Development and Applications of a Dynamic DVB-H System-Level Simulator

David Gómez-Barquero, Jussi Poikonen, Jarkko Paavola, and Narcís Cardona

***Abstract*—This article discusses the need for dynamic system-level simulations for Digital Video Broadcast—Handheld (DVB-H), specifically to evaluate the overall system performance perceived by mobile users dynamically over time. Such simulations can be used as a complement of traditional radio coverage planning tools for analyzing quality of service and radio resource management aspects of the DVB-H network. The article describes a general simulation structure, the main models required, and measurement-based validation of a DVB-H physical layer performance model that enables these analyses. The article also provides illustrative applications of the simulator.**

***Index Terms*—DVB-H, dynamic simulations, mobile TV, performance models.**

I. Introduction

TRADITIONAL network planning for both analog and digital TV broadcasting networks is based on a static approach that targets to guarantee a certain coverage level (i.e., percentage of locations in which the average signal strength exceeds a given value with a target high probability). However, similarly to cellular networks, newly deployed mobile broadcasting networks require dynamic analysis over time as well, since the actual service quality perceived by the users depends on the time evolution of the transmission errors experienced by the users [1]. Therefore, quality of service (QoS) issues cannot be studied only from performance indicators that reflect an average within the service area, such as the coverage probability commonly used in network planning.

For DVB-H (Digital Video Broadcast—Handheld) [2] the service availability at a certain location can be defined as the probability of correctly receiving a time-sliced burst. One location is considered as sufficiently covered if the average burst error rate is below 5% [3]. Hence, a 5% burst error rate is typically considered as the degradation point for DVB-H services. However, this metric does not take into account the QoS experienced by the user at service level.

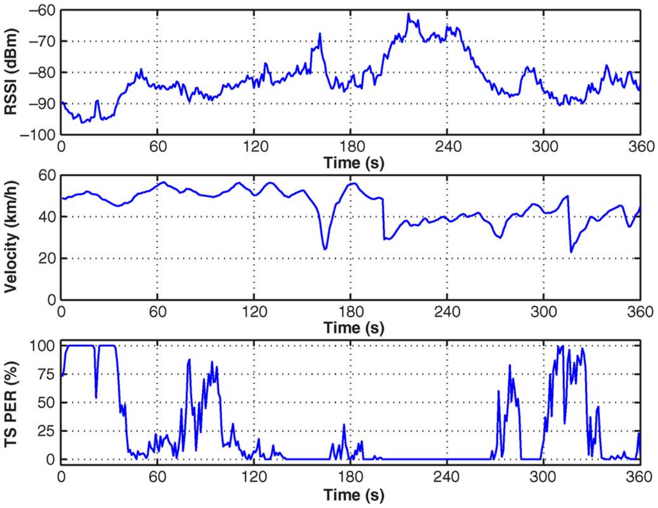

Fig. 1. Example data of vehicular DVB-H field measurement: received signal strength, velocity, and TS packet error rate.

In DVB-H, multimedia content can be delivered either as a streaming service or as a file delivery service. For streaming services, a representative metric that characterizes the operative limit of DVB-H under mobility conditions is whether there are more than one erroneous second within an interval of 20 seconds [1]. For file delivery services, the most important metric is whether the file is correctly received or not, but files may span several time-sliced bursts and therefore it is necessary to monitor the reception conditions during the file transmission.

Field measurements are the most accurate way to measure the actual performance of any wireless communication system, see e.g., [4] and [5] for good examples of measurement-based optimization of DVB-H networks. Fig. 1 shows an example of the data recorded during a field measurement campaign in the DVB-H test-bed of the University of Turku (Finland). The measurements consist of MPEG-2 transport stream (TS) packet error information at the physical layer of the whole multiplex. By recording the packet error trace at the physical layer it is possible to reproduce the quality experienced by the measuring terminals across the measured trajectories for any type of service emulating the upper layers in software.

The main issue with field measurement campaigns is that their resource expenditure is often cost prohibitive. Moreover, results obtained apply only for the specific trajectories measured. In order to extract conclusions about the overall system performance experienced by users in a service area, a considerably large number of measurements are needed. If, for example, we would like to speak in terms of percentage of satisfied

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Manuscript received November 09, 2009; revised April 06, 2010; accepted April 14, 2010 Date of publication May 27, 2010; date of current version August 20, 2010. . This work was supported in part by the Spanish Ministry of Industry, Tourism and Commerce under Project FURIA (Futura Red Integrada Audiovisual).

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Digital Object Identifier 10.1109/TBC.2010.2049608

users for a given QoS satisfaction criteria, thousands of independent trajectories would generally be needed to obtain statistically consistent average results. If we take into account that the measurements are only useful for the specific DVB-H physical layer transmission mode and network configuration setting employed, the need of performing simulations becomes apparent.

Simulations are an essential tool when analyzing the performance of wireless communication systems. With simulations different transmission configurations can be compared and the system parameters can be tuned to maximize performance. Obviously, simulations do not replace measurements, and results should always be verified with field measurements in the scenario under study. But still the potential cost reduction is considerable.

Looking carefully at the field measurement depicted in Fig. 1, we can distinguish between three different processes that need to be modeled in order to obtain similar results. First of all, a mobility model is necessary to determine the trajectories and velocities of the users. Secondly, it is needed to model the wireless radio channel to predict the signal strength received by the users. Finally, a model for the DVB-H physical layer is required to determine which information is correctly received based on the time-variant reception conditions as indicated by the received signal strength and receiver velocity. It should be pointed out that we are interested in accurate and computationally efficient performance models, but not in modeling the complete physical layer. The simultaneous simulation of all the processes involved in the operation of a wireless communication system is very complex and time consuming. The commonly employed solution is to separately characterize and model the receiver performance at the physical or link layer. At system level, where many transmitters and receivers may be considered, instead of simulating individual receivers, simplified performance models are employed.

With the models mentioned above it would be possible to simulate a DVB-H network over time, and thus estimate the QoS experienced by the users in a very detailed manner, giving a better understanding of the network behavior. These simulations are usually referred to as system-level simulations, and are widely used in cellular networks. Dynamic system-level simulators allow evaluating the overall system performance perceived by the users statistically with Monte Carlo simulations. This means repeating the same experiment many times with different random seeds and computing the average results (the higher the number of repetitions, the more accurate the results). In the particular case of DVB-H, such system-level simulations can be used as a complement of traditional coverage planning tools for broadcasting networks for analyzing QoS and radio resource management (RRM) aspects of the transmission configuration.

In this paper we describe the computationally-efficient dynamic DVB-H system-level simulator developed between the Universidad Politécnica de Valencia (Spain) and the University of Turku (Finland) within the European COST2100 action [6], and provide illustrative applications of the simulator. The rest of the paper is organized as follows. We review the models required to simulate a DVB-H network over time in Section II. In Section III we describe a general simulation structure for a DVB-H system-level simulator. In Section IV we describe an accurate and computationally efficient DVB-H performance model suitable for system-level simulations, and validate its performance with laboratory and field measurements. Section V provides several illustrative use cases of the simulator as a complement of a traditional radio coverage planning tool. We give some concluding remarks in Section VI.

II. MODELS FOR DYNAMIC DVB-H SIMULATIONS

A. *Mobility Models*

Mobility models describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time. They play a significant role when evaluating the system performance with dynamic simulations.

Pedestrian mobility can be modeled as a random walk with a constant or lognormal-distributed average velocity. A good example of a detailed model that reproduces the walking behavior of pedestrians in urban areas can be found in [9]. A good example of a very sophisticated vehicular model is the simulation environment SUMO (Simulation for Urban MObility) [7], which takes into account traffic lights, turning probabilities, car densities etc. A good example of a statistical model for vehicular users relatively simple to implement but still able to provide realistic street patterns and terminal movements is presented in [8]. The model describes users' movements with three random variables: street distance, direction change at crossroads and average velocity. Basically, the model assigns to the users a new velocity, street distance, and a relative change in direction when they finish moving across their current street. The model provides a set of distribution functions with a limited number of parameters that can be easily derived for a particular city.

B. *Modeling the Wireless Radio Channel in SFNs*

The wireless channel between a transmitter and a receiver is traditionally modeled with three different processes: path loss, slow or long-term fading (shadowing), and fast or multipath fading [10]. These processes vary as the positions of the transmitter and receiver change relative to the fixed transmission environment and possible moving obstacles within the coverage area.

Single Frequency Networks (SFNs) differ from conventional wireless communication systems in the sense that all transmitters are frequency and time synchronized, which allows receivers to combine OFDM signals coming from several sites. Therefore, an OFDM signal combining model is required in order to predict how signals from the different sites contribute to the useful received signal or cause self-interference at each location. In the following, we briefly describe methods of modeling the effects introduced above.

1) Path Loss: The path loss is the average decrease in field strength as the distance between the transmitter and the receiver increases [10]. The physical processes behind it are the outward spreading of the radio waves from the transmit antenna and the obstructing effects of trees and buildings.

In order to calculate the attenuation as precisely as possible in real scenarios, numerous radio propagation models have been developed, although the accuracy of the results depends on the available geographic data and its resolution. In order to further increase the accuracy of the results, models can be calibrated based on field measurement campaigns. Some illustrative radio

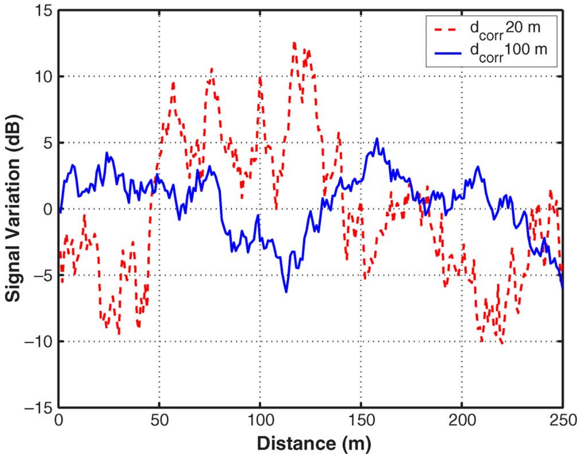

Fig. 2. Correlated shadowing. Shadowing standard deviation σ_l is 5.5 dB.

propagation models specifically derived from DVB-H measurements can be found in [4], [11] and [12].

2) Shadowing: Shadowing models the deviations from the mean distance-dependent signal level due to the particular obstructions (clutters) between the transmitter and the receiver [10]. It changes more rapidly than the path loss, with significant variations over distances of several tens of meters (comparable to the widths of buildings in the region of the mobile).

Shadowing is traditionally assumed to be log-normally distributed. That is, the distribution of the signal power is log-normal (the signal measured in dB follows a normal or Gaussian distribution). It is also referred to as log-normal fading. The spatial variation of the shadowing in dB is described by a zero-mean Gaussian random variable with standard deviation σ_l and correlation distance d_{corr} (distance over which the autocorrelation is reduced by a factor of e^{-1}).

The standard deviation of the shadowing distribution is known as the location variability, and it determines the spread of the signal field strength around the mean value. Its value increases with frequency, being greatest in suburban areas and smallest in open areas. The value typically employed for outdoor broadcasting signals in the UHF band is 5.5 dB [3], although it should be pointed out that it depends on the resolution of the path loss prediction, and that for high resolution maps (e.g., 5 × 5 m) a lower value may be more realistic. On the other hand, the spatial correlation of shadowing is usually modeled using a first-order exponential model [13]. A simple methodology to simulate one-dimensional correlated shadowing can be found in [10], see Fig. 2. A procedure to generate a bidimensional correlated shadowing map can be found in [14].

3) Fast Fading: Fast fading accounts for the signal level fluctuations due to constructive and destructive superposition of the multiple signals reaching the mobile terminal [10]. It involves variations on the scale of a half-wavelength, and frequently introduces variations as large as 35 to 40 dB.

For DVB-H, the typical urban 6-tap (TU6) channel model developed within the European COST207 action [15] has been shown to be representative to model fast fading for vehicular reception conditions [2]. For slowly moving pedestrian reception, specific tapped delay line channel models for DVB-H have been proposed, which are known as PI/PO (Pedestrian Indoor/Pedestrian Outdoor) channels [16].

For specifying the TU6 and PI/PO models it is necessary to determine the maximum frequency shift of the received signal due to Doppler effect, and the average carrier-to-noise ratio (CNR) of the channel, which describes the ratio of the useful signal power to the sum of the interference and noise powers. In DVB-H noise and self-interferences are additive, since signals consist of thousands of carriers modulated in phase and amplitude, resembling a Gaussian noise signal, and having a flat noise-like spectrum where its energy is distributed over the whole RF channel. For the UHF band where DVB-H was originally designed to be deployed (470–862 MHz), Doppler frequencies above 10 Hz are associated to vehicular reception, whereas Doppler around 1–3 Hz are associated to pedestrian reception (e.g., 2 Hz correspond to 3.6 km/h at 600 MHz).

4) OFDM Signal Combining Models: In SFNs interference consists of both external interferences and self-interference from the own network. For small-size networks, self-interferences are negligible provided that the transmitters are properly synchronized, but they cannot be neglected in a dense SFN [17]. Typically, signals received within the OFDM symbol guard interval are considered as useful and are assumed to contribute totally to the useful signal, whereas signals with a time delay larger than the guard interval are assumed to cause self-interference. A weighting function according to the signal delay is usually employed to determine the ratio between the useful and interfering contribution [18]. However, it should be taken into account that signal components with a delay shorter than the guard interval may cause interference depending on the frequency-domain pilot spacing used in the system. This is a direct consequence of the Nyquist sampling theorem, see [19]. Also, some degree of frequency synchronization error may be present in the SFN transmissions [20].

In an SFN the performance of the receivers strongly depends on the synchronization strategy used to determine the time synchronization point (FFT window time position). A good overview of the different synchronization strategies can be also found in [18]. When computing the CNR, it should be taken into account that both useful and interfering signals are assumed to have log-normal power distributions, which may be correlated [21]. A good overview of different summation methods of log-normal components can be found in [22].

C. Modeling the Performance of DVB-H

The DVB-H standard works with MPEG-2 TS packets at the physical layer (size 188 bytes). At the receiver, the physical layer FEC corrects bit errors within TS packets, and each packet is considered either completely received or completely erroneous. A DVB-H performance model shall then predict which TS packets are correctly received per burst. The input parameters for such model should be the following:

- Physical layer transmission mode.
- Channel model.
- Carrier-to-Noise Ratio.
- Doppler frequency.

The transmission mode—FFT size, OFDM symbol guard interval (GI), modulation, and code rate [2]—is fixed for any given simulation scenario.

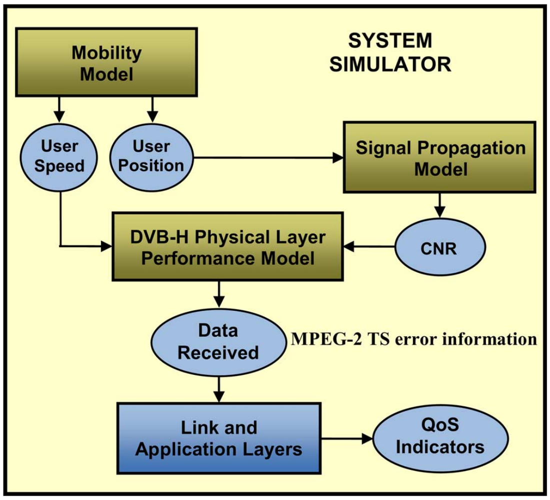

Fig. 3. DVB-H system-level simulator architecture.

It is mainly determined as a tradeoff between maximum system capacity, and parameters such as transmission robustness, maximum supported terminal velocity, and maximum distance between transmitters. The channel model may be considered fixed as well, for example TU6 for vehicular reception and PI/PO for pedestrian reception. Therefore, the only time-variant parameters are the CNR and Doppler frequency, which should be updated in short time intervals such that the receiving conditions can be considered piecewise stationary. In our case that means that path loss and shadowing can be considered constant within each interval, so that the only variations are due to fast fading. A good practice is to work with a time resolution equal to the burst duration, with typical values around 0.1–0.4 seconds [6].

III. DVB-H SYSTEM-LEVEL SIMULATOR

Fig. 3 shows a suitable modular architecture for a dynamic DVB-H system-level simulator, where four major modules can be identified: a mobility module, a signal propagation module, a DVB-H physical layer performance module, and a module to emulate the DVB-H link and application layers.

The simulator can be considered a discrete-event simulator, where the only events are the reception of data bursts by the users. Network dynamics are represented as a chronological sequence of events, simulated with a slot resolution equal to the cycle time between data bursts (time interval at which users' movements and received signal strengths are updated and errors in the received bursts are computed).

1) Mobility Module: This module moves users across the service area and computes the speed of the users when receiving a burst. Obviously different models are needed to account for the different user cases: pedestrian (indoor and outdoor) and vehicular (urban and motorway). Another important aspect is how to distribute the users initially over the service area. Typically they are distributed uniformly, unless specific information about population density is available.

2) Signal Propagation Module: This module computes the average CNR during the reception of a burst for each user, taking into account path loss and correlated shadowing (and OFDM signal combining effects in SFNs), together with system-specific information on the transmitter and receiver characteristics (link budget). Typical link budget values for DVB-H network planning can be found in [3]. Note that fast fading is accounted for in the DVB-H performance module.

3) DVB-H Performance Module: This module computes which TS packets of a burst are correctly received for each user for a given multipath fast fading channel model, based on the CNR and vehicle speed information provided by the radio coverage and mobility modules.

4) DVB-H Upper Layers Module: This module emulates the protocol decapsulation and FEC decoding at the link and application layers, and computes the QoS metrics. Common QoS metrics for streaming services in DVB-H are: burst error rate, also known as MFER (MPE-FEC Frame Error Rate), IP PER (IP Packet Error Rate), ESR (Erroneous Second Ratio), and ESR5(20), which represents the percentage of time intervals of 20 seconds with at most 1 erroneous second. For file delivery services the main indicator in terms of QoS is whether the user receives the file correctly or not. Additionally, the time required to receive the file is also of interest.

A. Implementation

A dynamic system-level simulator can be built on top of a traditional radio propagation tool employed for digital TV network planning, adding the mobility module, the DVB-H physical layer performance module and the DVB-H upper layers module. The signal propagation module can be associated with a coverage map with the average signal strength over the service area. The coverage is evaluated in a grid of test points over the service area with a spatial resolution given by the available cartography, and the values in-between can be obtained by means of interpolation.

In the previous section we have outlined modeling approaches for the mobility and signal propagation modules. Their specific implementation is dependent on the available data on the transmission environment and user characteristics. The main contribution of this paper is a computationally-efficient performance model for simulating the DVB-H physical layer. Its operation is described in detail in Section IV.

Regarding the coverage map, it should be pointed out that conventional coverage prediction predicts the signal availability rather than the signal level. The reason is that a fading margin of several decibels is added to the link budget to account for the local shadowing effects within each grid element of the coverage map. This margin, also known as correction location factor in broadcasting, depends on the shadowing standard deviation and the coverage probability target [3]. But this margin should not be considered in the system-level simulator, but correlated shadowing should be simulated instead.

IV. DVB-H PHYSICAL LAYER PERFORMANCE MODEL

In this paper we consider a DVB-H physical layer performance model based on parameterized 4-state aggregated Markov processes originally proposed in [23]. The model approximates the distributions of lengths of sequences of correctly and erroneously received TS packets, matching not only the average packet error rate but also the first order statistics of run length sequences (i.e., the mean error burst and error gap

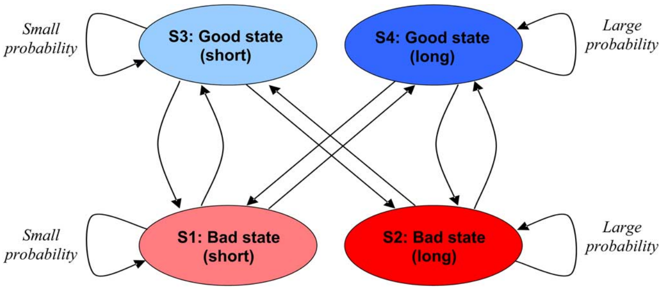

Fig. 4. State diagram of the four-state error model. The good states correspond to correct reception of a TS packet, and the bad states to erroneous reception.

lengths and their respective variances). The term run length is used to refer to the length of a sequence of consecutive erroneous or error-free received packets. In short, the model is based on initially determining—either from laboratory measurements or simulations—relevant run length statistics for a given DVB-H transmission mode and channel model. Then the measured/simulated statistics are parameterized as a function of the CNR and maximum Doppler frequency.

In the following, the structure and parameterization of the model are outlined. To facilitate the implementation of the model, straightforward procedures are given for calculating the model parameters. A more general description of the class of models from which the adopted model is obtained can be found in [24]. In the reference it is also shown that results obtained with a four-state model are not significantly improved by increasing the number of states.

A. Model Structure

Fig. 4 shows a conceptual state diagram of the error model with qualitative probabilities for staying in the states. Statistical properties of the model may be derived as given in [23]. The state transition probability matrix of the four-state Markov model can be written as:

$$\begin{pmatrix} \alpha_1 & 0 & (1-\alpha_1)w_3 & (1-\alpha_1)w_4 \\ 0 & \alpha_2 & (1-\alpha_2)w_3 & (1-\alpha_2)w_4 \\ (1-\alpha_3)w_1 & (1-\alpha_3)w_2 & \alpha_3 & 0 \\ (1-\alpha_4)w_1 & (1-\alpha_4)w_2 & 0 & \alpha_4 \end{pmatrix}, \tag{1}$$

where $0 \leq \alpha_i \leq 1, \forall i$, $w_1 + w_2 = 1$ and $w_3 + w_4 = 1$. Each state transition corresponds to one received packet. Transitions ending in states 1 and 2 are associated to the erroneous reception of TS packets, whereas states 3 and 4 correspond to correct reception of TS packets.

There are six independent parameters in the considered model which completely define the statistical characteristics of the model output. These parameters are selected according to the packet error statistics experienced by a DVB-H receiver for a given channel model. In the following, we define this parameter selection according to first-order run length statistics. In statistics, this approach is referred to as the method of moments.

The run length statistics considered in the model are the following. The packet error probability is defined as:

$$p_E = \frac{w_1}{(1-\alpha_1)\left(\sum_{k=1}^{4}\frac{w_k}{1-\alpha_k}\right)} + \frac{w_2}{(1-\alpha_3)\left(\Sigma_{k=1}^{4}\frac{w_k}{1-\alpha_k}\right)}. \tag{2}$$

The mean length of sequences of erroneously received packets is:

$$\mu_E = \frac{w_1}{(1-\alpha_1)} + \frac{w_2}{(1-\alpha_2)}, \tag{3}$$

the mean length of sequences of correctly received packets:

$$\mu_C = \frac{w_3}{(1-\alpha_3)} + \frac{w_4}{(1-\alpha_4)}, \tag{4}$$

the variance of lengths of sequences of erroneously received packets:

$$\sigma_E^2 = \frac{w_1\alpha_1(1-\alpha_2)^2 + w_2\alpha_2(1-\alpha_1)^2 + w_1w_2(\alpha_2-\alpha_1)^2}{(1-\alpha_1)^2(1-\alpha_2)^2}, \tag{5}$$

and finally the variance of lengths of sequences of correctly received packets:

$$\sigma_C^2 = \frac{w_3\alpha_3(1-\alpha_4)^2 + w_4\alpha_4(1-\alpha_3)^2 + w_3w_4(\alpha_4-\alpha_3)^2}{(1-\alpha_3)^2(1-\alpha_4)^2}. \tag{6}$$

The model parameters α_i, w_1 and w_3 can be obtained by solving numerically the two pairs of nonlinear equations given by (3) and (5), and (4) and (5) respectively $(w_2 = 1 - w_1; w_4 = 1 - w_3)$. Note that this differs from the results provided in [23], where a fifth equation defining the packet error probability was included. This equation is redundant, and removing it was found to improve the speed and accuracy of numerically solving the model parameters.

B. Model Implementation

1) Measure Run Length Statistics: First of all, it is necessary to obtain the run length statistics of interest for a given DVB-H physical layer transmission mode and channel model for a relevant range of average CNR (ρ) and maximum Doppler frequency shifts (f_d). This can be done either with physical layer simulations or laboratory measurements. Laboratory measurements have the intrinsic benefit of characterizing the receiver performance into the model. Note that measurements should be performed separately for each DVB-H transmission mode and channel model considered.

Each measurement corresponding to a fixed (CNR; Doppler)-pair should be long enough to provide consistent estimates of the required packet error statistics. The necessary measurement length depends on the CNR and Doppler values. It can be estimated for example by setting a margin of acceptable variation of the relevant output statistics, and calculating this variation using sliding windows of increasing length over the measured error traces, until the output variation is within the acceptable margin.

TABLE I
TU6 MODEL LSE COEFFICIENTS

$\tilde{m}$	μ_E	σ_E^2	μ_C	σ_C^2
c_1	$-2.1 \cdot 10^{-3}$	$-31.2 \cdot 10^{-3}$	$-2.5 \cdot 10^{-3}$	$-74.3 \cdot 10^{-3}$
c_2	-0.1271	-0.3467	0.5315	1.0474
c_3	4.7285	12.7569	-2.1663	-1.9857

In [24] it was found that measurement lengths of order 10^6 TS packets produce less than 5% standard deviation from the mean values of the relevant error statistics with the TU6 channel model and the following DVB-H physical layer transmission parameters: FFT 8K, GI 1/4, 16-QAM 1/2.

Another important issue is how extensive should be the set of measurements corresponding to different CNR and Doppler frequency values. As we are interested in modeling the transition between perfect reception to no reception, it is possible to measure the relevant CNR range (for example in 1 dB steps). However, due to the parameterization employed to interpolate the packet error statistics within the measured range, it is also possible to extrapolate the necessary statistics beyond the measured CNR range, reducing the number of CNR points necessary to be measured. The Doppler range should be measured according to the expected values (in 5–10 Hz intervals, for example). We will show that a relatively small CNR range of 5 dB with 1 dB intervals may already produce accurate simulation results compared to field measurements in diverse reception conditions [6].

2) Parameterization: The goal of parameterizing the model is to obtain relationships between the measured packet error statistics and the physical reception conditions described by the CNR and the Doppler frequency. The measured statistics are approximated as functions of the CNR and Doppler using planar least-squared error (LSE) approximation in the logarithmic scale.

Table I gives the coefficients obtained for the early prototype DVB-H receivers employed in the field measurements in Turku for the physical layer transmission mode FFT 8K GI 1/4 16-QAM 1/2 and TU6 channel model. Lab measurements were performed with CNR ranging from 14 to 18 dB in 1 dB steps, Doppler from 5 to 80 Hz in 5 Hz steps, and of order 10^6 TS packets per measurement. Approximated values for the relevant packet error statistics as functions of the reception conditions can be calculated from the given coefficient values as:

$$\tilde{m}(\rho f_d) = exp(c_1 \cdot f_d + c_2 \cdot \rho + c_3), \tag{7}$$

where $\tilde{m}(\rho; f_d)$ represents any of the considered statistics μ_E, σ_E^2, μ_C, and σ_C^2.

C. Model Application in the System-Level Simulator

Let N_{TS} be the number of TS packets per burst that depends on the burst size (maximum size 2 Mb). Assuming that the mean signal strength (considering path loss and shadowing) and receiver speed are stationary during the burst duration (with typical durations 0.2–0.4 s), error traces are generated using the proposed model by repeating the following steps for each of the simulated users:

1) Calculate the CNR and Doppler values corresponding to the given signal strength and vehicle speed.
2) Using the LSE estimation results as described in the previous section, determine the values of the packet error statistics needed to solve the finite-state model parameters.
3) Calculate the model parameters for the four-state model solving the two systems of equations (4)(8).
4) Generate N_{TS} output symbols. The initial state of the four-state model should be randomly selected according to the theoretical limiting state probabilities, which can be written as [23]:

$$\pi_i = \frac{w_i}{(1-\alpha_i)\left(\sum_{k=1}^{4} \frac{w_k}{1-\alpha_i}\right)}. \tag{8}$$

Steps 2 and 3 can be replaced by pre-calculating the model parameters for the relevant range of CNR and Doppler values to speed up the simulation process.

D. Model Validation With Laboratory Measurements

The accuracy of the error model can be verified with the difference between the run length statistics measured and simulated.

Fig. 5 provides illustrative validation results for the prototype receiver where we compare the average TS packet error rate (PER) as a function of the CNR for different maximum Doppler frequencies, and the sample distribution of error burst lengths of one particular measurement. Results obtained demonstrate the accuracy of the linear parameter estimation and the fit of the four-state model output run length distribution to the laboratory measurements used for determining the model parameters.

E. Model Validation With Field Measurements

The proposed model was also validated with vehicular field measurements by comparing the measured TS error traces to those obtained from simulations using the measured RSSI and vehicle speed values as inputs to the model. CNR values were calculated from the measured RSSI values assuming a constant background noise level and using receiver-specific calibration to obtain a conversion coefficient between RSSI and CNR. It should be noted that the laboratory measurements used to obtain the performance model parameters are independent of the field measurements used in this validation.

In [23] the accuracy of the model was preliminary verified with field measurements performed within the Wing TV project in the DVB-H pilot network in the Hague, the Netherlands. However, only one single six-minute trace was considered. Here we validate the model with a more extensive set of measurements at various locations and transitions around the city of Turku for the same physical layer transmission mode employed in the laboratory measurements (FFT 8K GI 1/4 16-QAM 1/2). The total measurement time was 2 hours (approximately $49 \cdot 10^6$ TS packets), divided into 20 individual measurements of length 6 minutes each [6].

1) Measured RSSI and Velocity Estimation Analysis: Fig. 6 shows an example of measured and simulated TS packet error rates (PER) over time for the measured trace shown in Fig. 1. Error rates are averaged over 1 second intervals. It can be seen

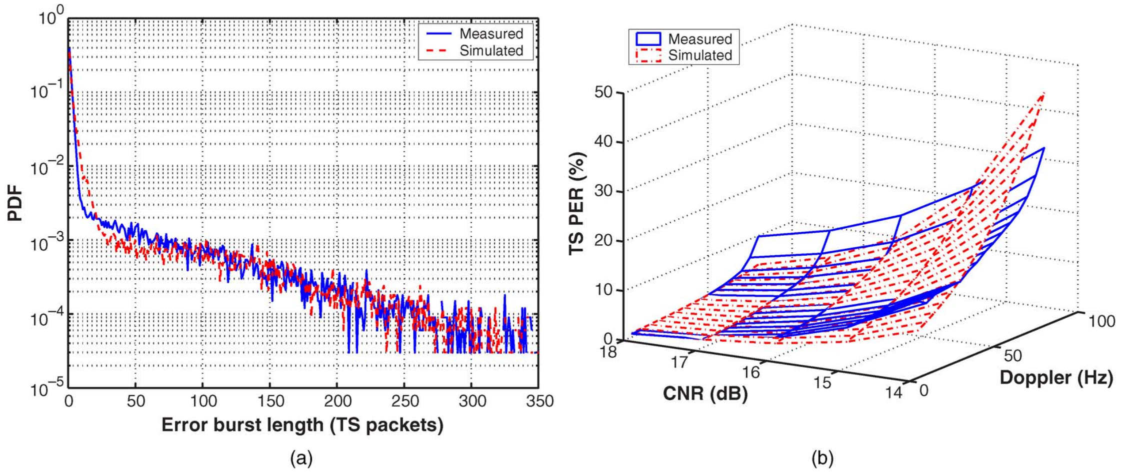

Fig. 5. Comparison between lab measurements and simulations for TU6 channel model: (left) average MPEG-2 TS packet error rate; (right) error burst length for CNR 17 dB and Doppler 10 Hz.

TABLE II
SIMULATED AVERAGE ERROR RATES (%) USING MEASURED SIGNAL STRENGTH AND SPEED INFORMATION. MEASUREMENT TIME IS 2 HOURS

Trace	TS PER	MPE SER	MFER	IP PER	ESR	ESR5(20)
Measured	3.9	4.9	4.2	3.7	5.1	11.9
Simulated	3.7	4.6	3.8	3.3	4.5	11.5

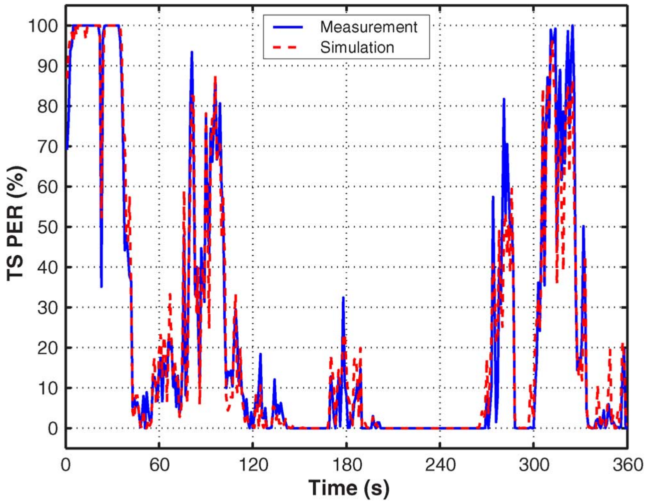

Fig. 6. Dynamic packet error simulation using measured time-dependent signal strength and vehicle speed values.

that the time-variant packet error rate of the simulated error trace follows very closely the measurement.

Table II compares the average statistics for the 2 hours of measurements in terms of TS PER, MPE section error rate (SER), MFER, IP PER, ESR and ESR5(20). Constant IP packet size 512 bytes and MPE-FEC code rate 3/4 with 1 Mb burst size have been assumed. In the table we can see how errors propagate in the upper layers of the protocol stack (e.g., MPE SER is higher than TS PER), and that the simulator provides slightly optimistic results compared to the measurements.

From these validation results it can be concluded that the accuracy of the proposed physical layer performance model is good with measured mobility and coverage information.

2) Imperfect RSSI and Velocity Estimation: We also investigated the influence of the degree of accuracy of the RSSI and speed estimation on the simulation results. In practice, it would be unrealistic to assume that the mobility and radio coverage models used in the system-level simulator provide ideal information on the time-variant reception conditions when compared to measurements. We found that the DVB-H radio coverage module is a critical element in the system-level simulator. As the physical layer of DVB-H is characterized by a very rapid transition from near perfect reception to no reception at all, an accurate coverage prediction is crucial in order to evaluate which information is correctly received by the users. However, as the aim of system-level simulations is to evaluate the overall QoS perceived by the users statistically, results obtained with a calibrated coverage map may reflect quite accurately the network performance [6].

On the other hand, it was shown that the effect of the speed on the simulation performance is relatively small compared to the effect of adding error in the RSSI estimation if the receiver speed is kept within a realistic range.

V. APPLICATIONS

Fig. 7 depicts the area coverage for pedestrian outdoor reception of the DVB-H test-bed of the University of Turku (Finland). The network is a single frequency network with two transmitters operating at 610 MHz (channel 38) covering the city center for pedestrian outdoor reception. The coverage map was computed by the Finnish broadcasting service provider Digita using the Canadian research corporation propagation model, terrain height, building and clutter information (pixel size 110 m); and assuming a standard deviation of 5.5 dB for the macro-scale

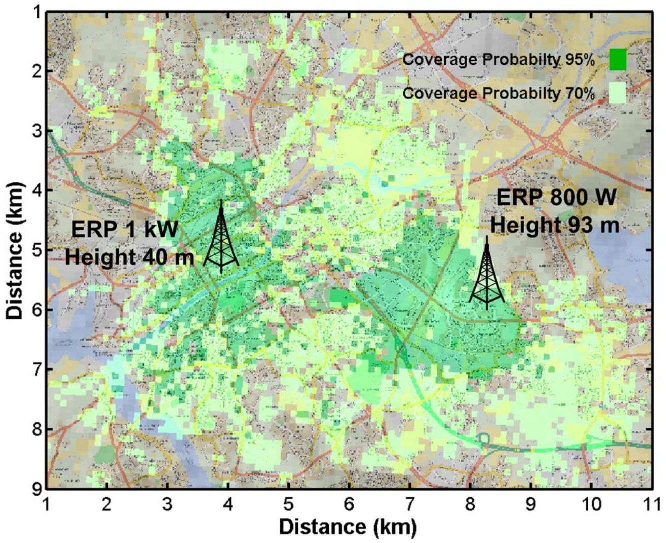

Fig. 7. Pedestrian outdoor coverage of the DVB-H test network of Turku (Finland). Transmission mode: FFT 8K, GI 1/4, 16-QAM 1/2, MPE-FEC 3/4.

variations of the field strength. The map was also calibrated with field measurements.

Results shown in Fig. 7 are the typical results obtained with traditional coverage planning tools for broadcasting networks. In this section we provide application examples of dynamic DVB-H system-level simulations for analyzing QoS and RRM aspects of the transmission configuration. A more detailed description of the simulations and the results obtained can be found in [25].

A. *Simulation Assumptions*

Signal level variations have been simulated by adding spatially correlated shadowing to the mean signal strength given by the coverage map from Digita. We employ the methodology proposed in [10], assuming a standard deviation of 5.5 dB and a correlation distance of 20 m.

In our simulations, 10.000 users are initially uniformly distributed within the central part of Turku (central area of 6 km × 4 km in Fig. 7). This allows for a 1% confidence interval for the results obtained in terms of user satisfaction. Users do not leave the service area but bounce at the edges.

Vehicular users move according to the statistical mobility model for in-car users in urban environments described in [8]. Pedestrian users move with a random walk with a constant speed of 3 km/h. The TU6 channel model and the PI/PO channels models have been employed for vehicular users and for pedestrian users, respectively.

The total runtime required to produce the 10.000 error traces used in the examples below (6 minutes duration) was approximately 11 hours using a 2.4 GHz tabletop PC with 2 GB of RAM. The time required by the performance model to produce one trace is only 0.15 seconds.

B. *Quality of Service Estimation for Streaming Services*

In this example we compute the percentage of satisfied users for different QoS criteria for a streaming service as a function of the MPE-FEC code rate for the different reception cases considered. We consider a 6 minutes service at 500 kb/s with a constant cycle time between bursts of 1 second. We assume a constant IP packet size of 1024 bytes and we compute the number of correctly received IP packets per burst for each user. The considered criteria for defining a satisfied user are that the percentage of lost IP packets (IP PER), erroneous bursts (MFER), erroneous seconds (ESR), and intervals of 20 seconds with more than 1 erroneous second do not exceed five percent, ESR5(20).

TABLE III
SATISFIED STREAMING USERS (%) FOR 5% ERROR RATE. MPE-FEC 3/4

Reception Case	IP PER	MFER	ESR	ESR5(20)
Vehicular Roof-top	94	90	90	58
Pedestrian Outdoor	85	84	84	68
Vehicular In-car	8	5	5	1
Pedestrian Indoor	1	1	1	0

TABLE IV
SATISFIED STREAMING USERS (%) FOR 5% ERROR RATE. MPE-FEC 1/2

Reception Case	IP PER	MFER	ESR	ESR5(20)
Vehicular Roof-top	96	95	95	81
Pedestrian Outdoor	86	85	85	71
Vehicular In-car	13	12	12	4
Pedestrian Indoor	2	1	1	1

Tables III and IV show the percentage of satisfied users for the different QoS criteria and reception cases considered, for MPE-FEC code rates 3/4 and 1/2, respectively. In the tables we can see that the ESR5(20) criterion is considerably much stringent than the rest. The MFER and ESR values are identical because the cycle time is fixed to 1 second. The IP PER is the less restrictive criterion because it accounts for correctly received IP packets in partially received bursts. In the tables we can also see that the effect of varying the code rate is not very significant for pedestrian reception. From the results obtained it can be concluded that it is possible to provide streaming services to pedestrian outdoor and vehicular rooftop users.

C. *Coverage Estimation for File Delivery Services*

In this example we show how dynamic system-level simulations can be used to configure a file transmission, in the sense of providing the right amount of transmitted data for a given targeted percentage of users receiving the file. The transmission parameters that the network operator has to configure are the cycle time between bursts, the burst size, the upper layer FEC scheme (link layer MPE-FEC or application layer AL-FEC), and the amount of repair data transmitted (code rate or FEC overhead) [25]. However, the amount of parity data transmitted is ultimately the most important parameter, as on the one hand very little overhead may result in a lack of robustness in the transmission, which does not allow most users to recover the file, and on the other hand a very robust transmission consumes resources that could be used for other services.

In our file download simulations we compute the percentage of users able to decode a 16 Mb file (acquisition probability) with AL-FEC as a function of the bursts transmitted for the different reception cases considered, see Fig. 8. Similar performance evaluation results comparing the performance

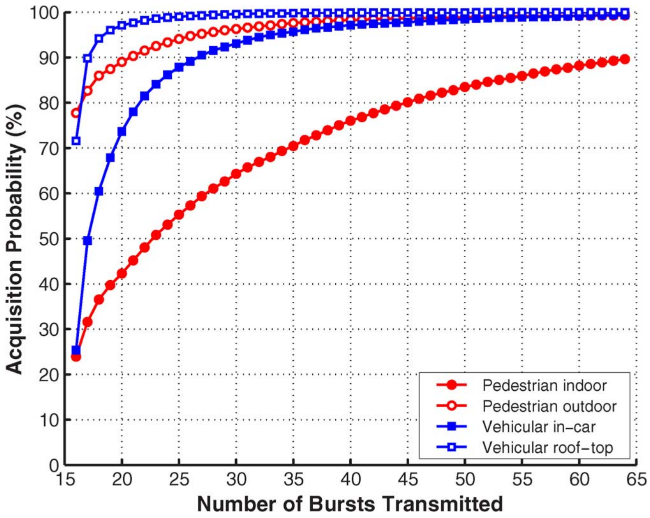

Fig. 8. Acquisition probability of a 16 Mb file as a function of the number of transmitted bursts in DVB-H with AL-FEC for different reception cases.

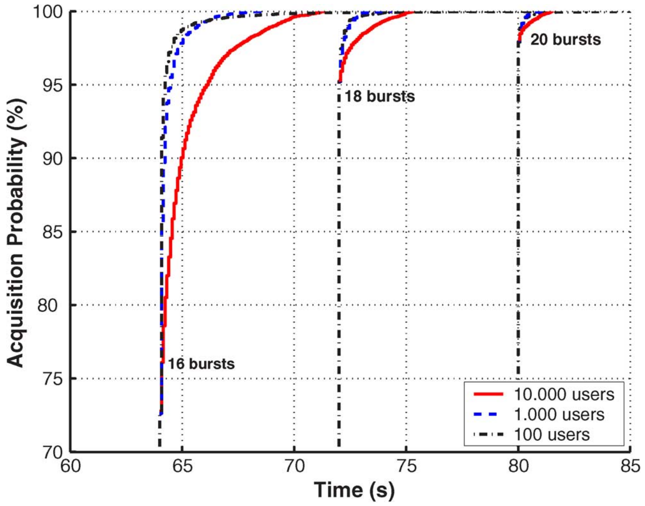

Fig. 9. File acquisition probability of a 16 Mb file for vehicular rooftop users using DVB-H and HSDPA with AL-FEC.

of AL-FEC with MPE-FEC can be found in [25]. We have assumed a constant download data rate of 250 kb/s (1 Mb burst size and 4 s cycle time between bursts). The case without AL-FEC corresponds to 16 bursts containing the original source data file. Additional bursts contain parity (repair) data to correct potential errors in the source data bursts.

Obviously, the more parity bursts transmitted, the higher the probability of receiving the file successfully. However, the gain obtained by transmitting an additional parity burst decreases as the total number of parity bursts grows. The gain is larger for higher receiver velocities because of the higher spatial diversity experienced by the users. In the figure it can be observed that it is relatively easy to serve vehicular in-car users with a network infrastructure dimensioned for outdoor pedestrian reception. In terms of link margin gain, that means that about 8.5 dB gain is achieved (7 dB due to the additional vehicle penetration loss and 1.5 dB due to larger CNR requirement). With AL-FEC file download services can be efficiently provided to mobile users over networks with partial coverage transmitting large amounts of repair data until the users receive the file.

D. RRM in Hybrid DVB-H/Cellular Networks

In this example we present simulation results for a file download service in a hybrid DVB-H/HSDPA network, where the cellular network is used to repair errors of the DVB-H broadcast transmission. File delivery requires an error-free reception of the files, which cannot be guaranteed for each and every user after a DVB-H transmission because some users might have experienced too bad reception conditions. Moreover, in a realistic scenario there may be users that experience significantly worse DVB-H reception conditions than the majority, such that it may be more efficient to serve them through the cellular network.

Dynamic system-level simulations can be used to investigate the potential cost delivery savings that can be achieved if a cellular network is used to repair errors of the DVB-H transmissions, as well as to dimension the post-delivery cellular repair phase. Another application would be to solve the problem of predicting the optimum configurations beforehand. In this case, in our simulations users not able to decode the file after the initial DVB-H transmission connect to the cellular network to complete the reception of the file. We compute the amount of repair data needed by each of the users that do not manage to decode the file. For the cellular network we consider a synthetic scenario with 24 sites uniformly distributed over the service area shown in Fig. 7. A detailed description of the scenario and the models employed can be found in [25].

Fig. 9 shows the evolution of the acquisition probability of a 16 Mb file for vehicular rooftop users as a function of the time for different number of transmitted bursts in DVB-H and for different number of active users. In the figure it can be seen that the cellular performance depends on the absolute number of users in the system. As the number of users increases, it becomes more convenient to transmit more repair bursts in DVB-H. The optimum transmission configuration will depend on the relative cost of transmitting one additional repair burst in DVB-H compared to using the cellular network to serve a given percentage of users.

VI. CONCLUSIONS

In this paper we have discussed the need of complementing the conventional static approach used for analyzing terrestrial digital TV broadcasting networks with dynamic analysis in DVB-H, as the actual service quality perceived by the users depends on the time evolution of the transmission errors suffered.

We have also motivated the need for dynamic DVB-H system-level simulations, in order to evaluate the overall system performance perceived by the users statistically giving a better understanding of the network behavior. Basically, the goal of the simulator is to accurately predict which data is correctly received in each burst for each user moving across a service area. Moreover, this should be achieved in a computationally efficient manner to enable simulation of large groups of users. These simulators can be integrated with conventional DVB-H coverage planning tools, making it possible for example to evaluate the influence of additional sites not only in terms of area coverage, but also in terms of service quality perceived by the users. Another important application is to optimize the transmission configuration.

The main models required to perform such simulations in DVB-H have been outlined, and a possible architecture for a system-level simulator has been described. A mobility model moves users across the service area and computes the speed of the users when receiving a burst, a signal propagation model computes the average received signal strength during the reception of a burst for each user, and finally a DVB-H performance model computes which data are correctly received per burst for each user based on the information of the time-variant reception conditions obtained from the mobility and signal propagation models.

We have considered a parameterized 4-state aggregated Markov process to model the performance of the DVB-H physical layer as a function of the CNR and maximum Doppler frequency shift for a given transmission mode and channel model. The model approximates the distributions of lengths of sequences of correctly and erroneously received MPEG-2 TS packets, matching not only the average packet error rate but also the first order statistics of run lengths sequences (i.e., the mean error burst and error gap lengths and their respective variances). The model has been validated with laboratory and field measurements, yielding very satisfactory results. We found that good dynamic simulation performance is achieved using the proposed performance model with accurate mobility and radio propagation estimates. Furthermore a relatively small set of lab measurements is required to produce good simulation results compared to field measurements.

ACKNOWLEDGMENT

This work has been performed within the European COST2100 action "Pervasive Mobile & Ambient Wireless Communications,"www.cost2100.org.

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