On Wireless Links for Vehicle-to-Infrastructure Communications

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***Abstract*—Future intelligent transportation systems (ITS) will necessitate wireless vehicle-to-infrastructure (V2I) communications. This wireless link can be implemented by several technologies, such as digital broadcasting, cellular communication, or dedicated short range communication (DSRC) systems. Analyses of the coverage and capacity requirements are presented when each of the three systems are used to implement the V2I link. We show that digital broadcasting systems are inherently capacity limited and do not scale appropriately. Furthermore, we show that Universal Mobile Telecommunications System (UMTS) can implement the V2I link using either a dedicated channel (DCH) or a multimedia broadcast/multicast service (MBMS), as well as a hybrid approach. In every case, such V2I systems scale well and are capacity limited. We also show that Wireless Access in Vehicular Environments (WAVE) systems scale well, provide ample capacity, and are coverage limited. Finally, a direct quantitative comparison of the presented systems is given to show their scaling behavior with the number of users and geographical coverage.**

I. Introduction

Intelligent transportation systems (ITS) have recently attracted much attention from car manufacturers, road operators, and standardization bodies. The primary aim of ITS is to increase the road safety by means of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Considerable effort has been dedicated to defining architectures, services, and application scenarios for both V2V and V2I paradigms. The introduction of V2I services is expected in the near future. On the other hand, the more challenging nature of V2V communications in ITS scenarios demands continued research and development and hence has a farther deployment horizon.

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A. Target V2I Applications

Besides the delivery of infotainment services, the role of typical V2I systems will include the provisioning of safety-related, real-time, local, and situation-based services, such as speed limit information, safe distance warning, lane keeping support, intersection safety, traffic jam warning, and accident warning. All these services aim to prevent accidents by providing timely information directly to the car and/or to the driver.

An initial set of services for use by V2I systems on European highways has been defined within the European Commission project on CO-OPerative SystEms for Intelligent Road Safety (COOPERS) [1]. Included are 7 safety-critical services (such as accident warning, variable speed limit, and roadwork information) and 5 convenience services (such as estimated journey time and road charging).

In this work we focus on the safety-critical services delivered on highways via V2I systems. Hence, all presented scenarios reflect this setting. This applies particularly to the shared downlink capacity model which is presented in Section III-A and used throughout this paper. The model requires careful parameterization and the choice of all parameter values reflects these realistic scenarios.

B. Transmission Technologies

The problem of ensuring timely and reliable communication amongst vehicles and infrastructure elements remains a central issue in the development of V2I systems. In order to implement this link, various wireless transmission technologies can be deployed, either in isolation or as a complimentary mix of multiple, coexisting technologies. In this work we explore the feasibility of V2I communication based on the three major classes of wireless transmission technologies that are currently considered for ITS, namely:

- Digital Broadcasting: Digital Video Broadcasting-Handheld (DVB-H),
- Cellular systems: Universal Mobile Telecommunications System (UMTS), and
- Dedicated Short Range Communications (DSRC): Wireless Access for Vehicular Environments (WAVE).

The results we present for DVB-H are in fact general and apply equally well to any digital broadcasting systems.

The deployment of any of these technologies requires precise parameterization of the wireless system in question (e.g. density and location of roadside units, power levels, spectrum allocation, etc.), in order to balance meeting the requirements of the V2I system with minimizing the rollout and operational costs. Hence, estimating the requirements of the V2I system, both in terms of coverage and capacity, is a critical step in its deployment.

C. Contributions

The main contribution of this paper is the analysis of the coverage and capacity limitations of the three main classes of wireless transmission technologies listed above. The results enable us to give a direct cross-system comparison, which is another original contribution of this work. Finally, we show each system to be either capacity or coverage limited.

The remainder of this paper is organized as follows. The coverage requirements of the three transmission technologies are considered in Section II. Section III presents an analytical model of the shared downlink capacity requirements of a V2I system, followed by a quantitative comparison of how each of the three systems can be parameterized to meet these requirements. A direct comparison of the three systems, with emphasis on the scaling behavior with the number of users and the coverage area, is given in Section IV. Finally, the conclusions of the paper are given in Section V.

II. Coverage Analysis

One of the critical aspects that must be studied when deploying any wireless system to implement V2I communications is the provision of adequate coverage. The various wireless systems under consideration are fundamentally different in terms of center frequency, modulation, transmission power, cell size, network structure, etc. However, they all must be properly parameterized to provide adequate coverage over the entire road network. In this section, we analyze the particular coverage requirements of each wireless system and the necessary parameterization to achieve these requirements.

A. Digital Broadcasting

Digital broadcasting systems such as Digital Audio Broadcasting (DAB), Digital Multimedia Broadcasting (DMB), Digital Video Broadcasting-Handheld (DVB-H) or Digital Video Broadcasting-Terrestrial (DVB-T) are invariably based on single frequency networks (SFNs). In these networks, all the transmitters broadcast the same signal in the same frequency band. This results in self-interference, where multiple copies of the same signal arrive at each receiver. This transmit diversity can be exploited to improve reception.

Since digital broadcasting systems are designed to send the same signal over large geographical areas, it is not surprising that a typical transmitter has a coverage radius of several kilometers, e.g. over 40 km for DVB-T [2]. For the purposes of V2I systems, a single DVB-T transmitter can cover tens to hundreds of kilometers of the road network. A DVB-T SFN can provide adequate coverage even with relatively few transmitters over the largest nation-wide road networks spanning thousands of kilometers.

It is important to note however, that the SFN concept deliberately removes the ability of the transmitter to act locally and forces the network to provide an identical signal to all receivers in a large geographical area. This also means that the deployment of additional transmitters may increase the coverage area, but it cannot result in a higher data rate. In fact, as the system coverage grows, the per user capacity decreases. This limitation of digital broadcasting systems will be explored further in Section III-B.

B. Cellular Systems

In UMTS, coverage is provided to user equipment (UE) by the set of nodes B in the system, each creating a cell with a particular range. In order to estimate the maximum cell range, we present here a link budget analysis for V2I services. The output of a link budget calculation is the maximum allowable path loss (MAPL) under the following criteria:

- Type of service (data type and speed)
- Type of environment (terrain, building penetration)
- Behavior and type of mobile (speed, max. power level)
- System configuration (antennae, transmit power, cable losses, handover gain)

A propagation model is then used to estimate the maximum cell range from the MAPL. The calculation is reported in Table I by considering the V2I communication scenario. More specifically, some of the values are set according to the following considerations:

- Maximum transmitter power: It is dictated by the UE class [3]. While for a handheld device a maximum value of 21 dBm is permitted, for vehicle-mounted equipments a maximum value of 24 dBm is possible.
- Cable and connector losses: For handheld devices this item is normally zero due to the use of internal antennae. In vehicle-mounted equipment we can assume a value of 2 dB.
- Transmitter antenna gain: For mobile internal antennae this value is normally zero. Equipment with external antennae can have a gain between 3 dBi and 6 dBi.
- Bandwidth factor: It depends on the user data rate r as $10\log(r)$. which in our case gives 40.79 dBHz.
- Interference margin: Also known as the ”rise over thermal”. This value is needed because the load of a cell affects the coverage. In the coverage-limited case this value is below 3 dB. In the capacity-limited case it can grow up to 6 dB for an allowed load of 75%.
- Required E_b/N_t: It represents the energy per bit over noise and interference spectral density needed to meet the QoS requirements. It depends on several factors, including the bearer rate, multipath fading channel, and mobile speed. We derived this value from the service requirements given in the 3GPP specifications [3] for a bearer rate of 12 kbps and a high-speed mobility multipath fading channel.

By using the Okumura-Hata propagation model with the road-side unit (RSU) height of 30 m, on-board unit (OBU) height of 1.5 m, and carrier frequency of 1965 MHz, we obtain the values shown in Table I, which lead to a maximum cell range of 3 km. In Section III-C we will show that the capacity

Initial parameters	
System	UMTS
Frequency	1965 MHz
Bearer rate	12 kbps

	Link budget calculation	
(a)	Maximum transmitter power	24 dBm
(b)	Cable and connector losses	-2 dB
(c)	Transmitter antenna gain	6 dBi
(d)	**Total transmitter e.i.r.p. (a+b+c)**	**28 dBm**
(e)	Thermal noise density	-174 dBm/Hz
(f)	Bandwidth factor	40.79 dBHz
(g)	Thermal noise floor (e+f)	-133.21 dBm
(h)	Receiver noise figure	5 dB
(i)	Load	0.75
(j)	Interference margin	-6 dB
(k)	Required E_b/N_t	5 dB
(l)	**Sensitivity (g+h-j+k)**	**-117.2 dBm**
(m)	Receiver antenna gain	17 dBi
(n)	Cable and connector losses	-3 dB
(o)	**Rx attenuation and gain (m+n)**	**14 dB**
(p)	Other losses (in-building,in-vehicle,body)	0 dB
(q)	Soft handover gain	3 dB
(r)	Log-normal fade margin	-8 dB
(s)	**Propagation components (p+q+r)**	**-5 dB**
(t)	**Maximum path loss (d-l+o+s)**	**154.2 dB**

TABLE I
LINK BUDGET

limitation of UMTS is much more constraining than this coverage limitation.

C. DSRC Systems

To analyze the coverage requirements for DSRC systems, we calculate the number of RSUs that is required in order to cover one segment of length $l_{\text{max}} = 1500\,\text{m}$, which is typical in highway scenarios considered in this work (see Section I-A). For this calculation we use different models for the prediction of the path loss and compare the results of these models.

It is very difficult to predict the real coverage for DSRC systems. Since the technology is relatively new, there exist only a few radio channel measurements for DSRC and no suitable model for path loss prediction have been developed yet. Problems for such a prediction are the relatively high center frequency ($5.9\,\text{GHz}$), low antenna heights, and the complex highway environment.

We investigated three different models for the path loss prediction. Not all of them were developed for V2V or V2I scenarios. However, due to the lack of a proper model, we can estimate the covered distance in a vehicular scenario by comparing the three models. For our investigation we selected the following models:

- Exponent-3-model,
- COST-Hata-model, and
- Inter-vehicle-model.

It will be shown later that the path loss estimate is upper and lower bounded by the COST-Hata and the Inter-vehicle models respectively. The Exponent-3-model is equal to the free space path loss model (see Section 4.1 of [4]), but with an attenuation exponent 3 instead of 2. The free space path loss model is a simple model for calculating path loss in free space. Since in vehicular communications scenarios the antenna heights are very low, we cannot consider a free space wave propagation. Therefore we assume a higher attenuation exponent of 3, which results in a higher path loss.

The second investigated model is the COST-Hata-model [5]. This model was developed for cellular systems in urban areas. Therefore the validation range of the parameters, center frequency, antenna heights, and distance is different from the parameter values from the considered V2V and V2I scenarios. Table II shows the validation range for this model. The upper bound of the frequency range is 2 GHz. However, there are investigations of this model demonstrating its validity also at higher frequencies. Therefore, the frequency is not the limiting factor when using this model for V2V and V2I scenarios. A limiting factor is the lower bound on the base station height (30 m). The height of RSU is approximately 1 m to 6 m, depending if it is placed beside or above the road. The second limiting factor is the lower bound on the distance (1000 m). This is approximately the upper bound on the interesting coverage range of DSRC systems.

Parameter	**Range**
Center frequency (f)	$1500 - 2000\,\text{MHz}$
Base station height (h_{base})	$30 - 200\,\text{m}$
Mobile station height (h_{mobile})	$1 - 10\,\text{m}$
Distance (d)	$1000 - 20000\,\text{m}$

TABLE II
PARAMETER VALIDATION RANGE FOR THE COST-HATA-MODEL

The third model, an inter-vehicle-model for prediction of line-of-sight propagation loss [6], is compared with the other models. This model is developed specifically for DSRC systems. The model results were validated only by one measurement campaign in [6] that was carried out during the night, i.e. with no or at least low traffic and in line-of-sight conditions between transmitter and receiver. This does not mean that it is necessarily valid for ”real” traffic scenarios, where also non line-of-sight conditions occur. Since it is developed for DSRC systems the parameter validation range fits much better than the parameters of the COST-Hata-model, see Table III. Only the maximum transmitter and receiver heights are slightly lower than our assumed maximum height for RSUs (6 m). The inter-vehicle model is derived from multi regression analysis from computer simulations. These computer simulations are using ray tracing calculations, based on the geometrical optics theory. The inter-vehicle model saves calculation time compared with the computer simulations. There are fewer parameters in this model than in the computer simulations and it has therefore an easy handling.

Parameter	**Range**
Center frequency (f)	$400 - 6000\,\text{MHz}$
Transmitter height (h_{Tx})	$0.5 - 3.5\,\text{m}$
Receiver height (h_{Rx})	$0.5 - 3.5\,\text{m}$
Distance (d)	$2 - 1000\,\text{m}$
Street width (W_{s})	$8 - 60\,\text{m}$

TABLE III
PARAMETER VALIDATION RANGE FOR THE INTER-VEHICLE-MODEL

For the calculations of the path loss a center frequency of 5.9 GHz is used, as proposed in the Wireless Access for Vehicular Environments (WAVE) draft standard [7]. The height of the RSU is chosen with 5.5 m, a typical height of equipment which is placed above the road (e.g. section control equipment). The OBU height is set to 1.5 m, which is the average height of the roof of a car, and the street width is set to 20 m. Table IV gives an overview of these parameters for each investigated model. Not all models need the whole set of parameters. The exponent-3-model requires only the frequency as parameter, the COST-Hata-model the frequency and both antenna heights, and the inter-vehicle-model additionally the street width.

Model	Exponent-3	COST-Hata	Inter-vehicle
Center frequency (f)	5.9 GHz	5.9 GHz	5.9 GHz
RSU height (h_{RSU})	-	5.5 m	5.5 m
OBU height (h_{OBU})	-	1.5 m	1.5 m
Street width (W_s)	-	-	20 m

TABLE IV
PARAMETER SETTINGS FOR THE THREE DIFFERENT MODELS

Figure 1 presents the path loss over the distance for all of the three models. There are considerable differences between the path loss calculated with each model: at a distance of 1000 m the difference between the inter-vehicle-model (98.9 dB) and the COST-Hata model (163.4 dB) is more than 60 dB. The path loss curve calculated with the COST-Hata-model can be seen as the upper bound, while the lower bound is represented by the inter-vehicle-model.

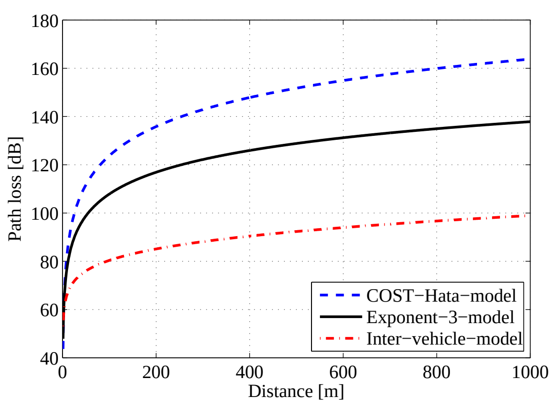

Fig. 1. Path loss vs. distance for the three different models

In the following, calculations of the achievable distances at certain data rates are presented for each model. We consider two different data rates, namely the lowest and the highest mandatory data rates for a 10 MHz channel defined in the draft WAVE standard [7], $R_1 = 3$ Mbit/s and $R_2 = 12$ Mbit/s. For these two data rates the minimum receiver sensitivities are $P_{\text{Rx},1} = -85$ dBm and $P_{\text{Rx},2} = -77$ dBm. For the transmit and receive antennae an antenna gain of $G_{\text{Tx}} = G_{\text{Rx}} = 10$ dBi is assumed, which is a realistic value for monopole antennae in the 5 GHz band [8]. Together with the transmit power, we calculate the path loss, as it is depicted in the link budget in Figure 2. The transmitter- and receiver antenna gain allow a higher path loss and therefore a larger covered distance.

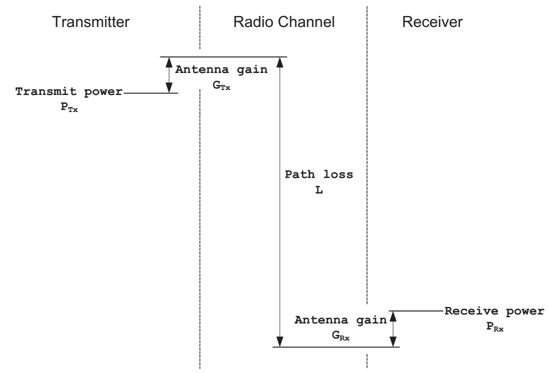

Fig. 2. Link budget

The path loss is calculated for two different transmit powers: $P_{\text{Tx,a}} = 44.8$ dBm, which is the highest allowed transmit power in the public safety case, and $P_{\text{Tx,b}} = 33.0$ dBm, which is the highest allowed power in the private usage case. With these assumptions we calculate the maximum allowed path loss with (1), where the powers and the gains are expressed in dBm and dB, respectively.

$$L|_{\text{dB}} = P_{\text{Tx}}|_{\text{dBm}} - P_{\text{Rx}}|_{\text{dBm}} + G_{\text{Tx}}|_{\text{dB}} + G_{\text{Rx}}|_{\text{dB}} \quad (1)$$

Table V shows the resulting path losses. The highest allowed path loss is equal to $L_{\text{a},1} = 149.8$ dB, which is achieved in the public safety case with the lowest data rate of 3 Mbit/s.

	Public safety	Private use
3 Mbit/s	$L_{\text{a},1} = 149.8$ dB	$L_{\text{b},1} = 138$ dB
12 Mbit/s	$L_{\text{a},2} = 141.8$ dB	$L_{\text{b},2} = 130$ dB

TABLE V
ALLOWED PATH LOSSES FOR PUBLIC AND PRIVATE USE CASES, WITH DIFFERENT DATA RATES

With these maximum allowed path losses and considering the path loss curves for the different models in Figure 1, we calculate the maximum achievable distances. Results are shown in Table VI.

	Public safety		Private use	
	3 Mbit/s	12 Mbit/s	3 Mbit/s	12 Mbit/s
Exponent-3-model	$>$ 1000 m	$>$ 1000 m	1000 m	550 m
COST-Hata-model	450 m	280 m	230 m	140 m
Inter-vehicle-model	$>$ 1000 m	$>$ 1000 m	$>$ 1000 m	$>$ 1000 m

TABLE VI
MAXIMUM COVERED RANGES FOR PUBLIC AND PRIVATE USE CASES, WITH DIFFERENT DATA RATES AND ALL THREE DIFFERENT MODELS

In the public safety case, the communication distance is larger than 1000 m for the exponent-3-model and the inter-vehicle-model for both data rates. The COST-Hata-model yields a maximum distance of 450 m and 280 m at 3 Mbit/s and 12 Mbit/s, respectively. Considering the results of the exponent-3-model or inter-vehicle-model and a segment length of 1500 m, one RSU is needed for each segment, because the RSU is able to transmit data up to 1000 m in both directions of the road. Considering the path loss of the COST-Hata-model, two RSUs for the lower data rate and three RSUs for the higher data rate are required.

In the case of private usage, the coverage ranges are shorter, because of the lower transmit power, $P_{\mathrm{Tx,b}} = 33\,\mathrm{dBm}$. The inter-vehicle-model again predicts the need for only one RSU per segment for both data rates. The exponent-3-model predicts ranges of $1000\,\mathrm{m}$ for the lower data rate, i.e. one RSU per segment, and $550\,\mathrm{m}$ for the higher data rate, i.e. two RSUs per segment. The COST-Hata-model predicts much lower ranges, and thus requires 4 and 6 RSUs per segment for the lower and higher data rates respectively.

1) Antenna Height: In the following, the influence of the RSU height on the path loss is presented. Figure 3 shows the path loss over the RSU height at a distance of $200\,\mathrm{m}$, calculated with the COST-Hata-model. The path loss is decreasing with increasing antenna height. At a height of $1\,\mathrm{m}$ of the RSU we get a path loss of $142.7\,\mathrm{dB}$ and at a height of $10\,\mathrm{m}$ a path loss of $133.4\,\mathrm{dB}$, i.e. a difference of $9.3\,\mathrm{dB}$ between these two heights. Considering the maximum allowed path loss of $138\,\mathrm{dB}$ in the private usage case and with the lower data rate of $3\,$Mbit/s, (see Table V), the RSU height has to be at least $3.2\,\mathrm{m}$.

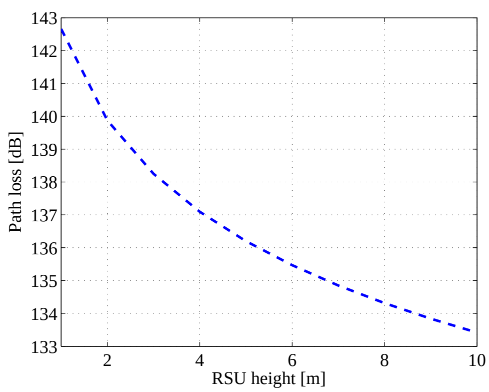

Fig. 3. Path loss vs. RSU height at a distance of $200\,\mathrm{m}$, calculated with the COST-Hata-model

Figure 4 shows the path loss over RSU height at a distance of $200\,\mathrm{m}$, calculated with the inter-vehicle-model. The path loss decreases quickly until the RSU height of around $3\,\mathrm{m}$. Notably, the trend changes when a value of $6\,\mathrm{m}$ is reached. This phenomenon has no physical background, but the validation range of the RSU height of the inter-vehicle-model is between $0.5\,\mathrm{m}$ and $3.5\,\mathrm{m}$ of RSU heights. The difference between the maximum path loss at $1\,\mathrm{m}$ height and the minimum path loss at $6\,\mathrm{m}$ height is $2.8\,\mathrm{dB}$. Compared with the COST-Hata-model the path loss dependence on the RSU height is smaller in the inter-vehicle-model.

The exponent-3-model has no parameters for transmitter or receiver height, i.e. the dependence of the path loss on the RSU height is not taken into consideration.

In summary, in the worst case of private use, with the highest mandatory data rate, RSU and OBU heights of $5.5\,\mathrm{m}$ and $1.5\,\mathrm{m}$ respectively, and using the COST-Hata model, up to 6 RSUs are needed to provide adequate coverage for a $1500\,\mathrm{m}$ road segment. In general the COST-Hata model

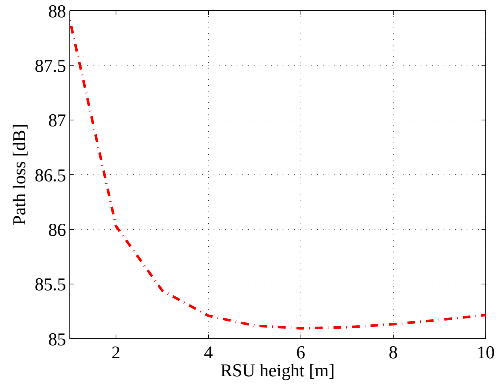

Fig. 4. Path loss vs. RSU height at a distance of $200\,\mathrm{m}$, calculated with the inter-vehicle-model

yielded the highest path losses and therefore the smallest RSU cell sizes. This model will be used for further calculations in the following sections, because the resulting path losses describe an upper bound.

III. CAPACITY ANALYSIS

Another critical aspect to be considered when deploying any wireless technology to implement a V2I system is the required downlink capacity (data rate). Of particular interest is the scaling of the capacity requirement with the number of users in the system, the geographical area to be covered, and the number and complexity of the offered services. Each choice of wireless technology brings with it a particular capacity requirement and scaling behavior.

Since the downlink capacity in any broadcast or multicast schemes is shared among several users, an analytical model taking this shared medium into consideration is required. In this section, we present such a model for V2I systems, followed by an analysis of the capacity requirements of digital broadcasting, cellular, and DSRC systems.

A. Shared Downlink Capacity Model

As mentioned above, in V2I systems that employ broadcast or multicast schemes, several or all the users (in one, many, or all the road segments in the system) share the same downlink data stream. Thus, the data stream needs to be time-division multiplexed, in a so-called carousel scheme. Approaches in which localized and global services are combined have been proposed [9]. Nonetheless, the fundamental fact that a single data stream is shared cannot be alleviated.

However, it would not be correct to assume that the information content across all the segments and users is strictly independent. In fact, significant overlap in the information being transmitted to various segments and users may exist. This overlap can be exploited to compress the downlink data stream, effectively reducing the required downlink capacity.

Clearly the extent of compression that can be achieved varies with the actual data content. Thus, what is needed is a measure of the true information content present in each update round of the carousel scheme. This measure describes the lower bound on the amount of data that will in fact be transmitted on the downlink of the V2I system, effectively defining the capacity requirement of the downlink channel.

The measure of true information content in a data stream is referred to as information entropy as introduced by Claude Shannon [10]. A data stream characterized by low entropy, or in Shannon's words "choice" of possible information content, offers the possibility to achieve a relatively high degree of compression, and thus has a low overall downlink data rate requirement. Conversely, a data stream characterized by high entropy, or a great variety of information content, offers a relatively low degree of achievable compression, and thus has a high data rate requirement.

In order to model the entropy content of the downlink data stream of V2I systems we introduce two independent entropy parameters: the user entropy, η, and the segment entropy, ϕ. User entropy expresses the variety of information content for any given service across the various users in each segment, while segment entropy expresses the variety of information content for that same service across the various road segments that the V2I system comprises.

Both entropy parameters in the presented model are normalized, such that $\eta \in [0,1]$ and $\phi \in [0,1]$. When $\eta_j = 0$, this signifies that during the current update all the users in the given segment are receiving the same information for the particular service j. Conversely, if $\eta_j = 1$, this means that each individual user is receiving information content different to that of all the other users. An analogous interpretation holds for the values of segment entropy: when $\phi_j = 0$ service j delivers the same information content to all the segments in the system and when $\phi_j = 1$, service j delivers unique information content to each segment.

A key characteristic of both entropy parameters is their highly dynamic nature. Since they represent the current information content in the raw downlink data stream, their values change with each update period in the carousel scheme, which is typically in the order of a few seconds.

It is important to note that neither of the entropy parameters is designed to represent the performance of any particular compression scheme. They aim rather to expose the inherent upper bound on the achievable compression in the raw downlink data stream, which is also the lower bound on the required downlink capacity. These results are optimistic in that they assume a zero overhead (in terms of data volume) for the compression operation.

Based on these entropy parameters, we developed a model for downlink capacity requirements of V2I systems [11] in collaboration with the European Commission research project on Co-operative Systems for Intelligent Road Safety (COOPERS) [1]. In particular, the service structure defined within the COOPERS project [12] and the project's test sites are taken into account.

Both the infrastructure (length of road, number of segments, number of lanes, speed limits, offered services etc.) and current traffic conditions (number of vehicles, average speed, weather conditions, traffic jams, etc.) are taken into consideration as parameters in the model. A list of all the parameters is shown in Table VII.

Description	Symbol	Unit
Total length of the covered road network	c	m
Number of segments in the system	s	-
Segment length	$\boldsymbol{l}$	m
Number of lanes in segment s	$\boldsymbol{m}$	-
Speed in segment s	$\boldsymbol{v}$	m/s
Retention time of segment s	$\boldsymbol{t}$	s
Following tempo	t_{fol}	s
Following distance in segment s	$\boldsymbol{l}_{fol}$	m
Length of a vehicle	l_{veh}	m
Number of users in segment s	$\boldsymbol{u}$	-
Probability of a traffic jam	x	-
Segment occupancy (load)	$\boldsymbol{o}$	-
Number of services in the system	n	-
Fundamental data volume for service n	$\boldsymbol{b}$	bits
Service activity	$\boldsymbol{a}$	-
User entropy for service n	$\boldsymbol{\eta}$	-
Segment entropy for service n	$\boldsymbol{\phi}$	-
Data volume for service n in segment s	$\boldsymbol{J}$	bits
Update period for service n in segment s	$\boldsymbol{P}$	s
Maximum speed	v_{max}	m/s
Minimum retention time of segment s	$\boldsymbol{t}_{min}$	s
Maximum update period for any service in segment s	$\boldsymbol{p}_{max}$	s
Data rate for service n in segment s	$\boldsymbol{D}$	bit/s
Total data rate for service n	$\boldsymbol{d}$	bit/s
System data rate	r	bit/s

TABLE VII
V2I SYSTEM PARAMETERS

The capacity model itself is expressed as a set of equations modeling the relationships among these parameters. We use variables i and j to index segments and services respectively. Hence $i \in [1,s]$ and $j \in [1,n]$. The segment length $\boldsymbol{l}$ is calculated directly from the total system coverage and the number of segments in the system:

$$l_i = \frac{c}{s}. \tag{2}$$

The following distance between vehicles, $\boldsymbol{l}_{fol}$, is a function of the vehicle speed in the segment, which is assumed uniform over all vehicles, and the following tempo, or the inter-vehicle time, as

$$l_{fol_i} = v_i t_{fol}. \tag{3}$$

How long a vehicle stays in a given segment is the segment's retention time, $\boldsymbol{t}$. It is a function of the segment's speed and length parameters, as

$$t_i = \frac{l_i}{v_i}. \tag{4}$$

The number of users in a given segment, $\boldsymbol{u}$, is calculated as

$$u_i = \frac{m_i l_i o_i}{l_{veh} + l_{fol_i}}, \tag{5}$$

where $\boldsymbol{m}$ is the number of lanes, l_{veh} is the length of a vehicle, and $\boldsymbol{o}$ is the segment occupancy, or load. For a given service in a given segment, the data volume to be transmitted, $\boldsymbol{J}$, is

$$J_{i,j} = a_j b_j (1 + \eta_j (u_i - 1)), \tag{6}$$

where the activity of each service is represented by $\boldsymbol{a}$ and the data volume to be delivered in each update is given by $\boldsymbol{b}$. The achievable compression over the users in the segment is expressed by $\boldsymbol{\eta}$. The required update period for each service

Parameter	Value	Unit
Length of the road network (c)	2,000,000	m
Segment length ($\boldsymbol{l}$)	1500	m
Number of segments (s)	1333	-
Maximum speed (v_{max})	50	m/s
Number of lanes ($\boldsymbol{m}$)	4-10	-
Update period ($\boldsymbol{P}$)	7	s
Speed ($\boldsymbol{v}$)	25-27.8	m/s
Occupancy ($\boldsymbol{o}$)	0.4-0.6	-
Traffic jam probability (x)	0.02	-
Number of services (n)	8	-
Length of a vehicle (l_{veh})	7.5	m
Following tempo (t_{fol})	2	s
Fundamental data volume ($\boldsymbol{b}$)	400	bits
Service activity ($\boldsymbol{a}$)	(0.02,0.03,0.03,0.07,1,1,1,1)	-

TABLE VIII
PARAMETER VALUES

in a given segment is given by $\boldsymbol{P}$ and helps us derive the data rate requirement $\boldsymbol{D}$ as

$$D_{i,j} = \frac{J_{i,j}}{P_{i,j}}. \quad (7)$$

Hence, the system-wide data rate requirement for each service, $\boldsymbol{d}$, is calculated as

$$d_j = \frac{\sum_i D_{i,j}}{s - \phi_j(s-1)}, \quad (8)$$

where the achievable compression over the various segments is represented by $\boldsymbol{\phi}$. Finally, this lets us compute the required total data rate for the entire system, r, as

$$r = \sum_j d_j. \quad (9)$$

B. Digital Broadcasting

Recently, much interest has been shown for using digital broadcasting systems as the downlink transmission technology in V2I systems. The SFN networks these systems are built on have high spectral efficiencies and are optimized for delivery of the same content to many users in a large geographic area. While this model at first glance suits the needs of V2I telematic systems well, it also implies severe restrictions. The most important of these is the need to deliver all the V2I system's services, to all the users, in all the geographic parts of the system, using the one shared downlink stream. Therefore, this downlink stream must be time-division multiplexed between the various services, users, and geographic segments in the system. The total capacity requirement on the downlink stream thus becomes the design bottleneck for V2I systems based on digital broadcast systems.

In order to gauge the capacity requirements of digital broadcasting systems, a realistic deployment scenario must be evaluated using the capacity model presented in Section III-A. Hence, we will use the model to represent the complete highway network of Austria under normal operating conditions. To this end, the parameter values shown in Table VIII will be used.

The accumulated length of the existing highway network in Austria comes up to approximately 2000 km. For operational reasons, this network is divided into sections, or segments, of varying length (typically 800-2000 m). For simplicity, we model the highway network as made up of equal segments of 1500 m each. Each of these segments contains a number of lanes (in the range of 4-10) taking into account both driving directions. Each segment also has a given probability of being in a traffic jam, assumed here to be 0.02.

Typically, average vehicle speed under free flow conditions on Austrian highways lies in the range 90-100 km/h (55.9-62.1 mph or 25-27.8 m/s). In addition to this, we assume the speed of the fastest traveling vehicles to be 180 km/h (111.8 mph or 50 m/s). The occupancy parameter expresses the number of vehicles in the segment normalized to the maximum possible number of vehicles given the current speed, vehicle length, and following tempo (inter-vehicle time). Under free flow conditions, the occupancy is in the range 0.4-0.6.

The vector of values for the parameter $\boldsymbol{a}$ represents four irregular, "bursty" services (such as accident warning or weather warning) followed by 4 regular, "always on" services (such as variable speed limit or estimated travel time). For simplicity, the update period and the average message size (data volume to be transmitted per update period) are modeled equal for all services as 7 s and 50 bytes (400 bits) respectively. All these parameter values are based on the set of real services created in the COOPERS project [1].

The required total system data rate r is derived using the downlink capacity model given in Section III-A and is expressed as a function of two parameters, user and segment entropies $\boldsymbol{\eta}$ and $\boldsymbol{\phi}$ respectively. These are rapidly changing parameters inherent in the data stream as it is being transmitted, and thus need to be considered in their entire range. Both $\boldsymbol{\eta}$ and $\boldsymbol{\phi}$ are modeled to be uniform across all the services in the system, i.e. $\boldsymbol{\eta} = \eta \cdot \mathbf{1}_n$ and $\boldsymbol{\phi} = \phi \cdot \mathbf{1}_n$, where $\mathbf{1}_n$ is the all-one vector of length n.

Hence, the data rate r is plotted as a series of curves, each curve expressing r with respect to η, and each separate curve in the series representing a particular value of ϕ. The values of ϕ extend from 0 (always corresponding to the lowest data rate requirement) to 1 (always corresponding to the highest data rate requirement) in steps of 0.25, i.e. $\phi \in \{0, 0.25, 0.5, 0.75, 1\}$, thus giving five curves, as shown in Figure 5.

To summarize, the peak system data rate requirements for the Austrian highway network under normal operating conditions is 36.6 Mbit/s. It should be noted that this result is conservatively low, in that it assumes perfect dynamic data compression with no overhead. The overall data rate requirement translates directly to the required allocation of frequency bands.

For example, if a Terrestrial DMB (T-DMB) system is to be deployed to implement the downlink of the V2I system over the Austrian highway network, a sufficient number of frequency channels must be reserved to fulfill the calculated requirement. Since each of the 1.712 MHz channels of a T-DMB system practically provides 1.06 Mbit/s of downlink capacity [13], 35 channels must be permanently assigned to the V2I system! These could cover just the normal operating conditions and an additional contingency for changing traffic conditions would also be required.

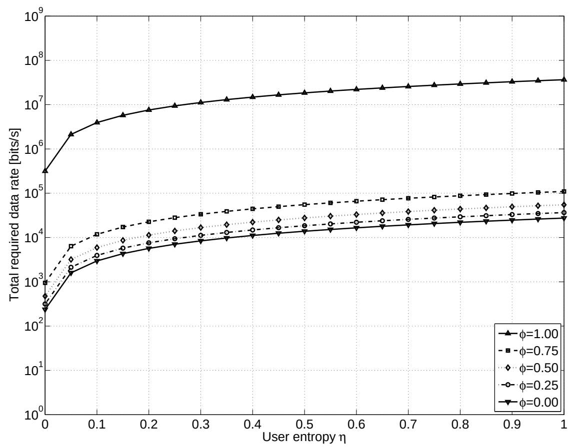

Fig. 5. Austria site in the normal operation scenario

C. Cellular Systems

Cellular systems such as UMTS also exhibit limitations in the downlink capacity. We compare the legacy UMTS network as conceived in 3GPP Release 5 (dedicated channel, DCH regime) with the new multimedia broadcast/multicast service (MBMS), as introduced in 3GPP Release 6. It should be noted that unlike the DCH regime, the MBMS regime makes use of a common channel, which can be seen as a common resource shared by several users.

In both cases, UMTS cell capacity in the downlink is ultimately limited by the total available power at node B. In [14] we presented an analytical model for estimating cell capacity in V2I scenarios with and without the MBMS channel overhead. We summarize here the main results.

The model is based on the assumption that UE in the DCH are able to get exactly the required E_b/N_0 (energy per bit to noise power spectral density ratio), i.e. the fast power control works ideally:

$$\left(\frac{E_b}{N_0}\right)_i = \frac{\dfrac{E_{c,i_{\mathrm{DPCH}}}}{L_{m,i}}\left(\dfrac{W}{R_i}\right)}{(1-\alpha_i)\dfrac{I_{\mathrm{or}}}{L_{m,i}} + \sum\limits_{\substack{n=1\\n\neq m}}^{N}\left(\dfrac{I_{\mathrm{or}}}{L_{n,i}}\right) + P_N} . \quad (10)$$

Here $E_{c,i_{\mathrm{DPCH}}}$ is the expected transmission power at node B to UE *i*, W is the chiprate, R_i is the bitrate for the selected service, $L_{m,i}$ is the path loss from the serving node B to the UE *i*, $L_{n,i}$ is the path loss from another node B *n* to the UE *i*, N is the number of relevant neighboring nodes B, I_{or} is the total transmission power of the nodes B (assumed to be equal for all the surrounding nodes B), α_i is the codes orthogonality factor for UE *i* ($\alpha_i = 1$ means perfect orthogonality), and P_N is the thermal noise power. Note that the first and the second terms in the denominator represent respectively the intra-cell and inter-cell interference.

The maximum number of users in DCH is reached when:

$$\sum_{i=1}^{N_{\mathrm{users}}} E_{c,i_{\mathrm{DPCH}}} = (1-\mu_{\mathrm{OH}}-\mu_{\mathrm{MBMS}})I_{\mathrm{or}} , \quad (11)$$

where μ_{MBMS} is the power overhead due to the MBMS introduction and μ_{OH} is the power overhead due to the other common channels. Note that μ_{MBMS} depends only on the MBMS quality requirements and the MBMS bearer bitrate.

Solving (10) for $E_{c,i_{\mathrm{DPCH}}}$ and substituting into (11), we obtain

$$\sum_{i=1}^{N_{\mathrm{users}}} \frac{\left(\dfrac{E_b}{N_0}\right)_i R_i}{W}\left[(1-\alpha_i+f_{\mathrm{i,DL}})I_{\mathrm{or}} + P_N L_{m,i}\right] = (1-\mu_{\mathrm{OH}}-\mu_{\mathrm{MBMS}})I_{\mathrm{or}} , \quad (12)$$

where $f_{\mathrm{i,DL}} = \sum_{n=1,n\neq m}^{N}\frac{L_{m,i}}{L_{n,i}}$ represents the interference factor for UE *i* (sometimes refered to as *other-cell to own-cell interference ratio*).

By restricting the model to the traffic telematic services, it is reasonable to assume that all connections will present the same bitrate and quality requirements. Equation (12) leads to

$$N_{\mathrm{users}}\left[\frac{\dfrac{E_b}{N_0}R}{W}\left(1-\alpha+f_{\mathrm{DL}}\right)I_{or} + \frac{\dfrac{E_b}{N_0}R}{W}P_N L\right] = (1-\mu_{\mathrm{OH}}-\mu_{\mathrm{MBMS}})I_{\mathrm{or}} , \quad (13)$$

where α is the average orthogonality factor, L is the average path loss, and f_{DL} is the average interference factor. The estimated maximum number of users on the dedicated channels[1] is therefore given by

$$N_{\mathrm{users}} = \frac{(1-\mu_{\mathrm{OH}}-\mu_{\mathrm{MBMS}})I_{\mathrm{or}}}{\dfrac{\dfrac{E_b}{N_0}R}{W}\left(1-\alpha+f_{\mathrm{DL}}\right)I_{\mathrm{or}} + \dfrac{\dfrac{E_b}{N_0}R}{W}P_N L} . \quad (14)$$

1) ITS-over-UMTS: As a starting point we explore the performance that can be achieved when ITS services are offered through conventional dedicated channels, i.e in the DCH regime. In other words, MBMS functionalities are not utilized, i.e. $\mu_{\mathrm{MBMS}} = 0$.

During the study it turned out that the communication performance is affected by several operator-dependent parameters in the radio network: inactivity timers and thresholds, handover and cell-reselection parameters all have a strong impact on the global system efficiency. The dynamic nature of the traffic conditions makes it very difficult to find an optimal static setting. The critical requirements change dramatically in the two extreme road situations: traffic jam and fluent high-speed traffic. In the case of traffic jam, greater cell capacity is needed, while for high speed traffic the support of mobility becomes critical. Notably different radio channel models have to be considered in the analysis of different road conditions. We evaluate the cell capacity both for the stationary and the high speed mobility case. For the latter we use the channel model defined as "case 3" in the UMTS standard [3] and described in Table IX. Note that E_b/N_0 is mostly a function of the mobility channel and service requirements as defined in [3].

[1]Note that we do not consider here the channelization code limit as we verified that in our scenarios it was much looser than the power limit

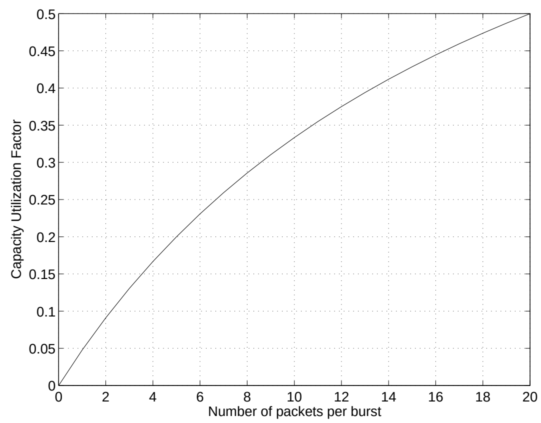

Fig. 6. Capacity Utilization Factor vs. Number of packets per burst

We analyze the performance of a UMTS Release 5 configuration in terms of the number of users that use the ITS services. The unicast nature of the DCH places a strict limitation on the maximum number of users-per-cell that can be served by the V2I system: a separate DCH must be setup for each user, causing multiple content duplications, hence wastage of the overall capacity. The spreading factor (SF) of the DCH plays an important role in the calculation of the maximum offered cell capacity. We found that SF=256 is sufficient to meet the considered ITS service requirements, i.e. each user being able to receive simultaneously up to 8 service updates of 400 bits. Table X summarizes the results obtained by using equation (14). Following [15, page 194] and considering macrocells with 3 sectors, we set $F_{DL} = 0.65$. Regarding the average orthogonality factor α, we need to account for its dependency on the multipath propagation. Therefore we used $\alpha = 0.9$ for the stationary case (ITU Pedestrian A channel) and $\alpha = 0.5$ for the high-speed mobility case (ITU Vehicular A channel).

Note that the calculation in (14) does not consider the additional delay overhead caused by the channel assignment/release procedures. Hence, the values in Table X represent a theoretical performance bound. These additional delay components are much larger than the transmission time of a few packets and reduce the achievable capacity utilization. The latter depends on the number of service updates that are sent in the same transmission burst. In other words, the achievable cell capacity is obtained by multiplying the results in Table X with a capacity utilization factor γ defined as

$$\gamma = \frac{T_{\text{burst\_transmission}}}{T_{\text{assignment}} + T_{\text{release}} + T_{\text{burst\_transmission}}}. \tag{15}$$

Figure 6 depicts the value of γ as a function of the number of packets per burst. We have considered an allocation delay of 900 ms (following [15, page 281]) and an inactivity timer of 100 ms. Although such a small value for the inactivity timer is unusual in operational UMTS networks optimized for world wide web (WWW) and wireless application protocol (WAP) [16], it represents an optimal choice for ITS, where the minimization of resource consumption is of primary importance and the interval between traffic bursts is predictable.

	Relative Delay (ns)	Relative Mean Power (dB)
1st detected path	0	0
2nd detected path	260	-3
3rd detected path	521	-6
4th detected path	781	-9

TABLE IX
MOBILITY CHANNEL

Road condition	Congested	Fluent
Channel model	Stationary	High-speed mobility
$E_{c,\text{DPCH}}/I_{\text{or}}$	-22.6 dBm	-19.8 dBm
Max number of simultaneous users	136	71
Max downlink cell capacity	1.6 Mbps	866 Kbps

TABLE X
DOWNLINK CELL CAPACITY

From the values in Table X it can be seen that when 8 messages are sent in the same transmission burst ($\gamma = 0.29$) the effective achievable cell capacity would reach only 450 Kbps in the stationary scenario and 250 Kbps in the high speed case. In summary, the DCH regime is inefficient and the average capacity in terms of transferred data per second is inadequate to support ITS services.

2) ITS-over-MBMS: MBMS [17] introduces a new point-to-multipoint transmission bearer by using shared network resources in the service layer, in the core network, and in the radio access network. MBMS data uses a high rate forward access channel (FACH) that is in turn carried by the secondary common control physical channel (S-CCPCH). MBMS provides two modes of operation:

- **Broadcast Mode**: Data is transmitted to all the MBMS capable UEs in a broadcast service area without any subscription procedure;
- **Multicast Mode**: Data is delivered only to the UEs in a multicast service area that have joined a multicast group after a subscription procedure.

Both streaming and file download services are provided by MBMS [18]. In the streaming mode, a continuous data flow provides a stream of media with optional additional text and/or still images. In the file download mode, the MBMS bearer distributes binary files and utilizes file repair procedures for providing reliability. The bitrate of a single MBMS bearer can range between 10 Kbps and 384 Kbps. In our scenario each car is equipped with a full 3GPP Release 6 compliant OBU. All the authorized OBUs join the multicast group where ITS messages are distributed. Each message is sent in the form of binary data by the RSU through the file download service provided by the MBMS architecture. We assume that the UMTS network covers the road regions served by the ITS completely - the ”multicast service area” in [17]. The road is divided into road segments. Each segment forms a ”local multicast area”, where the same multicast content is delivered. Different local multicast areas may have different contents and bearers. Therefore, we do not include the segment entropy in the evaluation of ITS-over-MBMS.

The proposed architecture is depicted in Figure 7. Note that some new entities are introduced in comparison to the conventional UMTS architecture: the broadcast/multicast-

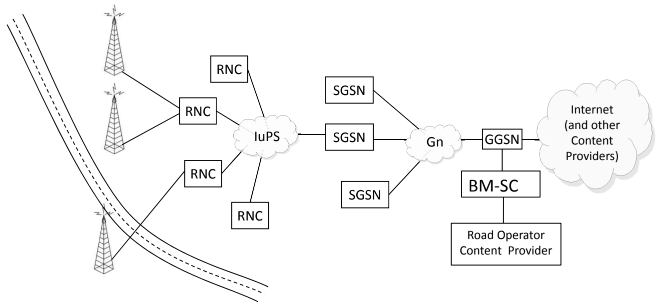

Fig. 7. ITS-over-UMTS Architecture with Release 6 functionalities

service center (BM-SC) and the road operator content provider (ROCP). The BM-SC belongs logically to the UMTS operator and can be implemented in the gateway GPRS support node (GGSN) or as an independent entity. It serves as an entry point for content delivery services, which are provided by an external content provider, i.e. the ROCP. In other words, the ROCP delivers binary data through the UMTS network in a real multicast mode to registered OBUs, where a higher layer client application decodes the information. The use of a real multicast transmission reduces the requirements in terms of downlink capacity: as the same content is distributed to different users the required capacity scales with the number of services and is independent on the number of receivers.

The efficiency of using MBMS depends on the relative fraction of dedicated content over the total volume of ITS traffic, captured by the parameter η defined in Section III-A. We considered as worst case a traffic jam scenario. The input parameters for the system capacity model are listed in Table XI.

Parameter	Value	Unit
Number of segments, s	1	-
Number of services, n	8	-
Segment length, l	1500	m
Update period of each service, $\boldsymbol{P}$	7	s
Message size, $\boldsymbol{b}$	400	bits
Car length + distance to next car, l_{veh}	7.5	m
Number of lanes, m	10	-
Service activity, $\boldsymbol{a}$	1	-
User entropy, η	0-1	-
Following distance, l_{fol}	0	m
Occupancy, o	1	-
Speed, v	0	m/s

TABLE XI
SERVICE BASED PARAMETERS

We propose two different methods for handling the transmission of dedicated content in the MBMS regime. The first method consists in using MBMS for multicast messages and the remaining DCHs for unicast transmissions of dedicated contents. In this case the limiting resource is again the available power at the base station. As MBMS consumes part of the available cell capacity, it limits the number of DCHs that can be established. Recall that MBMS is typically carried by the FACH channel, in which no fast power control is implemented. Therefore the node B is required to pre-assign a certain amount of power to the MBMS services. The 3GPP specifications provide an estimation of the required MBMS power overhead, obtained by link-level simulations [19]. Clearly, this overhead depends on the expected MBMS bearer bit rate and whether trasmission diversity is enabled or disabled. By applying 3GPP estimates of μ_{MBMS} to equation (14) the residual cell capacity on the DCH can be estimated. Results for the combined MBMS/DCH scenario are presented in Table XII.

The second method uses pure broadcasting and makes use of a carousel transmission inside the MBMS session. With this approach dedicated contents are broadcast in the whole area and an application layer addressing mechanism at the OBUs is in charge to selectively identify the messages to be processed or discarded. Two advantages can be achieved by using this approach: a single bi-sectorial macro-cell can meet the capacity requirements and coexistence with voice users is eased since the remaining DCHs remain untouched.

The choice between the two approaches depends on the value of the user entropy η, which in turn determines the total required data rate. Figure 8 depicts the data rate requirements for different values of η in our reference scenario. At one

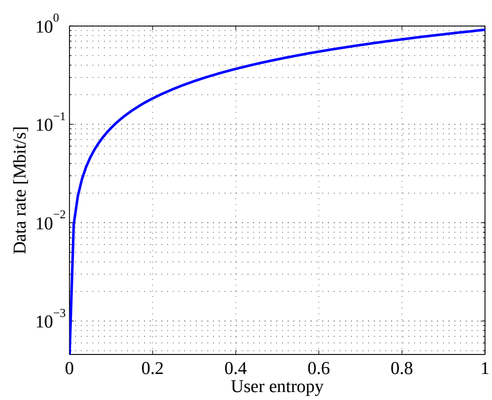

Fig. 8. Required data rate vs. user entropy

extreme point $\eta = 1$, i.e. when only dedicated content is transferred to all users, up to approximately 1 Mbps is required. As expected, a typical ITS scenario, where $0 \leq \eta \leq 0.3$, requires only 300 Kbps.

We now proceed to evaluate a hybrid bi-modal scheme that switches automatically between DCH and carousel transmission modes for dedicated content. The switching logic is based on thresholds on the number of registered OBUs present in the cell and on η. We consider the following cases:

1) free road;
2) congested road, low η;
3) congested road, high η.

MBMS datarate	Residual sustainable users	
	TX diversity disabled	TX diversity enabled
16 Kbps	123	128
32 Kbps	107	117
64 Kbps	84	101
128 Kbps	20	82

TABLE XII
COMBINED MBMS/DCH SCENARIO

In case 1 only few cars are on the road (e.g. during the night). The allocation of the MBMS multicast radio bearer is unjustified since the power that would be required to serve the users directly on the DCHs is less than the power required to setup an MBMS FACH transmission. Therefore, the users should be served via normal DCHs. When the number of cars with registered OBUs exceeds a certain threshold (case 2) the network switches automatically to the MBMS multicast transmission. In this case all the OBUs are served through the MBMS channel and dedicated contents are sent via carousel transmissions. If ROCP needs to send several dedicated messages, i.e. high η (case 3), the remaining dedicated channels should be used in support of the MBMS multicast transmission. The feasibility of this approach is guaranteed by the ”MBMS counting” functionality introduced in [17], which lets the radio access network identify the number of UEs with activated MBMS services within a cell.

D. DSRC Systems

DSRC systems also need to be parameterized according to the required downlink capacity requirement. In this section we investigate this capacity requirement by finding the number of RSUs necessary in order to cover one whole segment with a sufficient data rate. The maximum required data rate in one segment is obtained when the segment is full occupied. We therefore assume a traffic jam situation and use the downlink capacity model shown in Section III-A.

We consider the case of an isolated segment (i.e. $s = 1$), with 8 different services, each sending messages of size 400 bits. All the services are assumed to be always-on services with an update period of 7 s. We consider the segment length of 1500 m and an inter-vehicle distance (including car length) of 7.5 m in case of a traffic jam, corresponding to the maximum number of cars in the segment. The number of lanes is set to 10, accounting for both directions. Due to the traffic jam situation, the following distance between the cars, l_{fol}, is reduced to 0, the segment is fully occupied, and the speed of all vehicles is 0. For the calculation of the required data rate, we used the values already provided in Table XI. Note that we consider a carousel scheme, where all users share one DSRC downlink channel. Further we make the optimistic assumption of the transmission of the pure message data without overhead, e.g. for signaling, and no acknowledgment messages on the uplink channel. That means that there is no time spent for the acknowledgment phase. The datarate requirements shown in Figure 8 are therefore valid in the DSRC study as well. With a user entropy of 1, i.e. with each user getting a dedicated message from each service, the maximum required capacity per segment is approximately 0.9 Mbit/s.

In the following we calculate the theoretical offered capacity from one RSU and compare it with the required data rate calculated above. The theoretical offered capacity from the RSU can be seen as the upper bound on the required data rate. Based on this comparison we get the maximum distance that can be achieved in order to cover the whole RSU cell with the required data rate. For this calculation we again consider the worst case when user entropy is maximal ($\eta = 1$). The required data rate per RSU cell depends on the size of this cell. As mentioned in the last section the required data rate depends on the number of users (vehicles). Considering a traffic jam scenario with full loaded RSU cells the number of vehicles per RSU cell depends on the cell size. Therefore the required data rate is a function of the RSU cell size. The theoretical offered capacity is given by

$$C_{\text{offered}} = B \log_2 \left(1 + \frac{\sigma_1^2}{\sigma_0^2}\right). \quad (16)$$

Here B is the signal bandwidth of the DSRC channel of 10 MHz, σ_0^2 is the noise power and σ_1^2 the receive power. The noise power is given by

$$\sigma_0^2 = k\ T\ B, \quad (17)$$

where k is the Boltzmann constant, T is the temperature of 290 K, and B is again the signal bandwidth. The receive power is calculated with the COST-Hata-model with the parameters defined in Tab. IV for the V2I scenario. The transmit power is set to the common value of 33 dBm (maximum power in the private usage case), the transmit and receive antenna gain is equal to 10 dBi, and additionally a small scale fading margin of 4 dB is added. Figure 9 shows the schematic diagram of required data rate and offered capacity. It can be observed that the offered capacity decreases as the distance increases together with the required data rate. Since the offered capacity is an overall capacity, it does not make a difference if the required data rate of 0.9 Mbit/s is accumulated over several users or one single user requires this 0.9 Mbit/s. For this reason we compare the offered capacity and the required data rate. The intersection point between the offered capacity curve and the required data rate curve is the maximum achievable distance at which sufficient capacity is provided. With this calculation the maximum capacity-limited RSU cell size can be calculated.

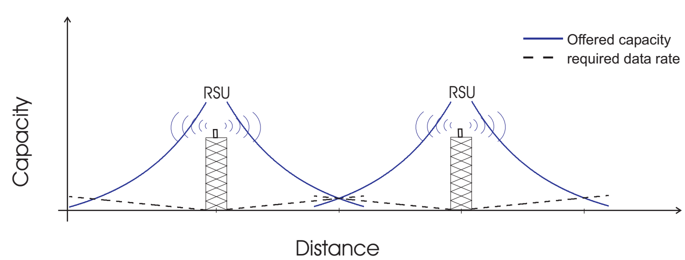

Fig. 9. Schematic diagram of required data rate and offered capacity

Figure 10 shows the two curves representing offered capacity and required data rate. For a better view the curves are shown only between the distances of 700 m and 1050 m. The maximum achievable distance is about 1000 m. As shown in Figure 9 the RSU cell size is twice the value of the distance, and therefore about 2000 m. At the intersection point the required data rate is higher than the required data rate for one segment calculated in the last section (0.9 Mbit/s). This is because the calculated RSU cell size is larger than the segment size and therefore there are more users in it.

To summarize the two major results above, the highest worst-case required data rate is 0.9 Mbit/s for a segment of

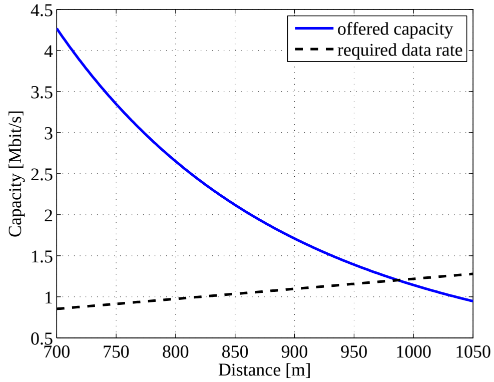

Fig. 10. Required data rate and offered capacity vs. distance

$1500\,$m, while under the same conditions the maximum RSU cell size that achieves the required capacity is about $2000\,$m. Hence, only one RSU per road segment is quite sufficient to meet the capacity requirements in the given scenario.

IV. Direct Comparison

The three presented systems – namely digital broadcast, cellular, and DSRC systems – each have different limitations which need to be considered in designing the proposed dedicated V2I link. Each of these systems has been shown to be either capacity or coverage limited. A summary of these results is given in Table XIII.

For capacity limited systems, the critical design parameter will be the number of users in the system and in the local segment, so that the ability of the system to simultaneously support all the users with all the services within the required time limits can be achieved. For coverage limited systems, the critical design factor will be the range achieved by the infrastructure, so that sufficient coverage can be achieved.

It has been shown that digital broadcast systems are not coverage limited, but are severely capacity limited. For a given bandwidth which has been assigned to the dedicated V2I link, the system can support up to a certain critical number of users, and no further rollout of infrastructure can alleviate this situation. This is not the case with cellular and DSRC systems.

We have also shown that the UMTS DCH scheme imposes a severe limit on the sustainable number of users. In high density areas, i.e. traffic jam scenarios, the cell coverage is strictly limited by the capacity requirements, where up to 8 bi-sectorial cells would be required per segment. It was also shown that the UMTS MBMS scheme greatly mitigates such a problem by means of a real multicast/broadcast transmission. Notably, we did not consider the uplink capacity in our analysis. In theory the uplink capacity eventually saturates due to acknowledgement packets from an increasing number of users. However, due to the fact that only a limited number of services requires acknowledgement packets, and that these packets are only a few bits long, the uplink saturation point is far from reachable in the given scenarios.

Finally, it has also been shown that DSRC systems are coverage limited, where up to 4 RSUs would be required to provide complete coverage in the given scenarios. It should be noted that under these conditions, the deployed DSRC system has ample capacity to support both a growing number of users and a growing complexity of future services.

System	Limitation
Digital broadcast	Capacity (available bandwidth)
UMTS DCH	Capacity (8 cells/segment)
UMTS MBMS	Capacity (Uplink eventually saturates)
DSRC	Coverage (4 RSUs/segment)

TABLE XIII
Summary of coverage and capacity limitations

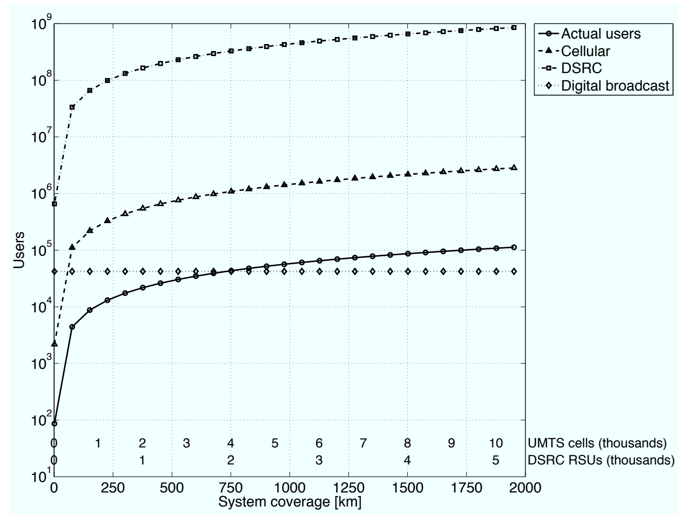

Fig. 11. Comparison of scaling of digital broadcast, cellular, and DSRC systems

An illustration of how each of the three system types scales with the growing size of the overall system is shown in Figure 11. The system coverage, i.e. the length of road network covered by the system, is shown on the horizontal axis, as measured in kilometers. On the verticals axis, the number of users is plotted for each curve.

Firstly, the curve labeled *Actual users* shows how many users will in fact be present in the system, given the parameter values shown in Table XIV, representing traffic flowing freely and uniformly through all the segments in the system. For a detailed description of each parameter, see Section III-A.

The curve labeled *Digital broadcast* represents the maximum number of users that can be supported by a digital broad-

Parameter	Value
Segment length $\boldsymbol{l}$	$1500\,$m
Number of lanes $\boldsymbol{m}$	6
Speed $\boldsymbol{v}$	$80\,$km/h
Occupancy $\boldsymbol{o}$	0.5
Number of services $\boldsymbol{n}$	8
Length of a vehicle l_{veh}	$7.5\,$m
Following tempo t_{fol}	$2\,$s
Fundamental data volume $\boldsymbol{b}$	$400\,$bits
Service activity $\boldsymbol{a}$	(0.02, 0.03, 0.03, 0.07, 1, 1, 1, 1)
Update period $\boldsymbol{P}$	$7\,$s

TABLE XIV
Parameter values for the cross-system comparison

cast systems using the same parameters given in Table XIV and assuming the data rate available to this system is 10 Mbps. As shown in Section III-B, the number of supported users does not grow with any rollout of new infrastructure and hence does not scale with the system coverage. It can immediately be noted that this digital broadcast system saturates at the coverage of approximately 750 km, and at larger system sizes cannot support all the existing users.

Using the same parameter values in Table XIV, the number of users that can be supported by a UMTS DCH system, with 8 bi-sectional cells per segment, is represented by the curve labeled *Cellular* in Figure 11. Although the UMTS DCH system is capacity limited, and hence designed to support the actual number of users present in the system, its curve is more than one order of magnitude higher than that of the actual users. This is due to the fact that the system must be over-designed, to support high stress situations (accident, traffic jam) in any of its segments.

Finally, the curve labeled *DSRC* represents the number of users that can be supported by a DSRC system with 4 RSUs per segment. It can easily be noted that this curve exceeds the number of actual users in the system greatly, by almost 4 orders of magnitude. This is due to the fact that DSRC systems are coverage limited, and not capacity limited, as was shown in Table XIII. In other words, the design of this system is governed by providing adequate spatial coverage and provides ample capacity which can be exploited by future additional services on the dedicated V2I link.

In order to illustrate the scaling of the required infrastructure in the UMTS and DSRC systems, the number of required UMTS bi-sectional cells and WAVE RSUs are represented in Figure 11 along the horizonal axis (shown in thousands). As explained earlier, for the UMTS DCH system, 8 bi-sectional cells are required per road segment of 1.5 km, resulting in 1000 cells for every 187.5 km. Similarly for the DSRC system 4 RSUs are required per road segment, resulting in 1000 RSUs for every 375 km.

V. Conclusions

Analyses of the coverage and capacity requirements of digital broadcasting, cellular, and DSRC systems for the implementation of V2I communications have been presented. Digital broadcasting systems have been shown to be inherently capacity limited and not to scale appropriately. We have shown how UMTS can be used to implement the V2I link in both dedicated channel and MBMS regimes, as well as in a hybrid approach. In every case, such V2I systems have been shown to scale well and be capacity limited. We have also shown that WAVE systems scale well, provide ample capacity, and are coverage limited. A direct quantitative comparison has also been presented, showing the scaling behavior of all three types of systems with the number of users and geographical coverage.

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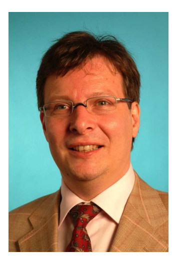

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