Channel Sensitive Transmission Scheme for V2I-based Floating Car Data Collection via LTE

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***Abstract*—In this paper, we present a channel sensitive transmission scheme which reduces the negative impact of Vehicle-to-Infrastructure (V2I) traffic on the Quality of Services (QoS) of Human to Human (H2H) communication in cellular networks. The performance evaluation of Long Term Evolution (LTE) for different traffic characteristics is based on an introduced Markovian model. This describes the utilization of the shared LTE Resource Blocks (RBs). The model is parameterized by laboratory measurements and ray tracing simulations. We present blocking probabilities for an LTE network with heterogeneous V2I and H2H traffic and propose different transmission strategies for V2I data with the goal to minimize the impact on human users. The results show that the number of V2I devices can be doubled by using channel sensitive transmission schemes ensuring equal QoS for H2H communication compared to periodically data transmission.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) based cellular networks are typically designed for high data rate applications [1]. However, new services in the area of Vehicle-to-Infrastructure (V2I) communication as part of Machine-to-Machine (M2M) communication can be found in these systems. This paper is especially motivated by the example of traffic jam prognosis, where devices in cars collect sensor information - Floating Car Data (FCD) - and transmit them to a server via LTE. In contrast to other V2I applications, this data is not time critical, because the data can be collected from a large number of cars.

The characteristics of V2I traffic are different from H2H communication [2]. Usually, V2I applications receive or transmit only a small amount of data. Hence, a heterogeneous framework for modeling V2I and H2H users is required for performance evaluation. Typically simulations are used to analyze scenarios with a huge number of V2I devices. However, a lot of effects occurring in communication systems are difficult to model and simplifications are necessary. On the other hand, such investigations carried out in field trials are very complex and a limited control of system parameters and the environment is given. Therefore, we perform measurements with real equipment by using a fading channel emulator in cooperation with an LTE base station emulator. Thereby, the performance evaluation of single users with different requirements regarding the number of RBs is possible.

Next, we combine the results for single users via a Markovian model, which is introduced for OFDM systems in [3], to evaluate the influence of many V2I devices with different QoS requirements on the overall cell capacity. For this purpose, the distribution of the Signal to Noise Ratio (SNR) in a cell is calculated by ray tracing simulations.

Typically, scheduling decisions are made by the base station. The base station can distribute the spectrum to all subscribers which need to transmit data. Before the actual transmission, the registration of the users in the cell is realized by a random access procedure which has to be performed by every user. With the deployment of V2I devices, hundreds of new users occur within one cell. Therefore, we propose a local channel sensitive preselection of the devices, which are allowed to transmit their data. The decision is based on a transmission probability which depends on the SNR and the velocity. The higher the SNR for a device, the higher is the transmission probability for the data of this user. This guarantees that many devices with good channel conditions can transmit their information.

The goal of this paper is to evaluate the influence of different V2I transmission strategies including channel sensitive transmission on the user experience of H2H users. By means of the results, the maximum number of V2I connections in an LTE cell is determined that can be served without a significant influence on the blocking probability for H2H communication. Hereby, the utilization of the LTE RBs is the bottleneck in our scenario. A detailed investigation of the signaling procedure and the random access, which are often critical in V2I scenarios, is not necessary in our approach, because this becomes crucially only for much more devices in one cell [4]. In our case, the number of nodes is limited by the number of cars and the number of active devices is reduced by the channel sensitive transmission.

The proceeding of this paper is organized as follows: In Sec. II, the related work for the performance evaluation of LTE especially for V2I is presented. Sec. III gives an overview about the used system model including the laboratory measurements [5] and the Markovian model. The results regarding the number of possible V2I devices in an LTE cell and the resulting distribution of the position of users in the scenario is described in Sec. IV. Finally Sec. V concludes the work.

II. Related Work

The inclusion of M2M communication into common traffic of cellular communication systems is one of the main goal in the standardization process of LTE-Advanced [2], [6]. In this context, the impact of hundreds of M2M devices on the QoS constraints of normal H2H communication should be as small as possible.

In [7] a study of the impact of mixed traffic on the LTE performance is presented. The authors of [7] focus on different multimedia and Internet applications. For the performance evaluation of LTE, field trials are often used in order to analyze the impact of velocity on the performance of OFDMA-based links. For example, the performance of LTE is evaluated by a testbed in [8]. For throughput measurements, a monitoring car with an average speed of around 30 km/h is used. Hereby, it is very difficult to drive a car with a constant and preset speed to evaluate the influence of velocity.

To evaluate the channel conditions for cellular networks, ray tracing simulations are a well known method. In [9] coverage and achievable peak data rates for an urban area with a three-dimensional building model are investigated using a ray tracing simulation for an LTE-Advanced relay scenario.

In [10] and [11], Markovian models are used to model OFDMA networks. Thereby, different states in the model are used for different channel characteristics. Markovian models for resource allocation, where one state represents a part of the shared resources, can be found in [12]. In [3], a multiclass Erlang loss model is introduced for OFDM systems. Every state in the model represents one subcarrier. The same Markovian model is used in this paper, but we adapted the model to make it more practice-oriented for LTE systems by using the RBs as states. Furthermore, we parameterize the model based on measurements and ray tracing simulations.

III. System Model

In order to evaluate the performance of LTE, an efficient system model consisting of a laboratory setup, ray tracing simulation and a Markovian model is presented (see Fig. 1). We measured User Datagram Protocol (UDP) uplink data rates for single users depending on the SNR and the number of allocated RBs per user. One RB is the smallest unit, which can be allocated to an LTE user. The distribution of the SNR for the outdoor scenario is determined by a ray tracing simulation.

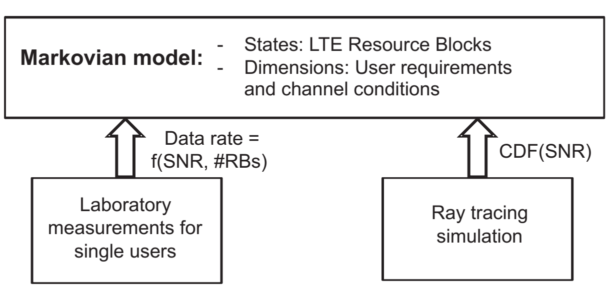


Fig. 1: System model for the evaluation of the influence of V2I communication on the utilization of the LTE radio interface

In the next step, the system behavior for many users in an LTE cell is modeled by a Markovian approach. Assigning the user request to different classes of resources, each class is described by one dimension of the Markovian model. According to the reduction of dimensions of Markovian models [16], an LTE cell with users having different QoS requirements and various SNRs can be modeled.

We divide the users by its requirements (Video streaming, which is a typical H2H application and FCD for V2I UDP data; see Tab. I), the SNR and the user velocity. By means of the Markovian model, the blocking probability is evaluated for different user behaviors and transmission strategies.

TABLE I: Overview of the different user classes

Type	H2H: Video streaming	V2I: FCD
Requirements	Data rate: 250 kbit/s	Data: 1 kByte
Distribution of users	Uniformly	Channel sensitive
# RBs	Channel dependent	Fixed: 10

A. Laboratory Measurement Setup

In the laboratory, we are able to perform close-to-reality investigations regarding an LTE cell with one user without expensive field trials. The parameters for the measurements are listed in Tab. II. More details about the measurement setup for a comparable scenario can be found in [5]. The setup composed of:

- A *Base Station Emulator (BSE)* allows for the creation of a mobile network cell in a laboratory environment. A detailed parameterization of the LTE base station signal in terms of modulation and coding scheme, transmit power, (Hybrid) Automatic Repeat Request ((H)ARQ) and the number and the position of allocated RBs in the spectrum is possible.
- The *channel emulator* fades the signal in a predefined manner. This includes fast fading effects due to mobility and multipath propagation in the scenario. Furthermore, it is possible to add different kinds of interference and noise (for example Additive White Gaussian Noise (AWGN)) to the Radio Frequency (RF) signal. For the emulation of the mobile radio channel the ITU Vehicular A channel model [15] is used in the uplink channel.
- The *Device Under Test (DUT)* is remote controlled by a client PC via USB. Due to the fact that the setup is bidirectional, we establish a standard conform radio connection between the BSE and the DUT.
- For *application testing*, the BSE is connected to an Ethernet-based network in which iPerf runs on a server. This allows for End-to-End testing between the server and the connected client. We measured the UDP uplink data rates for a single user in an LTE cell as a function of the number of allocated RBs.

B. SNR Estimation by Ray Tracing Simulations

The distribution of the SNR for an urban and a rural outdoor scenario is determined via ray tracing simulations. The parameters for the simulation are shown in Tab. II. We

TABLE II: LTE system parametrization

Measurement parameter	Value
Carrier frequency	LTE band 7
Channel bandwidth	10 MHz (50 RBs)
Fast Fourier Transform size	1024
Duplexing scheme	Frequency Division Duplexing
SNR	0-30 dB
User Equipment (UE) category	3 (Samsung GT B3730)
RLC ARQ mode	Acknowledge mode
Ray tracing parameter	**Value**
Ray tracing model	3D Intelligent Ray Tracing [14]
UE transmit power	23 dBm
UE antenna gain	1 dBi
UE noise figure	6 dB
BS antenna opening angle	120°
Downtilt	3°
Cell radius	400 m
Noise	Thermal noise

used typical urban and rural scenarios with one base station and three different frequencies from LTE band 7 (reuse 3) to minimize the interferences between the different sectors. Antenna (Ant.) 1 uses 2.62 GHz, Ant. 2 uses 2.63 GHz and Ant. 3 uses 2.64 GHz center frequency.

C. Analytical Markovian Model

In order to model different resource requirements of users in an analytical way, this subsection deals with a Markovian model (multi class Erlang loss model) for the traffic within an LTE cell. Assuming that the inter-arrival time and duration of customer service requests follows a negative exponential distribution with respect to time, an analytical Markovian model can be developed. Assigning the user requests to different classes of resources, each class is modeled by one dimension of the Markovian model. According to the reduction of dimensions of Markovian models [16], an LTE cell with different QoS requirements and different channel conditions regarding the SNR can be modeled as shown in Fig. 2. Thereby, the j^{th} state denotes the allocation of j resource blocks from the LTE OFDMA signal. Moreover λ_s and μ_s denote the mean arrival and mean service rate of the class s. As an example Fig. 2 shows three service classes, class 1 allocates one RB, class 2 two RBs and class 3 allocates k-1 RBs.

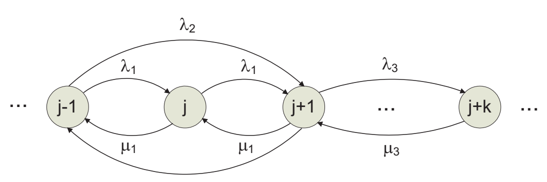


Fig. 2: Exemplary one-dimensional Markovian model

According to [16], the stationary distribution π_c, which characterizes in our case the probability that c RBs are allocated, can be determined in a recursive way

$$\pi_c = \frac{\widetilde{\pi}_c}{\sum_{c=0}^{C} \widetilde{\pi}_c} \quad \text{with} \quad \widetilde{\pi}_c = \begin{cases} 1 & c = 0 \\ \sum_{s=1}^{S} \frac{a_s c_s}{c} \widetilde{\pi}_{c-c_s} & c > 0 \, , \end{cases}$$

where C is the total number of RBs in an LTE cell, a_s the offered traffic of class s, c_s the resources of class s and S the number of service classes, i.e. dimensions of the model. The blocking probability p_{b_s} of class s and the overall traffic load Y can now be calculated as

$$p_{b_s} = \sum_{c=C-c_s+1}^{C} \pi_c \quad \text{and} \quad Y = \sum_{c=1}^{C} c\pi_c \, .$$

The Markovian model incorporates a First In First Out (FIFO) scheduling algorithm with same priority for H2H as well as V2I traffic. If the number of RBs requested by the UE is available in the cell, the UE will get the resources. If the number of free RBs is smaller than the requested number of RBs, the request from the UE will be rejected.

In the following, we use 12 different classes (two different user requirements (V2I and H2H), three different SNRs and two different velocities). The arrival rate of all H2H users is a_H and we denote a_M as the arrival rate of all V2I users. For λ_s and μ_s the same indices are used. The service rate for the H2H users is set to 1 per second while the offered traffic is adjusted by the arrival rate. For V2I users, the service rate is calculated as data rate taken from the laboratory measurements divided by the data size (1 kByte).

D. Channel Sensitive Transmission Scheme

The number of active V2I devices is represented by the arrival rates of the different classes in the Markovian model. It is well known that users with very bad channel conditions need a higher amount of RBs than users with good channel conditions to achieve the same data rate. As V2I applications are not time critical in our scenario, we propose that the transmission of V2I data should be channel sensitive. For good channel conditions the V2I application transmits with a higher probability compared to worse channel conditions. Hence, we propose a transmit probability p:

$$p = \left(\frac{SNR}{SNR_{max}}\right)^{\alpha} \cdot \left(\frac{v_{max}}{v}\right)^{\beta}$$

p is normalized by SNR_{max} which is the SNR for which the highest data rate can be achieved and by v_{max} which represents the highest velocity in the scenario. For the presented results, a SNR_{max} of 40 dB and a v_{max} of 150 km/h is used. A method for estimating the SNR in a real OFDM system is shown in [13]. The parameters α and β control the intensity of the channel sensitive transmission scheme. For the Markovian model, we divided the SNR in $N = 3$ parts and the velocity in $M = 2$ parts. The number of devices which transmit data should be independent on the coefficient α. Therefore, we have to normalize the transmit probability:

$$p_{i,j} = \frac{\left(\frac{SNR_i}{SNR_{max}}\right)^{\alpha} \cdot \left(\frac{v_{max}}{v_j}\right)^{\beta}}{\sum_{l=1}^{N} \sum_{k=1}^{M} \left(\frac{SNR_l}{SNR_{max}}\right)^{\alpha} \cdot \left(\frac{v_{max}}{v_k}\right)^{\beta}}, i = 1...N, j = 1...M$$

Here, $p_{i,j}$ is the normalized transmit probability for class i, j. The channel sensitive transmission scheme implicates that the transmission probability depends on the channel quality. This probability is included in the arrival rate of the different classes of the Markovian model. The arrival rate for each class is multiplied with $p_{i,j}$. If the probability should be very small for very bad channel conditions, the arrival rate for the class with a low SNR is very low, too.

For traffic forecasts it is very important that the users which transmit the FCD are homogeneously distributed in the scenario. If only users with very good conditions transmit their FCD, many users with a small distance to the base station or with a LOS connection are active. This means that no FCD could be collected from positions with a small SNR. Hence, there is a trade off between the impact of the V2I communication on the human users and the information content of the transmitted data.

The Theil Index T [17] describes how homogeneously the users are distributed in the scenario.

$$T = \frac{1}{K} \sum_{i=1}^{K} \left(\frac{x_i}{\bar{x}} \cdot ln \frac{x_i}{\bar{x}} \right)$$

Thereby, the scenario is divided into K parts, where we used $K = 16$. $\bar{x}$ is the average number of users in one part and x_i is the number of users in part i. Hence, the index is null if the number of users per part is the same for all parts. The higher the difference of the users in the parts the higher the Theil Index.

IV. Results

A. Laboratory Measurements

The UDP data rates as a function of the SNR for 50 Resource Blocks (RBs) per user for different Modulation and Coding Schemes (MCS) are described in Fig. 3. The description of the MCS can be found in [18]. We also measured the data rates for other numbers of RBs and identified that the UDP data rate per RB is dependent on the number of used RBs. The main reason for the different data rates per RB is the high overhead between Physical (PHY) layer and transport layer (UDP) for small data rates, because the Media Access Control (MAC) padding and the Protocol Data Unit (PDU) size in the Radio Link Control (RLC) layer depends on the incoming data rate. Therefore, the overhead for small data rates is much higher than for high data rates. Hence, we measured the data rate for all numbers of RBs per user and use these results as input for the Markovian model. We assume that always the MCS which allows for the highest data rate is chosen.

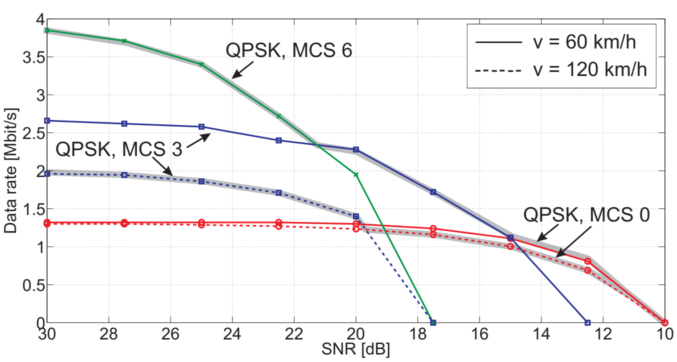


Fig. 3: Uplink data rate vs. SNR for 50 RBs per user

B. Ray Tracing

For the ray tracing simulation two scenarios are used (urban with a high building density and rural). In Fig. 4 the Cumulative Distribution Functions (CDFs) of the SNR for both scenarios are shown. From the measurements, we identified that the impact of the SNR is stronger than the impact of the velocity on the data rate (see Fig. 3). Hence, we differentiated the users for the urban scenario according to the SNR into three fractions with the same size

- SNR $\leq$ 18 dB: represented by 12 dB SNR (mean value)
- 18 dB $<$ SNR $\leq$ 26 dB: represented by 22 dB SNR
- 26 dB $<$ SNR: represented by 30 dB SNR

and by the velocity into two parts

- v $\leq$ 90 km/h: represented by 60 km/h
- 90 km/h $<$ v: represented by 120 km/h

The represented values are the weighted averages of the intervals.

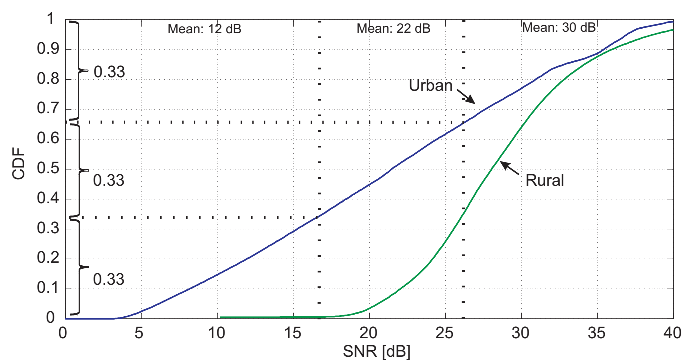


Fig. 4: CDF of the SNR in the environment

C. Markovian Model with Channel Sensitive Transmission

The FCD is relevant if the cars are on the highway and if the velocity is low. Typically, the base stations are positioned directly beside a highway. Hence, most of the cars on the highway have a LOS connection to the base station or a very high SNR. By applying the channel sensitive transmission schemes, many devices located on the highway can transmit their data. Cars with a low velocity are on the highway in a traffic jam or are driving on the streets of the urban area, where the SNR is much lower than on the highway. Therefore, the system gets data from many slow cars on the highway, because the channel sensitive transmission prefers users with a good SNR and a low velocity.

We have shown that the available data rate strongly depends on the channel quality between base station and UE (see Fig. 3). Hence, the number of required RBs for a service

TABLE III: Parameters of the Markovian model for $\alpha = 0$ and $\beta = 0$

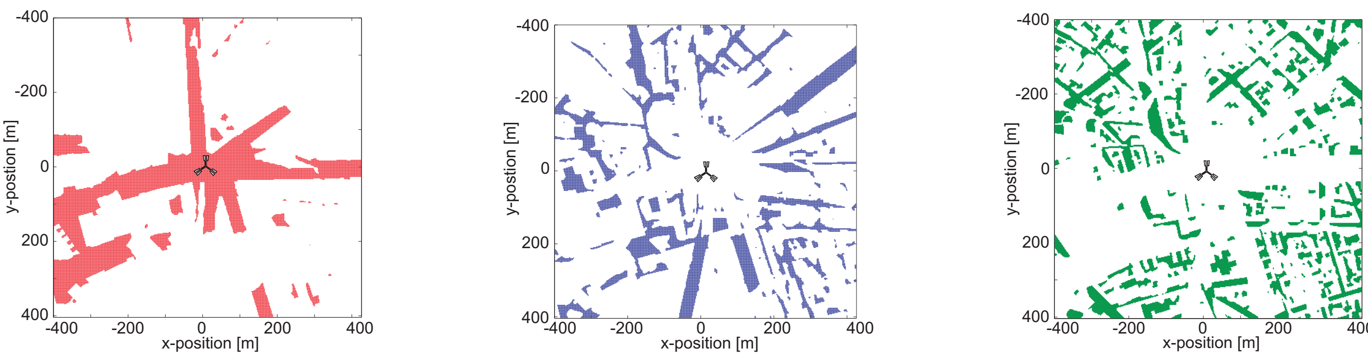
	$V2I_1$	$V2I_2$	$V2I_3$	$V2I_4$	$V2I_5$	$V2I_6$	$H2H_1$	$H2H_2$	$H2H_3$	$H2H_4$	$H2H_5$	$H2H_6$
SNR [dB]	30	30	22	22	12	12	30	30	22	22	12	12
Velocity (v, [km/h])	60	120	60	120	60	120	60	120	60	120	60	120
Service rate (μ, [1/s])	107.75	46	48	42	10	5	1	1	1	1	1	1
Number of RBs (c)	10	10	10	10	10	10	3	6	4	7	15	18

with a fixed data rate depends on the channel quality, too (see Tab. III). Thereby, different transmission strategies regarding channel sensitive transmission are compared while 10 RBs are statically allocated for the V2I users.

In Fig. 5 the positions of users with different channel conditions in the scenario are illustrated. These results are taken from the ray tracing simulation. The shaded areas describe the positions where the declared SNR is reached. For example, Fig. 5a denotes all positions with a SNR higher than 26 dB. It can be seen that in this urban scenario many positions with very good conditions (SNR $>$ 26 dB) are far away from the base station. This is due to the small cell dimension and the LOS component which dominates the channel conditions rather than the distance.

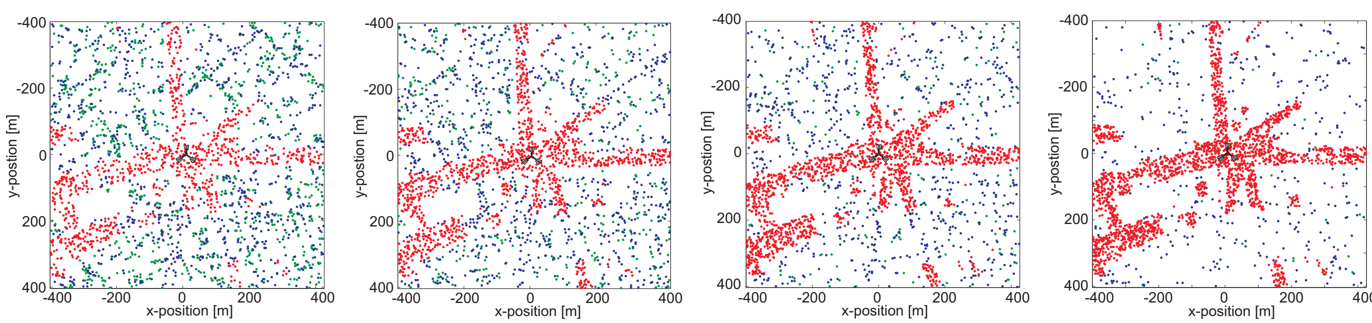
The distribution of all users in the scenario for different channel sensitive transmission schemes (for $\beta = 0$) is a linear combination of the maps illustrated in Fig. 5 and are shown in Fig. 6. The fractions of this linear combination are $p_{i,j}$. A very homogeneous distribution is reached without channel sensitive transmission ($T = 0.41$). For a very intensive channel sensitive transmission ($\alpha = 4$ and $\beta = 0$) most active V2I users have a LOS connection to the base station. Therefore, the distribution is more inhomogeneous ($T = 2.31$), but it can be seen that users can be found in all areas of the scenario, too.

The main advantage of the channel sensitive transmission of V2I devices is the lower influence of the transmission on the H2H communication. In Fig. 7, the blocking probability of H2H vs. arrival rate of V2I devices λ_M for differently intensive channel sensitive transmission schemes depending on the SNR in the urban scenario is shown. This is the result of the Markovian model. The parameters of the model are presented in Tab. III. Here, a traffic for the H2H class of $\lambda_s = 0.3$ per second is used. For an arrival rate for the V2I class λ_s of 74 per second and a transmission with $\alpha = 2$ the blocking probability for H2H is 10 %. Compared to that, the blocking probability is 35 % if no channel sensitive transmission ($\alpha = 0$) is used. Or rather, if the blocking probability should be smaller than 10 % (for QoS requirements) on average 74 V2I devices can be served per second if they transmit channel sensitively and on average



(a) $SNR > 26dB$ (b) $18dB < SNR < 26dB$ (c) $SNR < 18dB$

Fig. 5: User positions of the different SNR classes in the urban scenario; base station at position (0,0)



(a) $\alpha = 0$, $T = 0.41$ (b) $\alpha = 1$, $T = 0.85$ (c) $\alpha = 2$, $T = 1.31$ (d) $\alpha = 4$, $T = 2.31$

Fig. 6: User positions for data transmission using different intensive channel sensitive strategies in the urban scenario; $\beta = 0$; base station at position (0,0)

34 V2I devices can be served per second if they transmit without channel sensitively. Hence, our approach reaches an enhancement of 117 %. If the channel sensitive transmission scheme also depends on the velocity, the blocking probability can be further reduced, because the data rate is higher for smaller velocities (see Fig 8). For a blocking probability of 10 % , 90 V2I devices can be served per second if $\alpha = 2$ and $\beta = 2$ is used.

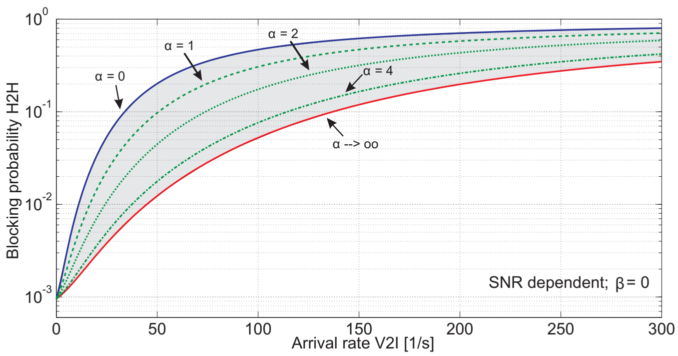


Fig. 7: Blocking probability of H2H users vs. arrival rate of V2I communication for differently intensive channel sensitive transmission schemes depending on the SNR

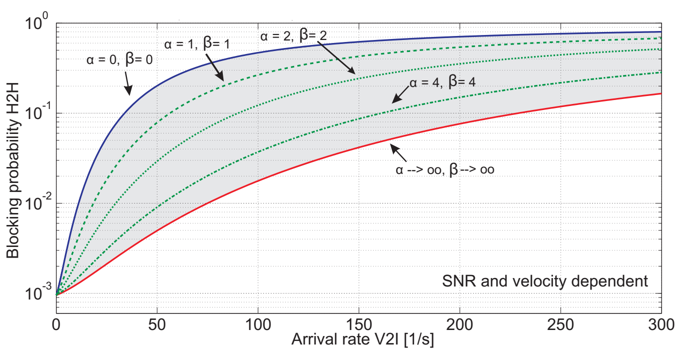


Fig. 8: Blocking probability of H2H users vs. arrival rate of V2I communication for differently intensive channel sensitive transmission schemes depending on the SNR and the velocity

V. Conclusion

In this paper, we have proposed an system model to evaluate the performance of cellular OFDMA-based communication systems with realistic channel conditions in the presence of H2H as well as V2I communication. For this goal, a Markovian model parameterized by laboratory measurements and ray tracing simulations is used. By means of the framework, the proposed transmission scheme with regard to channel sensitive transmission is evaluated. The influence of V2I data transmission on H2H communication should be as small as possible. We have shown that the utilization of an LTE cell can be clearly reduced by using our channel sensitive transmission scheme. For a QoS level of 10 % blocking probability, 34 V2I devices can be served per second if they transmit without channel sensitive transmission. In contrast, 90 V2I devices can be served per second if the channel sensitive transmission depending on the SNR and the velocity is used, although the same average UDP data rate for all users is reached. Hence, our appraoch is able to handle more than double the amount of V2I users, while ensuring the same QoS level.

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