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ABSTRACT - In this paper, the analytical methods and the analysis as well as the simulative tools developed for the performance evaluation and validation of the dedicated vehicle-roadside short-range communication (DSRC) protocols proposed for standardization in Europe (CEN / TC 278 / WG9) and in North America are presented. First, the basic concept of the medium access control protocol for vehicles entering the communication zone of a roadside beacon is described. Then, the analytical methods and tools (MARCO) for medium access using new multi-level Markov chain models are presented, in which the dynamic arrival of up to *n* vehicles and the completion of the full transaction (AFC, Automatic Fee Collection) is taken into account. Furthermore, the characteristics of the two simulative tools SIMCO-F/DSRC and SIMCO3++/DSRC are described. These tools are validated by comparison of the analytical results of the MARCO tool with the results of the simulative tools. Finally, the advantages / disadvantages and the recommended usage of these methods and tools for the validation of the dedicated vehicle-roadside short-range communications proposed for standardization as well as for DSRC system calibration are discussed.

1. Introduction

To support a variety of Road Transport Telematics (RTT) applications (e.g. Automatic Fee Collection AFC, Dynamic Route Guidance, etc.) Dedicated Short-Range Communication (DSRC) protocols, which are based on communications between vehicles and roadside beacons, have been developed and proposed for standardization in Europe (CEN / TC 278 / WG9) and in North America. The main important characteristic of beacon-vehicle communications is the limited communication zone / time, depending on transmission parameters, number of beacon heads, orientation and width of beam of antennas on beacons and vehicles, installation height of antennas, traffic intensity, speed of vehicles and supported application(s).

Due to the random arrival of vehicles, appropriate medium access schemes and efficient recovery algorithms after packet collisions are required to satisfy the communication needs of the relevant RTT applications (Automatic Fee Collection & Access Control, Dynamic Route Guidance, etc.), which rely on vehicle-beacon communications. Such access schemes have been proposed and were analyzed in [1], [2], [3], [4].

1.1 Beacon Configurations in Various Environments

With regard to the environment, the following typical beacon configurations are possible:

- Motorway Environment:
  - Single-lane scenarios (i.e. only one vehicle can be physically present in the communication zone)
  - Multiple-lane scenarios with:
    - one or more antennas for each lane mounted on a gantry acting synchronous in downlink transmissions and with Space Division Multiple Access (SDMA) in uplink direction to avoid uplink data collisions (see Figure 1 - Motorway Environment)
    - one or more antennas mounted on a gantry covering more than one lane (collisions on the uplink are possible - Time Division Multiple Access TDMA)
- Urban / Suburban Environment:
  - Single-lane scenarios in which the antenna is mounted on a roadside beacon
  - Multiple-lane scenarios covered by one or more antennas mounted on (a) roadside beacon(s) (RTDMA - see Figure 1).

Note: Data collisions on the uplink in the single-lane or SDMA scenarios described above are possible if more than one motor-cycle is present.

1.2 DSRC Medium Access Control Mechanisms

The medium access control sublayer of the DSRC data link (layer 2) protocol proposed for standardization [6] in Europe has the following main important characteristics:

- it is independent of the physical transmission medium used (e.g. 5.8 GHz or Infrared; but different DSRC layer 2 parameter settings might apply)
- uses asynchronous time division multiple access
- the fixed roadside equipment (beacon) MAC is responsible for the control of the physical medium by an asynchronous window mechanism, granting access to the physical medium to either:
  - the beacon by providing downlink windows, or
  - the vehicles by allocating uplink windows.

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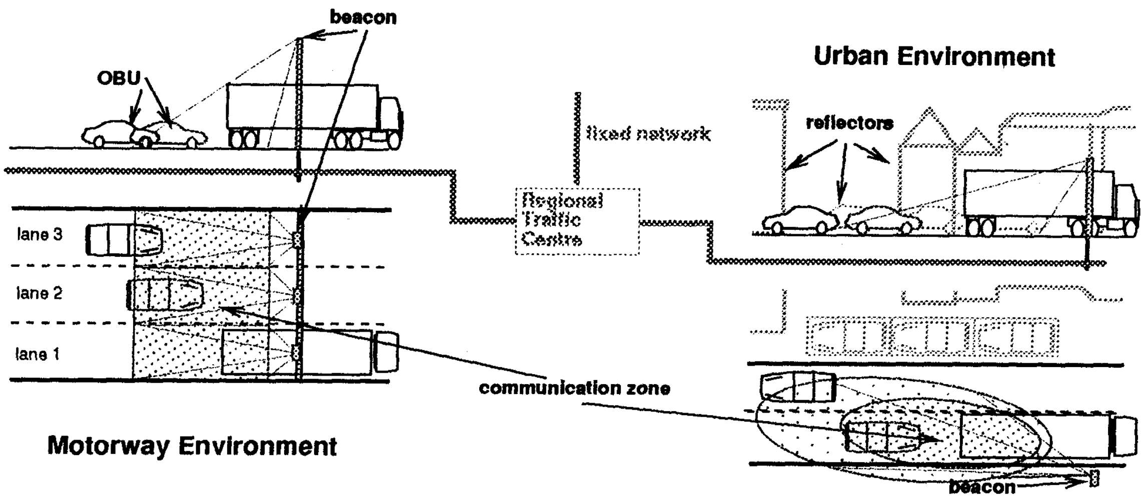


Figure 1: Typical Beacon Configurations in Various Environments

The uplink windows allocated to the vehicles are either:

- private uplink windows, exclusively reserved for one specific vehicle, or

- one (single-slot approach) or more (multiple-slot approach) consecutive public uplink windows (usually after the (downlink) transmission of a *Beacon Service Table* (BST), mainly used for (random) address acquisition of newly arriving vehicles in the communication zone.

Figure 2 shows examples of the random delay counter mechanism for the following parameter settings (N..number of consecutive public uplink windows; c..randomly chosen delay counter value in the range [1..C]; w..public uplink window counter):

- Single public uplink window (e.g. N=1, C=4)
- Multiple public uplink window, N equals C: (e.g. N=4, C=4)
- Multiple public uplink window, N greater than C: If N is a multiple of C (e.g. N=6, C=3), this approach enables time diversity (more than one uplink transmission within a given number of N consecutive uplink windows). Whether this approach is included into the emerging DSRC Layer 2 Standard is currently subject to further investigations.

Whenever a vehicle enters the communication zone of a beacon with which it intends to communicate, it randomly chooses a value c between 1 and C and sets the window counter to either :

- w := c - 1 (in case of a single public uplink window, thereby behaving according to the *immediate response* mechanism described in [3]), or to
- w := 0 (in case of consecutive multiple uplink windows)

This window counter value w is incremented with each public uplink window. Whenever the current window counter value equals the randomly chosen value c, the vehicle transmits in the current public uplink window, sets the window counter w to $w := c - C$ (thereby skipping the next $C - c$ public uplink window slots), and chooses a new value for c. If a retransmission becomes necessary, it transmits in the next public uplink window according to the algorithm described above (i.e. when w equals c).

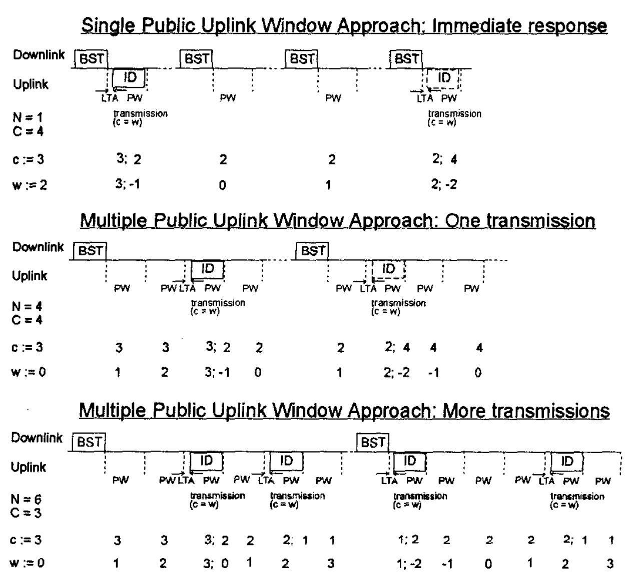


Figure 2: Medium Access Schemes for Single- and Multiple Consecutive Public Uplink Windows

2. Markov Chain Analysis Methods Using Dynamic Multi-Level Transaction Completion Models

For an accurate performance analysis of dedicated short-range communications between vehicles and roadside beacons, the Markov models described in [2] have been further developed to dynamic multi-level transaction completion models for up to n vehicles entering the communication zone simultaneously and/or successively until the address acquisition of a specific vehicle A was successful and the related transaction was completed. In these extended Markov models, in which not only the address acquisition phase, but the whole phase until transaction completion is considered, the following environment and communication characteristics / parameters are taken into account:

- Length of communication zone
- Speed of vehicles
- Number of lanes
- Arrival rate of vehicles according to traffic intensity
- Downlink and uplink transmission and packet error rate
- Downlink and uplink turn around time
- Number of bits in BST
- Number of consecutive public uplink windows (slots)
- Investigated medium access scheme / collision recovery algorithm (persistence or random delay counter mechanism) and parameters
- Maximum number of bits in public uplink window
- Number of bits in application related downlink and uplink data messages until transaction completion
- Processing delay time (e.g. for smart card operation)
- Transaction non-completion (non-success) rate

The final result of the Markov chain analysis using dynamic multi-level transaction completion models is the probability calculation of the transaction non-completion rate with regard to the (normalised) length of the communication zone, taking the investigated DSRC system scenario and parameter settings into account.

For the implementation of the Markov models described in this section, the new analysis tool MARCO (Performance Analysis of Medium Access Schemes for Roadside COmmunications using MARkov models) has been developed. The Markov chain analysis results using dynamic multi-level transaction completion models obtained by MARCO can be directly compared with the results of the simulation tools (SIMCO-F and SIMCO3++/DSRC) described in Section 3 and Section 4 below. The verification / validation of the Markov chain analysis results with the simulation results is presented in Section 5 below.

Using the Markov model for the persistence mechanism for single-slot public uplink windows as shown in Figure 3, the dynamic multi-level transaction completion models will be described in more detail.

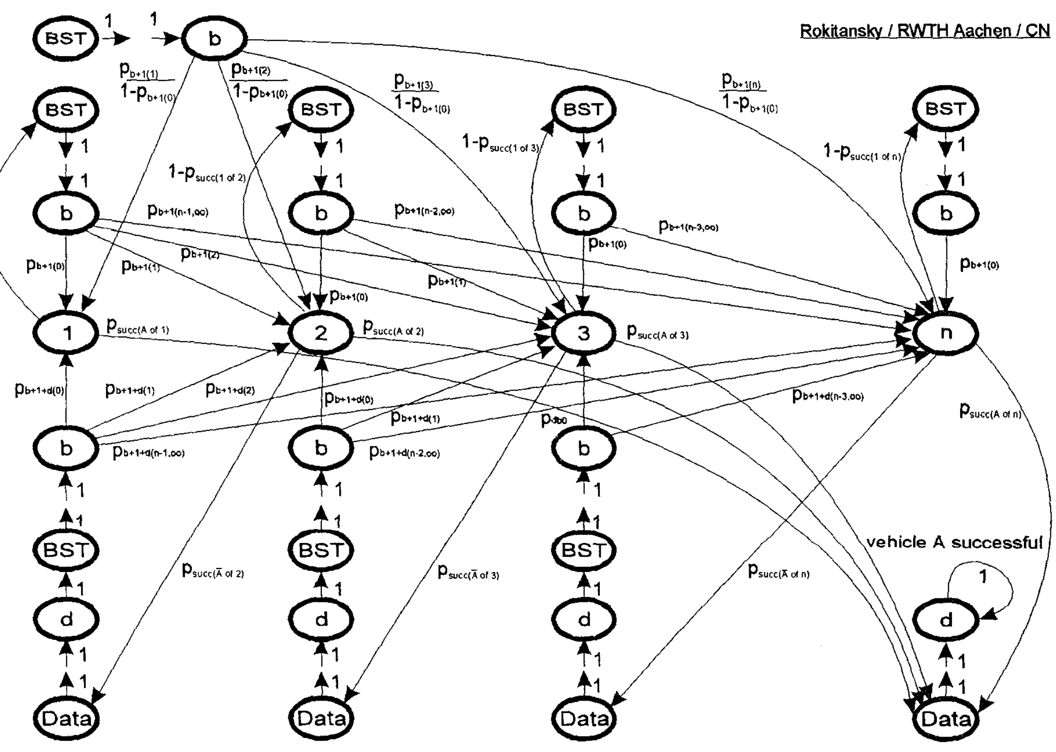


Figure 3: Markov Model of Dynamic Multi-level Transaction Completion Model for Single-Slot Persistence Mechanism

The Markov chain describes the communication process of a vehicle A that has succeeded in successful address acquisition and data exchange until completion of the transaction.

Time intervals: The time interval unit in the model corresponds to the time period allocated for a Public Uplink Window (1 slot).

Multi-levels: Each column denotes a different level of (conflict) situation involving 1, 2, up to n vehicles (right-most column). The number of involved vehicles is not limited by the model.

BST transmission: The time period required for the transmission of the BST is indicated by the state BST, followed by a number of states (total of up to b states, depending on the downlink turn around time, the downlink transmission rate and the number of bits of the BST).

Initialization: Initially it is assumed that no vehicle is in the communication zone and the beacon transmits (periodically) BSTs and allocates Public Uplink Windows. Depending on the vehicle arrival rate, the probability that k vehicles ($k = 1,2,..,n$) arrived during the transmission of the previous BST (b states, depending on length of BST + Public Uplink Window) is denoted by $p_{b+1}(k)$.

Address Acquisition: Each vehicle uses, in contention with other newly arrived vehicles, the Public Uplink Window for address acquisition. The states corresponding to the Public Uplink Window are denoted by $1..n$, depending on the number of concurrent vehicles in the communication zone.
The medium access and recovery algorithms investigated are the random delay counter and the persistence mechanism [2].
Possible results of vehicle(s) behaviour in a Public Uplink Window are:

- *no vehicle* was successful, due to data collision(s) or idle vehicle(s),
- *Vehicle* $\bar{A}$ (but not vehicle A) was successful, therefore the number of vehicles in contention is decremented by one, corresponding to a level change (next column to the left) in the Markov model, or
- *Vehicle A* was successful.

Transmission of application related data messages: Depending on the downlink / uplink rate, the link turn around time, the number of messages and the length of the messages in bit, the corresponding number of time units (d states) is taken into account in the Markov model. After the data messages, a *new BST* (b states) is transmitted, followed by a *Public Uplink Window*.

Arrival of new vehicles: In the dynamic multi-level Markov model the probability that none, one or more vehicles are arriving during the transmission of the BST and the Public Uplink Window and the application data transmission phase ($b+1+d$ states) is taken into account and denoted by $p_{b+1+d}(k)$, where $k = 0,1,..,n$.

Arrival rates: Assuming a Poisson arrival process, the probability $p_t(k)$ that k vehicles are arriving in t time interval units (e.g. $t = b+1$; or $t = b+1+d$) is:

$$p_t(k) = \frac{(\lambda \cdot t)^k}{k!} \cdot e^{-\lambda \cdot t} \qquad (1)$$

The value for λ is calculated taking the arrival rate a of vehicles, the maximum message length u in bit in a Public Uplink Window / slot, and the uplink transmission rate r into account:

$$\lambda = \frac{a \cdot u}{r} \qquad (2)$$

Success probabilities: Assuming k vehicles and using a persistence value p, the probabilities for success, idle and collision can be calculated as follows:

- none of k vehicles transmits (all idle):
$$p_{idle}(k) = (1-p)^k \qquad (3)$$
- one of k vehicles is successful (transmits):
$$p_{succ}(1 \text{ of } k) = k \cdot p \cdot (1-p)^{k-1} \qquad (4)$$
- Vehicle A is successful
(i.e. A transmits, k-1 vehicles do not transmit):
$$p_{succ}(A \text{ of } k) = p \cdot (1-p)^{k-1} \qquad (5)$$
- Vehicle $\bar{A}$ is successful
(i.e. one out of k vehicles transmits, but not A):
$$p_{succ}(\bar{A} \text{ of } k) = (k-1) \cdot p \cdot (1-p)^{k-1} \qquad (6)$$

The validation of the presented dynamic multi-level transaction completion model using Markov chains with simulation tools is discussed in Section 5 below.

3. SIMCO-F / DSRC Simulator

In addition to the MARCO analysis tool described in Section 2 above, the SIMCO-F(ast) tool (SImulation of Mobile COmmunication) has been developed for the performance evaluation of dedicated short-range communications and the standard protocols as currently being proposed in Europe (CEN TC 278 / WG 9 / SG.L1 & SG.L2) [6] and North America [5] were implemented.

The main purpose of this fast simulation tool (about 150 seconds for 100.000 vehicles on a 486/DX2/50 MHz PC) is the quick estimation of DSRC system performance and optimal parameter values. The following environment and communication characteristics / parameters are taken into account in the SIMCO-F tool: Length of communication zone; speed of vehicles; number of lanes; arrival rate of vehicles according to traffic intensity; downlink and uplink transmission rate, bit error rate, and link turn around time; number of bits in BST; number of consecutive public uplink windows (slots); number of consecutive downlink slots (fixed frame size); investigated medium access / collision recovery algorithm (persistence or random delay counter mechanism); maximum number of bits in public uplink window; number of consecutive messages in application related downlink and uplink data until transaction completion; link turn around time before each message transmission; number of bits in each message; processing delay time (e.g. for smart card operation); retransmission algorithm in case of packet errors.

The final result of the SIMCO-F tool is the calculation of the transaction non-completion (non-success) rate with regard to the (normalised) length of the communication zone, taking the investigated DSRC system scenario and parameter settings into account.

4. SIMCO3++ / DSRC Simulator

The stochastic simulation tool SIMCO3++ incorporates very detailed mathematical models of the road traffic mobility, the characteristics of the transmission channel and the communication protocol architecture. The tool (see Figure 4) is based on an object-oriented C++-class library CNCL (ComNets Class Library), which offers the basic functionality for event-driven, stochastic simulation, including a wide range of random number generation functions and tools for the appropriate statistical evaluation of the simulation results, such as determination of confidence intervals and batch-means methods.

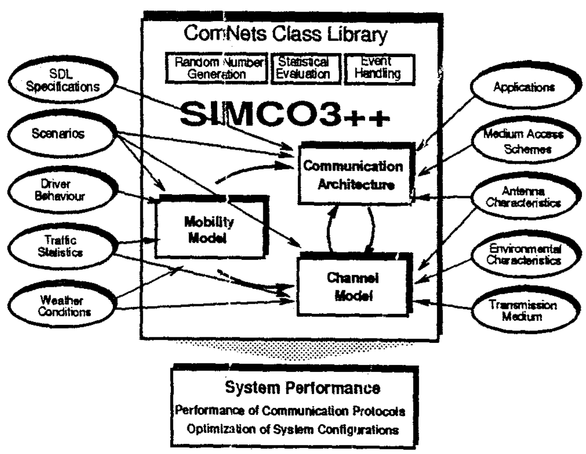


Figure 4: SIMCO3++/DSRC Simulation Concept

The simulation environment incorporates the following main modules (a detailed description is given in [7]):

- a **microscopic traffic model**, which allows to generate a realistic traffic flow according to given statistical distribution of head-ways between vehicles, speeds of vehicles, vehicle types, etc.. Several different vehicle generation processes have been implemented (such as Pearson Type 3-based generation processes as well as generation processes based on a state model, generating the traffic depending on different distributions for vehicles driving in a free-flow or platoon mode). The traffic generation processes have been validated using measurement data from Dutch as well as German motorways. Figure 5 shows exemplary results for a comparison of the head-way distributions for measureent data as well as data produced by the SIMCO3++/DSRC.
- **realistic models** of the communication channel, which allow to determine transmission errors, taking into account multi-access interference, shadowing and multi-path fading effects. Since the channel model dynamically takes into account the current traffic situation, it relies on the accurate input of the traffic model. This is for example of special importance for the calculation of shadowing effects for vehicles driving very close after one another. Models are available both for the transmission media microwave (5.8 GHz) as well as infrared.
- an **implementation of the communication architecture** according to the emerging standards. In order to allow an unambiguous and transparent specification of the implemented protocols the translation of formally specified communication protocols (SDL) into C++-Code, which can be directly used for the simulation, is enabled.
- a range of **tools for the evaluation** of the simulation results, such as an interactive debugging tool, which allows to follow each simulation step to analyse specific situations.

With the tool SIMCO3++/DSRC it is possible to give an indication on the absolute system performance, allowing to optimise a system configuration according to a given system environment. Therefore especially choices for optimal system components (such as antenna configurations) and protocol parameters (e.g. for the medium access control scheme) are supported.

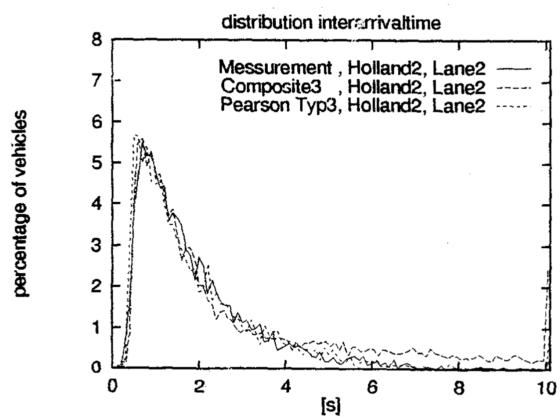


Figure 5: Netherlands A9, lane 2, headways

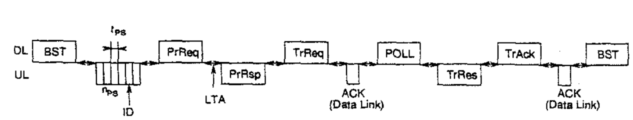


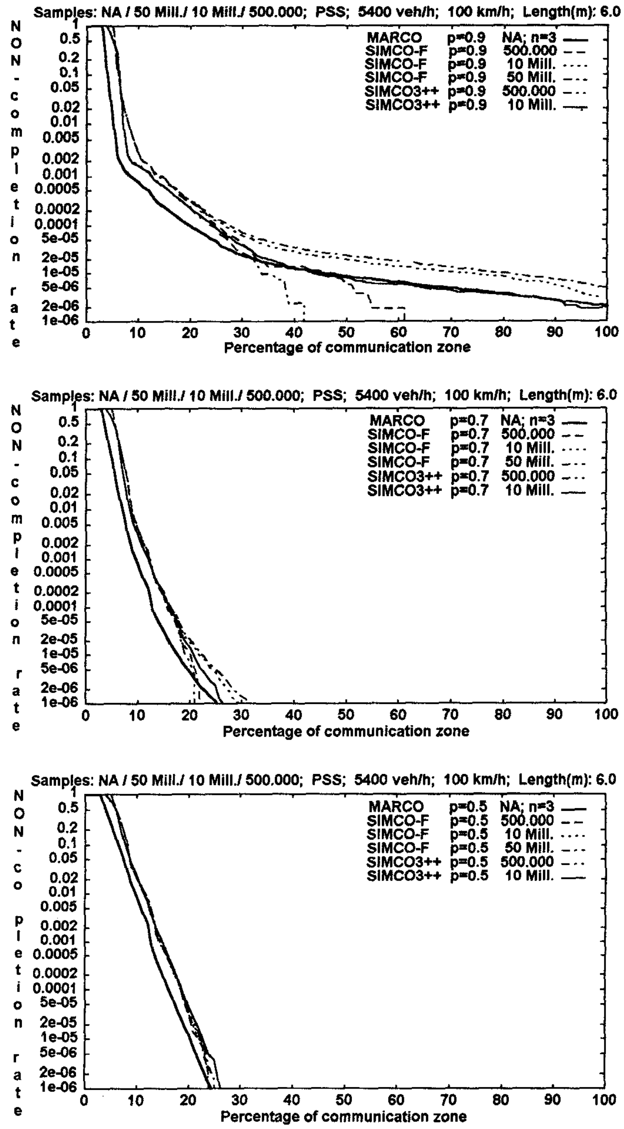
Figure 6: AFC Related Sequence of Messages for Validation

5. Validation of Performance Evaluation Tools for DSRC: MARCO, SIMCO-F and SIMCO3++

For the verification of the developed performance evaluation tools for dedicated short-range communications (DSRC), the analytic tool (MARCO) and the stochastic simulation tools (SIMCO-F and SIMCO3++) described above have been validated in a 3 lanes motorway environment with relatively high traffic intensity (1800 vehicles / hour / lane); 100 km/h speed; length of (multi-lane) communication zone: 6m; 500 kbit/s downlink and 250 kbit/s uplink transmission rate, downlink / uplink bit error rate: 10^{-6}; link turn around (LTA) times of 0.1 ms (downlink and uplink data transmissions) and 0.5 ms LTA in Public Uplink Windows. The length of messages (in bit) related to the Automatic Fee Collection (AFC) application (see Figure 6) was set as follows: BST: 400 bit, ID (Public Uplink Window): 125 bit, Presentation Request: 400 bit, Pres. Response: 500 bit, Transaction Requ.: 400 bit, ACK: 80 bit, Poll: 80 bit, Transaction Resp.: 400 bit, Transaction acknowledge: 240 bit, and final ACK: 80 bit. For the validation the Single Public Uplink Window using a persistence mechanism as analyzed in Section 2 above has been used, with the different values of p (0.9, 0.7, 0.5).

The analytical results of MARCO and the simulative results of SIMCO-F (500.000, 10 million, 50 million vehicles) and SIMCO3++ (500.000 and 10 million vehicles) with regard to these environmental characteristics and parameter settings are shown in Figures 7a to 7c and Figure 8. A comparison of the analytic results (MARCO) and the simulative results (SIMCO-F and SIMCO3++) show a very good correspondence between these tools, and an almost exact matching between the simulation tools (SIMCO-F and SIMCO3++), especially with regard to persistence values of $p=0.7$ and $p=0.5$ (Fig. 7b, 7c).

For smaller sample sizes (number of simulated vehicles e.g. 500.000) the results show clearly the advantages of the analytic tool (MARCO) over the simulative tools, especially as far as low transaction failure rates (< 10^{-6}) are concerned: Since the MARCO tool, using a dynamic multi-level transaction completion Markov model, calculates probabilities (corresponding to an infinite number of vehicles) for the completion / non-completion of the transaction within the given communication zone with regard to the percentage used, even very low transaction failure rates (e.g. 10^{-7}, 10^{-9}, etc.) can be taken into account easily. For a persistence value of $p=0.9$ (Fig. 7a) and a transaction completion of 99.999% of the vehicles (corresponding to a non-completion rate of 10^{-5}) only 38% (SIMCO3++) of the communicatio zone was used, compared to 47% (SIMCO-F and MARCO). In this scenario, 100% (SIMCO-F and SIMCO3++) of the simulated vehicles completed the transaction successfully, while 0.0025% (MARCO) were not successful. However, if the number of simulated vehicles is increased (SIMCO-F: 10/50 million; SIMCO3++: 10 million), the simulation results correspond very accurately with the analytic results (MARCO) especially for SIMCO3++ for a value of $p = 0.9$ and low non-



Figures 7a-c: Validation of MARCO, SIMCO-F, SIMCO3++

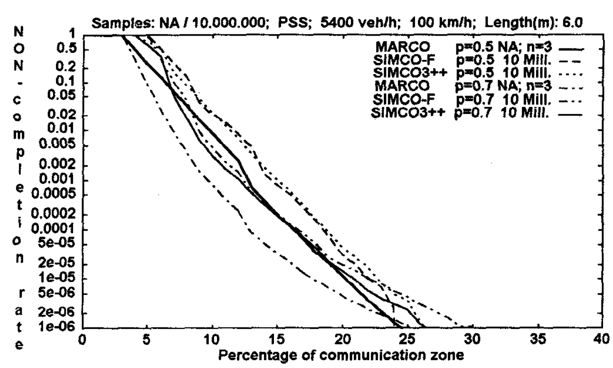


Figure 8: Optimum Value for Persistence p