandwidth and prevent channel overload [9], [10]. Their algorithm is designed for 1-hop broadcast. Therefore it is complementary to our approach for unicast traffic, which is particularly important because our target is a deployable solution.

The remaining sections are organized as follows: Sec. II describes the channel model and protocol assumptions of power-aware PBR. Sec. IV presents the protocol design. Sec.V analyzes the results of an experimental evaluation in a real testbed. Sec. VI summarizes and concludes the paper.

II. WIRELESS COMMUNICATION MODEL

The combined transmit power control and routing scheme proposed in this paper is based upon the propagation, reception and interference models described in the following.

Wireless propagation model. Signals (electromagnetic waves) transmitted over a wireless channel experience physical phenomena, like attenuation, reflection, refraction, and diffusion that degrade signal strength and quality. Particular important in vehicular environments is multi-path propagation due to reflections at buildings and moving vehicles. The superposition of signals transmitted over different paths results in spatial and temporal variations of reception which is also referred to as fading. One of the most common models for fading is the *log-normal multi-path fading model* [11]. Recently, a two-parameter *Nakagami* distribution has been derived from measurements in vehicular environments [12].

Reception and interference model. With respect to a wireless medium access based on CSMA/CA as in IEEE 802.11, the reception of a packet is determined by three parameters characteristic of the receiver:

- *Carrier Sense Threshold* CS_{Th} is the minimum power a signal must have in order to be *sensed* by the receiver in absence of interferences.
- *Receive Threshold* RX_{Th} is the minimum power a signal must have in order to be correctly received in absence of interferences. RX_{Th} is always higher than CS_{Th} .
- *Signal-to-Interference Threshold* SIR_{Th} is the minimum ratio of signal strength and interference needed to successfully receive a packet. Interference denotes the accumulative strength of all interfering signals and noise.

The two latter parameters determine the conditions for successful packet reception:

$$Pt_i G_{i \rightarrow j} \geq RX_{Th} \quad (1)$$

$$SIR_j = \frac{G_{i \rightarrow j} Pt_i}{Pn_j} \geq SIR_{Th} \quad (2)$$

where $G_{i \rightarrow j}$ is channel gain (loss) from node i to j , Pt_i the transmit power of i , SIR_j the signal-to-interference ratio and Pn_j the aggregated power of noise at node j .

In existing studies about IEEE 802.11-based MAC schemes represent CS_{Th} and RX_{Th} often as spatial ranges (Figure 2) and assume a single transmit power level for all transmitters. Omitting physical details, we can intuitively state that a reduced transmit power also decreases these two ranges since a smaller attenuation, i.e., higher gain, is needed to satisfy Eq. 1. Likewise on transmitter side, the spatial coverage of the transmitted signal varies according to the transmit power.

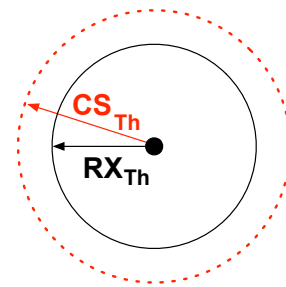


Fig. 2. Carrier sense and reception range

Carrier sense range and reception range determine the so-called *hidden node* and *exposed node* problems [13] that affect CSMA/CA medium access schemes. These phenomena have severe effects on the protocol performance. The so called RTS/CTS is a mechanism which alleviates the problems, but consumes bandwidth and is designed for static or low mobility scenarios. Therefore, it is not regarded to

be appropriate for VANETs, where bandwidth has to be shared among many highly-mobile nodes. In this matter, it is important to note that power control neither targets nor directly influences hidden and exposed node effects, as above mentioned ranges vary at both sender and receiver sides. On the other hand, transmit power strongly influences interference and therefore the possibilities of correct reception, in particular because it determines the value of aggregated noise (Pn_j).

III. MOTIVATIONS FOR TRANSMIT POWER CONTROL

In a scenario with a potentially high number of vehicles and data packets to be sent hop-by-hop through a forwarding chain, two main aspects lead to consider power control algorithm.

i) Adopting the minimum power needed to transmit the packet from a forwarder node (f) to the next hop (nh) reduces harmful interferences caused to other nodes. In fact, considering a distributed power control and the condition expressed in Eq. 2, the reduction of Pt_i is balanced by a higher reduction of factor Pn_j (i.e. interference caused by other nodes disturbing the next hop), which results in higher value of SIR_j and consequently a reduction of bit error rate.

ii) In comparison with adoption of full power, a controlled reduction of the transmit power partitions the VANET into many more, smaller clusters. This can be explained by the fact (see Sec. II) that a reduced transmit power implies a smaller carrier sense range of other nodes. Therefore, more localized simultaneous transmissions can take place as shown in Fig. 3, where the carrier sense range of node C is smaller due to the reduced transmit power of node A. At the same time the transmission ranges of nodes A and C get smaller and allow for two simultaneous, non-interfering transmissions.

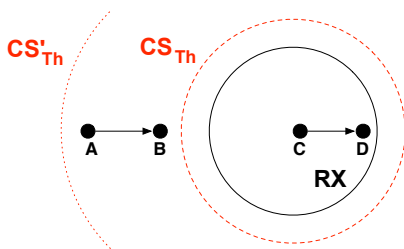


Fig. 3. Simultaneous transmissions with transmit power control

IV. PROTOCOL DESIGN

The proposed scheme enhances existing PBR with transmit power control. Basically, these enhance-

ments comprise two mechanisms: i) Assessment of the minimum transmit power and ii) Extensions of the greedy forwarding algorithm.

Assessment of the minimum transmit power. In principle, we identify three different options: i) *Channel gain prediction* attempts to determine the path loss between a forwarder to the next hop based on the known distance.² ii) With *control messages exchange prior packet transmission* the forwarder sends a request to the next-hop node, which replies with its current channel gain and interference level before transmitting the packet. iii) *Periodic control messages* are sent by every neighbor in order to inform them about the channel state information.

Power-aware PBR uses the last option: It makes use of periodic beacons (see Sec. I) that are always sent by every node to its direct neighbors with maximum transmit power. Since beacons are integral part of the position-based routing protocol, the additional overhead for transmit power control is minimal. In comparison, the second option control message exchange prior packet transmission would suffer from the same drawbacks as RTS/CTS (see Sec. II). Also, the first option is not feasible in practice due to high variations of the wireless channel characteristics in vehicular environments and does not allow to assess the interference.

The transmit power assessment works as follows: as the maximum transmit power is equal for every transmitter, a forwarder determines channel gain as $G_{nh \rightarrow f} = Pt_{nh} - SS_f$, where Pt_{nh} is the known maximum transmit power and SS_f is the received signal strength measured at f when the last beacon from nh was received. In order to assess the transmit power we make two assumptions: i) the channel is symmetric, i.e. $G_{f \rightarrow nh} = G_{nh \rightarrow f}$ and ii) the channel characteristics do not change considerably between two consecutive measurements. In order to satisfy the SIR condition in Eq. (2), every beacon message also carries the current interference level measured in the node at the point of time the beacon was sent.

Extensions of the greedy forwarding algorithm. The power-aware greedy forwarding algorithm requires every node to maintain the channel gain and interference level for every neighbor as soft state. The algorithm consists of two steps: First, the forwarder selects the optimal next hop among the neighbors according to the chosen policy (e.g. most-forward within radius). Then, the transmit power is calculated

²It could also include additional information, such as the environment like city or highway.

as shown in Eq. 3 by conversion of Eq. 1 and 2 and adding a guard value δ .³

$$Pt_{f \rightarrow nh} = \max \left(\frac{RX_{Th}}{G_{f \rightarrow nh}}, \frac{SIR_{Th} P n_j}{G_{f \rightarrow nh}} \right) + \delta \quad (3)$$

The algorithm is described as simplified pseudo-code below.

Algorithm 1 Power-aware greedy forwarding

LID is local ID, *NHID* is ID of next hop
 Unicast packet arrives at forwarder *f* from source *SID* with sequence number *SN*, time-to-live *TTL*, and destination *DID*
if $SN > SN(SID)$ **then**
 if $TTL > 0$ **then**
 $NHID = \arg \min_{i \in N} \{dist(D, N_i)\}$
 if $NHID \neq LID$ **then**
 $TTL \leftarrow TTL - 1$
 $SN(SID) \leftarrow SN$
 $Pt \leftarrow Pt_{f \rightarrow nh, min}$
 Forward packet to *NHID* with *Pt*
 else {no greedy route}
 Drop packet
 end if
 else {TTL = 0}
 Drop packet
 end if
else {Packet already seen}
 Drop packet
end if

V. EXPERIMENTAL EVALUATION

In order to proof the correctness of the protocol assumptions and to evaluate the performance of the power-aware PBR in real environments, we implemented the algorithm in our vehicular communication system with PBR as core, and conducted measurements in an experimental testbed.

For simplification we consider only a single link between sender and receiver, and hence exclude interferences from other nodes in our evaluation (see the discussion later).

A. Metrics

For comparison of power-aware PBR and simple PBR (without transmit power control) we consider three metrics. They are defined with respect to distance, more precisely we divide the distance into equidistant ranges.

³In practice, the wireless hardware has a minimum and maximum transmit power Pt_{min} and Pt_{max} . If $Pt_{f \rightarrow nh}$ is below Pt_{min} or exceeds Pt_{max} we set the transmit power to the respective border values.

Average Transmit Power Pt_{avg} is the transmit power assessed by the algorithm and averaged for all samples in a distance range. It measures the effectiveness of the transmit power control. Since the transmit power represents the spatial coverage of a packet, it is indirectly proportional to the saved bandwidth and hence a measure for the spectral efficiency. Pt_{avg} is limited by the minimum and maximum transmit power of the wireless hardware.

Average Received Signal Strength SS_{avg} represents the received power measured by the wireless device per received data packet and averaged for all samples in a distance range. The smallest possible value of SS_{avg} is the receive threshold RX_{Th} . The smaller SS_{avg} the better the power-aware PBR protocol works (when the interference is 0).

Probability of Reception PoR is defined as the ratio of successfully received data packets and sent data packets. The PoR with simple PBR represents an upper bound. Clearly, a power-aware scheme should converge to this upper bound as much as possible. A considerable deviation from the PoR with simple PBR would represent a drawback.

B. Scenario and Setup

The scenario is based on two cars that drive on a typical German highway (between Heidelberg to and around Frankfurt). The highway is almost plain and straight, has few small curves, 4 to 8 lanes, bridges, construction sites, regular week-day traffic, and few areas with traffic congestion. The cars drive in the same direction and continuously change their velocity between 60 and 140 km/h without overtaking each other. Due to the different velocity of the cars, the distance between cars oscillates between 0 meters and beyond transmission range and we can get samples of all possible distance values in different situations.

The car in front acts as a receiver and the car behind periodically generates unicast data packets with constant rate and size. In order to compare simple and power-aware PBR, packets are sent alternating with simple PBR and power-aware PBR. The alternation with a small inter-packet time ensures that the channel conditions for two subsequent packets sent with simple and power-aware PBR are similar.

We equipped the two cars with the following hardware: Notebooks, GPS, external antenna fixed with magmount on the car's roof, wireless LAN-based dedicated devices capable of per-packet transmit power control. The WLAN device was a prototype, called Wireless Radio Module (WRM) provided by DENSO Corp. It provides some features of

the upcoming IEEE 802.11p standard, such as per-packet control of MAC layer parameters as used in these experiments. As software we used our experimental software prototype for vehicular communication, *iperf* for data generation, both executed in the notebooks, and the proprietary WLAN driver in the WRM box.

Frequency	5.9 GMHz
Bandwidth	20 MHz
Min/max transmit power	0/20 dBm
Minimal power steps	1 dBm
Receive threshold in algorithm	
$RX_{Th} + \delta$	-82 dBm
RTS/CTS	Off
Antenna gain	5 dBi
GPS	DeLorme Earthmate (SBAS capable)
Beacon rate	1 Hz
Packet generation rate	10 Hz
Packet size	500 Bytes

TABLE I
MEASUREMENT PARAMETERS

C. Results

Fig. 5(a) and 5(b) illustrate the experiment: The duration of the measurement was almost 3000 s, and we measured a maximum transmission range up to 800 m, and the distance oscillated between 10 and 800 meters. The number of sent and received packets samples in Fig. 5(b) shows frequent outages due to loss in connectivity between the cars, either when the cars are out of transmission range or when obstacles (e.g. trucks) block the communication. In these situations, packets were not sent.

Fig. 4 depicts the probability of reception PoR over distance for both, power-aware and simple PBR. It can be seen that up to a distance of 300 meters almost no packet loss occurs. Beyond 300 meters the curve drops and settles down at a PoR of 0.1. From these results we can conclude that power-aware PBR does not aggravate the probability of reception. In fact, the curve shows extreme packet loss for large distances. However, the experimental comparison between power-aware and simple PBR proves that the packet loss is not caused by the reduced transmission power, but by other reasons like signal blocking from obstacles and others.

Fig. 5(c) shows the transmit power Pt_{avg} over distance. For distances up to 300 m, Pt_{avg} of power-aware PBR is clearly smaller than of simple PBR and converges to the maximum power beyond 300 m.

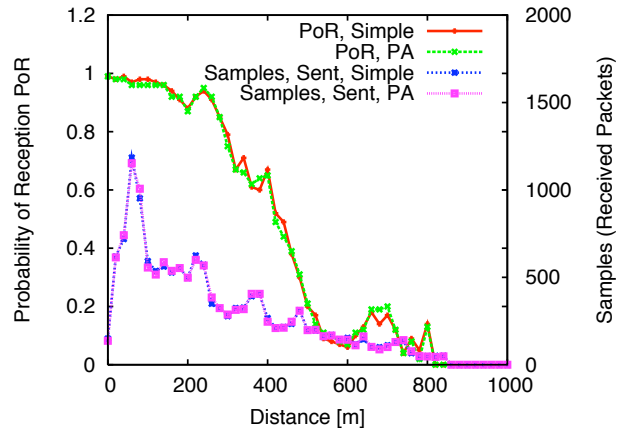


Fig. 4. Probability of Reception PoR over distance

Fig. 5(d) draws SS_{avg} over distance. We can observe a minimal receive threshold of -90 dBm. Both, Pt_{avg} and SS_{avg} show high fluctuations (standard deviation of more than 10 dB) which can be attributed to the different environmental conditions even for the same distance values.

Fig. 5(e) and 5(f) redraw the previous two figures in a different shape: The filled geometric forms represent Pt_{avg} for power-aware and simple PBR (and similar for SS_{avg}). The complement of the shapes expresses the gain of power-aware over simple PBR.

VI. SUMMARY AND CONCLUSIONS

We presented power-aware PBR for unicast communication in VANETs, a combined transmit power control and routing scheme. It adapts its transmit power to the minimum power needed to reach the next hop in a wireless multi-hop chain. Power-aware PBR reduces harmful interferences to other nodes, hence reduces the SIR and eventually the packet loss probability. Also, transmit power control increases the spectral efficiency.

We have set up an experimental testbed with IEEE 802.11-like wireless technology capable of per-packet control on MAC layer and our software prototype for vehicular communication. We conducted measurements in a highway scenario with two cars and examined probability of reception, signal strength and transmit power over distance. From our comparison of simple and power-aware PBR we can conclude that power-aware PBR saves transmit power for distances up to 300 m. Also, we have shown that the use of a reduced power does not result in higher packet loss probability.

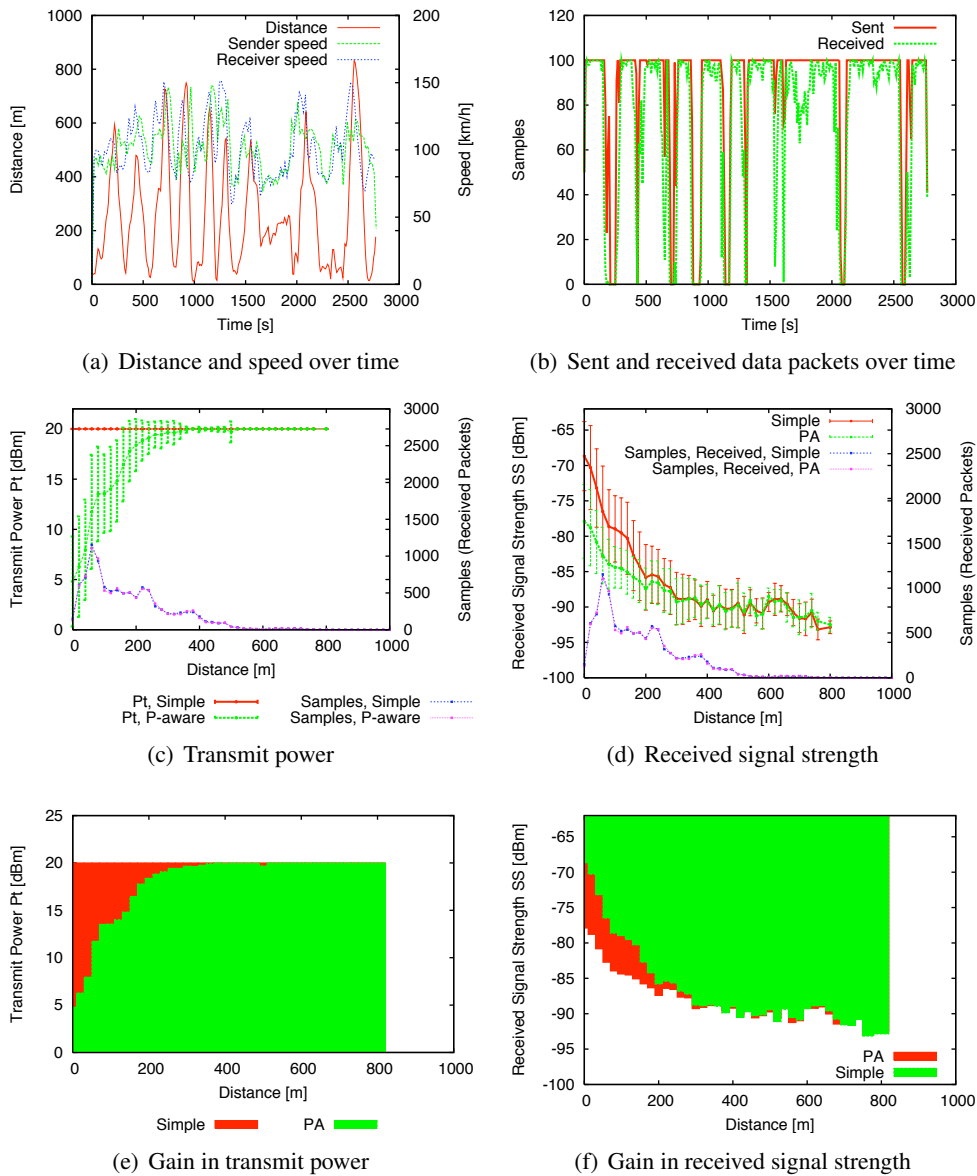


Fig. 5. Illustration of the experiment (a-b) and results (c-f)

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