An Entropy Based Model for System-Level Downlink Capacity Requirements in V2R Telematic Systems

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***Abstract*—The critical step in deploying a V2R system based on digital broadcast systems such as DAB or DVB-H is the estimation of its downlink capacity requirements. We present an entropy based model for the downlink capacity requirements that takes into consideration both the parameters of the fixed infrastructure of the V2R system, as well as the dynamic traffic conditions. This model is independent of the encoding and compression methods used. The results of applying the model to one regional and one nation-wide V2R system, both under normal and heavy traffic scenarios, are also presented. We show how these results can be used to parameterize any chosen digital broadcast system, in order to meet the requirements of the V2R system while minimizing the rollout and operational costs.**

I. Introduction

Vehicle-with-roadside (V2R) communication is the critical next step in the evolution of telematic systems. The roles of future V2R systems include the delivery of infotainment services, but also the timely and reliable provision of real-time, local, situation-based, safety-related, traffic and infrastructure status information. It is this latter function that makes them poised to replace both fixed and variable-message signs from the roadside infrastructure.

All V2R systems rely on a wireless link between the traffic participants - vehicles - and the roadside infrastructure. In order to implement this link, various wireless transmission technologies can be deployed, either in isolation, a complimentary mix, or multiple overlapping and coexisting technologies. Three major classes of wireless transmission technologies are currently considered for V2R systems, namely:

- cellular systems (e.g. Universal Mobile Telecommunications System, UMTS),
- dedicated short range communication (DSRC) systems (e.g. IEEE 802.11p), and
- digital broadcast systems (e.g. Digital Video Broadcasting - Handheld, DVB-H).

The deployment of any of these technologies requires careful 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 V2R system with minimizing the rollout and operational costs. Hence, estimating the requirements of the V2R systems is a critical step in its deployment.

When considering in particular digital broadcast systems, it can be noted that these are invariably based on single frequency networks (SFNs). These networks have high spectral efficiency, 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 V2R telematic systems well, it also implies severe restrictions. The most important of these is the need to deliver all the V2R 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 V2R systems based on digital broadcast systems.

In order to estimate the downlink capacity requirements of V2R systems based on digital broadcast systems, a capacity model is required, taking into consideration both the infrastructure (length of road, number of segments, number of lanes, speed limits, offered services etc.) and present traffic conditions (number of vehicles, average speed, weather conditions, traffic jams, etc.).

We present an entropy based capacity model that takes into consideration all of the above parameters. We also present the results of applying the model to regional and nation-wide V2R telematic systems under various traffic scenarios. The presented capacity model is independent of specific encoding and compression methods. The presented results apply directly to the air interface of an SFN, while for cellular and DSRC systems the results enable appropriate cell and backbone capacity planning.

The presented model was developed 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 [2] and the project's test sites were focused on while developing the presented capacity model.

The rest of this paper is organized as follows. In Section II the concept of entropy is shortly reviewed and its usage is motivated. The system capacity model is presented in Section III. Numerical results of applying the presented model to two different V2R systems, each under two different traffic scenarios, are displayed in Section IV, before we conclude in Section V.

II. Entropy

As explained in Section I, in V2R systems employing SFN transmission technologies such as Digital Audio Broadcasting (DAB), Digital Multimedia Broadcasting (DMB), or Digital Video Broadcasting (DVB), a carousel scheme must be employed where all the users in all the road segments in the V2R system share the one and same downlink data stream, which is time-division multiplexed.

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

For example, assume that seven segments are to be served with information, where packet p_1 is to be delivered to segments s_1, s_2, s_4 and s_7, and packet p_2 is to be delivered to segments s_3, s_5 and s_6. The data stream can be encoded naively as shown in the following pseudocode.

$$< s1 = p1 >< s2 = p1 >< s3 = p2 >< s4 = p1 >$$
$$< s5 = p2 >< s6 = p2 >< s7 = p1 >$$

This scheme does not exploit the information overlap that exists in the given data. By exploiting this overlap, we could compress the data stream as follows.

$$< s1 = s2 = s4 = s7 = p1 >< s3 = s5 = s6 = p2 >$$

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 data update in 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 V2R 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 [3]. 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 V2R systems we include two independent entropy parameters in the system capacity model. These are user entropy, η, and 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 V2R 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. Therefore, the results obtained by the presented model are applicable to any V2R system regardless of the actual compression scheme used. Also, these results are optimistic in that they assume a zero overhead (in terms of data volume) for the compression operation.

III. System Capacity Model

The model of downlink capacity requirements of V2R systems presented here has two components. Firstly, the essential parameters of the V2R system are identified, and secondly the relationships between these parameters are modeled.

A. Parameter Definition

The system parameters are divided into five groups. Each parameter has a certain dimensionality, a symbol to represent it, and possibly a unit in which it is measured. We use bold lower case letters to denote a (column) vector and bold upper case letters to denote a matrix.

The first set of parameters describes the construction of the road network which is served by the V2R system. Included here are parameters describing:

- Total length of the covered road network, c
- Number of segments the road network is divided into, s
- Vector of lengths of the individual segments, $\boldsymbol{l} \in \mathbb{R}^s$
- Vector of number of lanes in each segment, taking into account both directions, $\boldsymbol{m} \in \mathbb{N}^s$

The second set collects all parameters that describe traffic flow. These include:

- Vector of average speed in each segment, $\boldsymbol{v} \in \mathbb{R}^s$
- Vector of retention time of each segment, $\boldsymbol{t} \in \mathbb{R}^s$
- Time period at which vehicles follow each other, t_{fol}

- Vector of following distance between vehicles in each segment, $\boldsymbol{l}_{fol} \in \mathbb{R}^s$
- Vector of number of users (i.e. vehicles) in each segment, $\boldsymbol{u} \in \mathbb{R}^s$
- Probability that a given segment is in the state of a traffic jam, x
- Vector of loading of each segment, $\boldsymbol{o} \in \mathbb{R}^s$

The elements of the loading parameter, $\boldsymbol{o}$, are always contained in the range 0 to 1, i.e. $o_i \in [0, 1]$. Here 0 represents the situation where no vehicles are present in the segment, and 1 represents 100% loading, or a situation where no more vehicles can fit in the segment at the given speed and following distance.

The third group of parameters models the set of services offered by the system. Hence, the parameters in this group include:

- Number of services in the system, n
- Vector of fundamental data volume delivered by each service per update period, $\boldsymbol{b} \in \mathbb{R}^n$
- Vector of activity of each service, $\boldsymbol{a} \in \mathbb{R}^n$
- Matrix of data volume delivered for each service in each segment, $\boldsymbol{J} \in \mathbb{R}^{n \times s}$
- Matrix of update periods for each service in each segment, $\boldsymbol{P} \in \mathbb{R}^{n \times s}$
- Vector of user entropy for each service, $\boldsymbol{\eta} \in \mathbb{R}^n$
- Vector of segment entropy for each service, $\boldsymbol{\phi} \in \mathbb{R}^n$

A more detailed explanation of the $\boldsymbol{\eta}$ and $\boldsymbol{\phi}$ parameters is given in Section II. The elements of the activity parameter, $\boldsymbol{a}$, are always contained in the range 0 to 1, i.e. $a_i \in [0, 1]$. Here 0 represents the situation where the service never sends information, and 1 represents an "always on" service which is active in every update.

The fourth group of parameters deals with the upper bound on the allowable update period for each segment. Hence, this group includes:

- Maximum allowable speed in the system, v_{max}
- Vector of minimum retention time for each segment, $\boldsymbol{t_{min}} \in \mathbb{R}^s$
- Vector of maximum allowable update period for any service in each segment, $\boldsymbol{p_{max}} \in \mathbb{R}^s$

The fifth and final group of parameters describes the data rates present in the system. Thus, it includes:

- Matrix of data rates for each service in each segment, $\boldsymbol{D} \in \mathbb{R}^{n \times s}$
- Vector of system-wide data rates required by each service, $\boldsymbol{d} \in \mathbb{R}^n$
- Total data rate for the entire system, r

A summary of all the system parameters is shown in Table I.

B. Modeling Parameter Relations

The capacity model is expressed as a set of equations modeling the relationships among the parameters shown in Table I. Throughout this section, the conventions for index variables i and j are that i indexes sectors, and hence $i \in [1, s]$, and j indexes services, and hence $j \in [1, n]$.

Firstly, segment length $\boldsymbol{l}$ is calculated directly from the total system coverage and the number of segments in the system as shown in (1). Here, an assumption is made that all the segments in the system have the same length, being the average segment length. It can be noted that this is always an optimistic assumption, as any variation in segment length inevitably results in the existence of a segment shorter than the average length, thus reducing the value of the $\boldsymbol{p}_{max}$ parameter, as shown later on in (3), thus leading to an increase in the overall data rate r.

$$l_i = \frac{c}{s} \tag{1}$$

The minimum retention time $\boldsymbol{t}_{min}$ is a function of the maximum velocity and segment length as shown in (2).

$$t_{min_i} = \frac{l_i}{v_{max}} \tag{2}$$

In order to model $\boldsymbol{p}_{max}$, the maximum update period of any service in a given segment, its value is related to that of $\boldsymbol{t}_{min}$ as shown in (3). V2R systems based on SFNs employ carousel broadcast schemes which have a cyclic nature. Hence, in order to guarantee the delivery of the entire update frame within one segment, the maximum allowable length of the update frame is half of the minimum retention time for that segment. The delivery of an update within a segment needs to be guaranteed, especially in the case of geographically specific content (such as accident or weather condition warnings). Please note that this simplified model of p_{max} is optimistic, in that it assumes the acknowledgement phase (on the uplink channel) can be accomplished in zero time.

$$p_{max_i} = \frac{t_{min_i}}{2} \tag{3}$$

The purpose of modeling $\boldsymbol{p}_{max}$ is to impose an upper bound on the actual update periods for all the services in the system. In other words, in any given segment i no service may be updated more slowly than p_{max_i}. This constraint is hence given in (4).

$$P_{i,j} \leq p_{max_i} \tag{4}$$

Given a constant following tempo between vehicles - and this is generally prescribed by national road operators to be no less than two seconds for safety reasons - the following distance between vehicles is a function of speed in the segment and can be modeled as shown in (5). It should be noted that all the vehicles in the segment are modeled as moving at the same speed, i.e. the speed parameter $\boldsymbol{v}$ applies to all the vehicles in the segment. Hence, the vehicles are uniformly distributed within the segment.

$$l_{fol_i} = v_i t_{fol} \tag{5}$$

Similarly to $\boldsymbol{t}_{min}$ the actual retention time for a given segment, $\boldsymbol{t}$, is modeled as a function of the segment's speed and length parameters, as shown in (6).

Description	Symbol	Dimension	Unit
Total length of the covered road network	c	1	m
Number of segments in the system	s	1	
Segment length	$\boldsymbol{l}$	s	m
Number of lanes in segment s	$\boldsymbol{m}$	s	
Speed in segment s	$\boldsymbol{v}$	s	m/s
Retention time of segment s	$\boldsymbol{t}$	s	s
Following tempo	t_{fol}	1	s
Following distance in segment s	$\boldsymbol{l}_{fol}$	s	m
Length of a vehicle	l_{veh}	1	m
Number of users in segment s	$\boldsymbol{u}$	s	
Probability of a traffic jam	x	1	
Segment occupancy (load)	$\boldsymbol{o}$	s	
Number of services in the system	n	1	
Fundamental data volume for service n	$\boldsymbol{b}$	n	bits
Service activity	$\boldsymbol{a}$	n	
User entropy for service n	$\boldsymbol{\eta}$	n	
Segment entropy for service n	$\boldsymbol{\phi}$	n	
Data volume for service n in segment s	$\boldsymbol{J}$	$n \times s$	bits
Update period for service n in segment s	$\boldsymbol{P}$	$n \times s$	s
Maximum speed	v_{max}	1	m/s
Minimum retention time of segment s	$\boldsymbol{t}_{min}$	s	s
Maximum update period for any service in segment s	$\boldsymbol{p}_{max}$	s	s
Data rate for service n in segment s	$\boldsymbol{D}$	$n \times s$	bits/s
Total data rate for service n	$\boldsymbol{d}$	n	bits/s
System data rate	r	1	bits/s

TABLE I
V2R SYSTEM PARAMETERS

$$t_i = \frac{l_i}{v_i} \tag{6}$$

One of the key parameters in the capacity model is $\boldsymbol{u}$, the number of users in a given segment. This parameter is a function of the road structure (number of lanes and segment length) as well as traffic conditions (segment occupancy and vehicle following distance), as given in (7). It should also be noted that l_{veh} includes the physical length of the vehicle as well as the safety distance kept by drivers when queuing, thus representing the total distance from the front tip of one vehicle to the front tip of the vehicle in front of it in a traffic jam situation.

$$u_i = \frac{m_i l_i o_i}{l_{veh} + l_{fol_i}} \tag{7}$$

However, each segment has a non-zero probability of being in a traffic jam situation, as given by the parameter x. Hence, the state of each segment (traffic jam or not) is determined by a coin toss, with the probability $P(jam) = x$. For any segment i that is in the traffic jam situation, the parameters $\boldsymbol{v}$, $\boldsymbol{o}$, $\boldsymbol{l}_{fol}$, and $\boldsymbol{u}$ are affected, such that $v_i = 0$ (standstill situation) and $o_i = 1$ (full occupancy). Thus, according to (5) $l_{fol_i} = 0$, meaning that the cars are queued, and according to (7) $u_i = m_i l_i / l_{veh}$, meaning that the segment contains the maximum possible number of users.

The first step towards modeling the required data rate for the entire system is to model the actual volume of delivered data for each of the services in each segment. For a given service in a given segment, the data volume $\boldsymbol{J}$ is calculated as shown in (8). As discussed earlier in Section II, user entropy $\boldsymbol{\eta}$ varies between 0 and 1, thus expressing the achievable compression for the data of a particular service. It should be noted that (8) is optimistic in that it expresses the performance of an ideal compression scheme, and it does not take into account any overhead involved in this operation.

$$J_{i,j} = a_j b_j (1 + \eta_j (u_i - 1)) \tag{8}$$

The data rate requirement for each service in each segment is a function of the data volume as well as the required update period, as shown in (9).

$$D_{i,j} = \frac{J_{i,j}}{P_{i,j}} \tag{9}$$

In order to derive the total data rate each service in the system requires, the individual data rates for that particular service over all the segments in the system are summed up, as shown in (10). Here again, compression is achievable to a degree that depends on the entropy present in the actual data, expressed by the parameter $\boldsymbol{\phi}$. As before, this is an optimistic model which assumes perfect compression performance with zero overhead.

$$d_j = \frac{\sum_i D_{i,j}}{s - \phi_j (s - 1)} \tag{10}$$

The final output of the capacity model is the required total data rate for the entire system, r. This is modeled simply as a sum of the required data rates of the individual services, as shown in (11). This model assumes zero overhead for supporting multiple services.

$$r = \textstyle\sum_j d_j \tag{11}$$

Parameter	Berlin	Austria
Total length of the covered road network (c)	30,000	2,000,000
Number of segments in the system (s)	28	1333
Maximum speed (v_{max})	22.22	50
Number of lanes ($\boldsymbol{m}$)	4-6	4-10
Update period ($\boldsymbol{P}$)	6	7

TABLE II
SITE PARAMETER VALUES

Parameter	Value
Number of services (n)	8
Length of a vehicle (l_{veh})	7.5
Following tempo (t_{fol})	2
Fundamental data volume ($\boldsymbol{b}$)	800
Service activity ($\boldsymbol{a}$)	(0.02,0.03,0.03,0.07,1,1,1,1)

TABLE IV
GENERAL PARAMETER VALUES

The capacity model described via the above equations has been implemented in the Matlab environment and used to assess the downlink capacity requirements of various V2R systems. The results of these analyses for two selected V2R systems are given in Section IV.

IV. SIMULATION RESULTS

A range of realistic deployments has been evaluated using the capacity model described in Section III. In particular, two geographical sites where such a system might be applied are presented here, being the *Berlin* and *Austria* sites, and for each of the sites two scenarios have been considered, being the normal operation and the high stress scenarios. The Berlin site models the Demonstration Site 3 of the COOPERS project comprising city highways A111, A100, and A113, and the Austria site models the complete highway network of Austria, comprising all existing Autobahn and Schnellstrasse roads.

A different set of parameter values applies for each of the four combinations mentioned above. These parameter values have been divided into three sets: site, scenario, and general parameters. Site parameters describe the characteristics of the particular site (Table II), scenario parameters define the traffic conditions for a particular scenario (Table III), and general parameters are valid for all combinations (Table IV). Please note that the vector of values for the parameter $\boldsymbol{a}$ in Table IV 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).

Given the parameter values in Tables II, III, and IV, the required total system data rate can be derived for each of the four combinations using the capacity model. The required total system data rate r is in each case 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.

Scenario	Berlin	Austria
Normal operation	1.3Mbits/s	73.2Mbits/s
High stress	3.3Mbits/s	230.8Mbits/s

TABLE V
PEAK SYSTEM DATA RATE REQUIREMENTS

Hence, the data rate r is plotted henceforth 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. In all the plots 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 per plot.

Figure 1 shows the required total system data rate for the Berlin site in the normal operation scenario. Similarly, Figure 2 shows r for the Berlin site in the high stress scenario, while Figure 3 and Figure 4 show r for the Austria site, in the normal operation and high stress scenarios respectively.

To summarize, the peak system data rate requirements for both sites in both scenarios are listed in Table V. It can be noted that in all cases the peak data requirement value occurs when entropy is maximal, i.e. when $\phi = \eta = 1$. It should be noted that these results are conservatively low, in that they assume perfect dynamic data compression with no overhead.

These results provide critical insight into the capacity requirements of any V2R system that may be deployed on either of the two sites. In particular, these results apply most directly to wireless transmission technologies that use SFNs, such as DAB, DMB, and DVB. For such systems, the overall data rate requirements summarized in Table V translate 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 V2R system on the Berlin site, a sufficient number of frequency channels must be purchased to fulfill the requirements shown in Table V. Since each of the 1.712MHz channels of a T-DMB system practically provides 1.06Mbits/s of downlink capacity [4], exactly 2 channels must be permanently assigned to the V2R system, with a contingency for 2 further channels as demanded for by the changing traffic conditions.

V. CONCLUSIONS

An entropy-based model for estimating the downlink capacity requirements of V2R system has been presented. The model takes into consideration all relevant infrastructure and traffic flow parameters and is independent of the encoding and compression methods used. To demonstrate its versatility, the model has been applied to two different V2R systems, each under normal and heavy traffic flow conditions. The achieved results have been shown to be suitable for, and essential in, parameterizing any digital broadcast system when one is used to implement the downlink of a V2R systems.

Parameter	Normal		High stress	
	Berlin	Austria	Berlin	Austria
Speed ($\boldsymbol{v}$)	19.44-22.22	25-27.78	13.89-19.44	16.67-19.44
Occupancy ($\boldsymbol{o}$)	0.4-0.6	0.4-0.6	0.8-0.9	0.8-0.9
Traffic jam probability (x)	0.02	0.02	0.15	0.15

TABLE III
SCENARIO PARAMETER VALUES

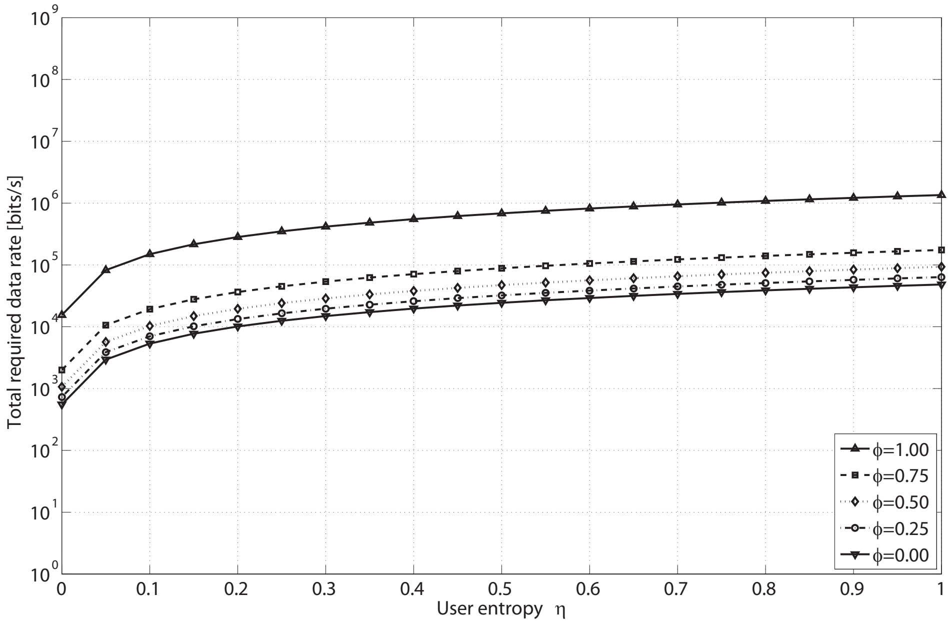

Fig. 1. Berlin site in the normal operation scenario

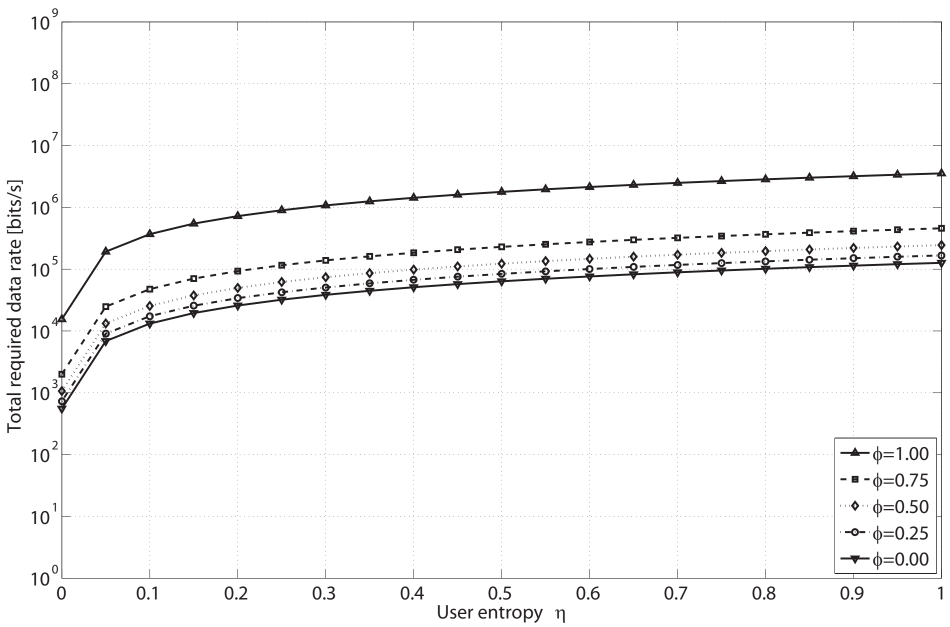

Fig. 2. Berlin site in the high stress scenario

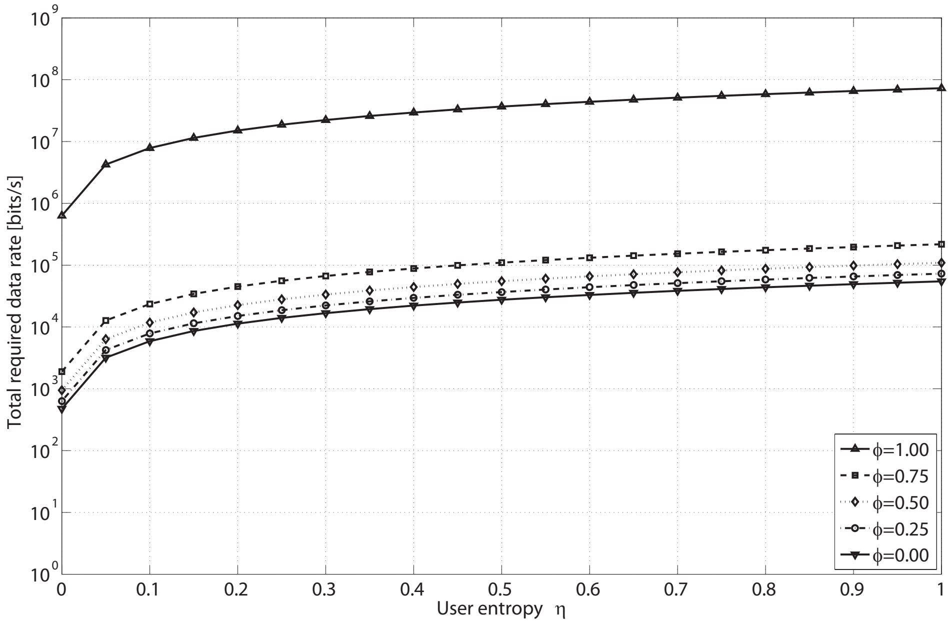

Fig. 3. Austria site in the normal operation scenario

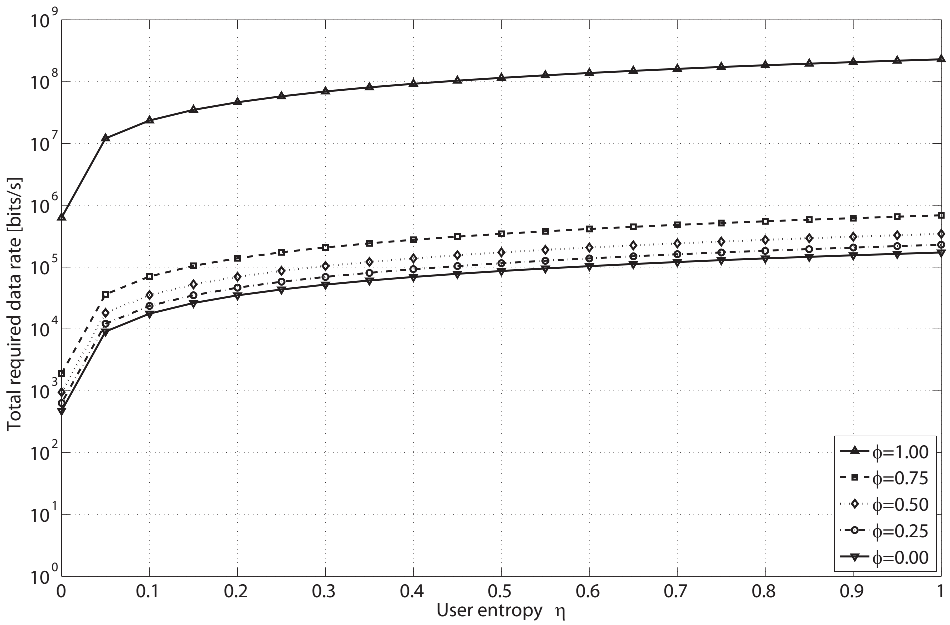

Fig. 4. Austria site in the high stress scenario

Future work on the presented model includes development of a time-based version of the model, where the dynamic nature of the traffic conditions can be more accurately represented and the time-variant behavior of the downlink capacity requirements can be more precisely studied.

Acknowledgements

The work presented in this paper has been supported in part by the European Commission Project COOPERS. The authors would like to acknowledge the kind cooperation of Alexander Frötscher and Thomas Scheider of AustriaTech.

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