INDOOR RADIO CHANNEL MODEL FOR PROTOCOL EVALUATION OF WIRELESS PERSONAL AREA NETWORKS

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Abstract - A finite state radio channel model for wireless personal area networks (WPAN) is presented. It is based on a semi-Markov process of the channel impulse response (CIR) energy. To improve the time variant behavior of traditional state models the proposed process includes the tendency of CIR energy fluctuations. The parameters of the model are extracted from a stochastic radio channel model which takes into account all relevant propagation effects in indoor environments. In a second step the energy states are mapped to bit error rates. This is done using the physical layer proposal from the future IEEE standard 802.15.3 for high rate WPANs. A comparison of the proposed model with an existing semi-Markov channel model concludes the work.

Keywords - Channel model, finite state, semi-Markov process

I. INTRODUCTION

Wireless personal area networks (WPAN) are short range communication systems covering an area around one node with a radius of about 10 m. These systems shall be cheap to produce and they are optimized to operate with low power consumption. The IEEE working group 802.15 is dealing with the standardization of WPANs.

For the analysis and simulation of protocols for WPANs appropriate models of the radio channel and the receiver are necessary. The performance of the data link control (DLC) layer and higher layer protocols strongly depend on the wireless link. For WPANs it is required to be aware of a fast time variance of the channel characteristics. The devices are typically carried by hand and they are often operated while moving. For typical WPAN frequencies in the 2.4 GHz band or higher bands this causes fast changes of the channel conditions.

Recent research and standardization work in the field of WPANs are focused on increasing data rate [1], introducing different service classes and improving coexistence and interoperability of different wireless systems. Especially the higher data rates and the introduction of quality of service (QoS) enable multimedia transmission for hand-held devices. QoS in wireless networks needs to cope with time variant channels which result in bursty transmission errors. The reliability and performance of the DLC protocol, higher layer protocols and multimedia applications can be evaluated using the channel model presented in this paper.

Protocols for wireless networks are often analyzed and simulated under simple assumptions concerning the physical layer and the wireless channel characteristics. For example a two state Markov process is often used as a model for channels with bursty errors. For many link layer simulations a two state process is not accurate enough [2]. Channel fading is a continuous process with certain correlation properties. For example new DLC protocols are designed to adapt to the current channel condition. Such algorithms can only be correctly evaluated with an appropriate channel model.

In the following sections a new approach for a discrete state radio channel model is presented. Based on a semi-Markov process proposed in [3], [4] a new model is proposed which includes the tendency of the fading process. Section II describes the general design process for discrete state models and in Section III the semi-Markov process for the new approach is presented. In Section IV the stochastic radio channel model is introduced which is used to determine the parameters of the finite state model. And finally in Section V the new model is compared with a reference semi-Markov model [4].

II. DISCRETE STATE RADIO CHANNEL MODELS

For analysis and discrete event simulations of DLC protocols or higher layer protocols simplified models with high levels of abstraction are necessary. The focus should be put on the time variant behavior. In general a model for the stochastic process describing the bit error rate (BER) is used. Such models include the physical layer signaling, the channel impulse response, the receiver and eventually coding to obtain a model for the BER. For a simplified implementation in an event driven simulation a continuous time, discrete state stochastic process is preferable. For systems with fixed length slots or fix length packets a discrete time, discrete state model is commonly used. These kind of models are based on discrete state changes and are therefore well suited for event driven simulations.

For discrete state models we need criterions for a good choice of the modeled parameter(s). Then the number of states and their mapping to the parameters, the state holding times and the transition probabilities have to be determined. The design of a novel model mainly depends on the choice of the parameters and their mapping to a certain number of states. For models which are based on simple parameter quantization the number of states is determined by the desired dynamic range and the quantization of the modeled parameter. All the other degrees of freedom like the state holding times and the transition probabilities can be derived from a given stochastic radio channel model or from measurements. The parameters are extracted from the original model or from measurements by estimation [2].

Different finite state Markov models have been studied until now. For example the classical two state Gilbert-Elliot model for bursty errors has been widely used and analyzed. Until now these models are often judged by their stationary properties. Concerning the time variant behavior more analysis and a state mapping beyond pure parameter quantization are needed. This work focuses on an improvement and evaluation of the time variance of finite state models.

III. EXTENDED SEMI-MARKOV MODEL INCLUDING THE TENDENCY OF CIR ENERGY FLUCTUATIONS

In the following section two discrete state models are introduced. The first model is based on simple quantization of the CIR energy. This is equivalent to the common approach in the literature [4], [2]. It serves as a reference model for the evaluation of the new approach. The new model additionally includes the tendency of the CIR energy variation.

For both approaches the modeled parameter is the CIR energy. Therefore the model is independent of the physical layer signaling and the receiver algorithms. The parameters only depend on the stochastic radio channel model (SRCM) which serves as a base model. The main parameters of the SRCM are defined in Section IV.

In a second step we assign to every state a mean BER by simulation depending on the modulation scheme, the receiver algorithms and the average signal-to-noise ratio (SNR). The state transition probabilities and the state holding times aren't influenced by the assignment of the BER. Therefore it is easy to adapt the model to different modulation schemes and receiver algorithms.

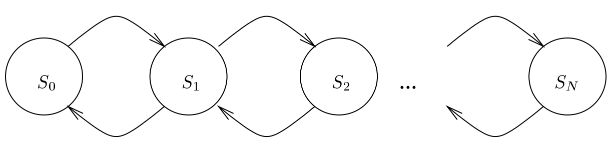

Fig. 1. State diagram of the semi-Markov process for the first model.

Figure 1 shows the discrete state process for the first model. The CIR energy is mapped on N states. The value of N depends on the range of fluctuations of the energy and the desired quantization. A logarithmic quantization is favorable to cover the large variations of the energy. Section IV explains the choice of N if the SRCM is chosen as a base model.

Discrete state stochastic processes with any kind of distribution for the state holding time are called semi-Markov processes [5]. The special case with exponential distributed state holding times is called Markov process. Simulations with the SRCM have shown that the state holding times are not exponential distributed, therefore a semi-Markov model is appropriate for this purpose.

The new model is shown in Figure 2. The number N of quantization levels for the CIR energy is the same like in the previous model. The number M of states of the new model is $M = 2N - 2$. The additional states are used to model the fading tendency. The sign of the difference of the CIR energy between the current and the last state

$$s_k = sign(\frac{E_h(t_k) - E_h(t_{k-1})}{t_k - t_{k-1}}) \quad (1)$$

is mapped on additional states. Where t_k is the time of the k^{th} transition and $E_h(t_k)$ is the CIR energy after the k^{th} transition. The state pairs which are vertical neighbors like e.g. S_1 and S_L or S_2 and S_{L+1} belong to the same CIR energy range. The upper row of states (S_L, S_{L+1}, S_{L+2},...) correspond to an increasing value of the energy $E_h(t)$. The lower row of states (S_0, S_1, S_2,...) correspond to a decreasing value of the energy $E_h(t)$.

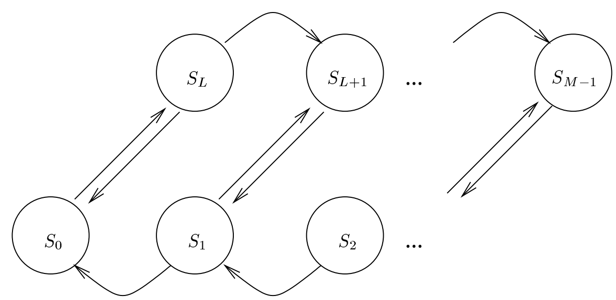

Fig. 2. State diagram of the semi-Markov process for the new model.

If a discrete state model is enhanced by higher order statistics the complexity increases significantly. In general the number of states and the number of possible transitions between the states increase exponential with the degrees of freedom. On the other hand the time variant behavior is strongly affected even for a small number of additional states. With the new model the correlation properties are closer to the original model with limited added complexity. Section V presents the evaluation of the performance of the two approaches.

IV. STOCHASTIC RADIO CHANNEL MODEL AND PARAMETER EXTRACTION

As mentioned in Section II there are different possibilities to determine the statistics of the finite state channel model. The parameters can be extracted from a large number of channel measurements. Other possibilities are the usage of a stochastic radio channel model (SRCM) or simulations with ray-trace models.

The model used here to determine the parameters of the state models is a wide-band, indoor SRCM [6] which has been introduced in the European project AC085 Magic WAND. With this model it is possible to generate time variant, complex valued CIRs $h(t,\tau)$. The SRCM includes all important effects of real indoor propagation environments. For example, it includes channel dispersion, large- and small-scale fluctuations and transceiver characteristics. The parameters of the model are adapted to WPANs operating in the 2.4 GHz band. The mean number of propagation paths is random with an assumed mean value of 10. The delay spread is assumed to be $\sigma_\tau = 10\,\mathrm{ns}$, keeping in mind the indoor propagation environment. In order to allow the process to be stationary the movement of the mobile terminal is set to $v_{ref} = 1\,\mathrm{m/s}$ (walking speed) with constant distance from the transmitter. The fact that the two communicating devices could move closer or further away will be modeled later in Section IV-C by including a path loss which leads to an average SNR at the receiver. More detailed information about the SRCM are given in [6].

The SRCM is used to calculate a large number of time variant CIRs $h(t,\tau)$. The process describing the energy fluctuations is given by $E_h(t) = \int_0^\infty |h(t,\tau)|^2 d\tau$. In order to obtain a discrete process, $E_h(t)$ is mapped to state S_k if $E_k < E_h(t) <= E_{k+1}$ for $k = 1..M-1$. E_k are the border values of the discrete process. The quantization is done in logarithmic scale by steps of 2 dB from $E_1 = -21$ dB to $E_{M-1} = 7$ dB. This corresponds to the energy region where the process stays with high probability [4]. The $h(t,\tau)$ calculated by the SRCM is sampled with $T = 0.1$ ms. T is well below the coherence time of the channel. Therefore the transitions in the discrete model are limited to neighboring states.

A. State Transition Probabilities

If we observe the semi-Markov process at the times of state transitions then we obtain the embedded Markov-chain of the semi-Markov process with the transition probabilities $p_{i,j}$. We define with $S(t_k) = S_j$ that the process stays in state S_j after the k-th transition at the time t_k. The state transition probabilities $p_{i,j}$ are defined as

$$p_{i,j} = P[S(t_k) = S_j | S(t_{k-1}) = S_i] \tag{2}$$

.

The semi-Markov process of the new model doesn't have any self-loops and from every state there are at most two possible transitions to an other state. Table 1 lists the state transition probabilities for the new model. A closer look at the table reveals that the new model can't be reduced to the simpler model shown in Figure 1. If both models would describe the same process the equation

$$p_{i-1,i} = p_{i-L,i}, \tag{3}$$

must be true for every S_i with $L+1 \le i \le M-1$ of the upper row of Figure 2 and

Table 1
State transition probabilities.

S_n	$p_{n,n-1}$	$p_{n,n+L}$	S_n	$p_{n,n-L}$	$p_{n,n+1}$
S_0	-	1	S_L	0.0027	0.997
S_1	0.61	0.39	S_{L+1}	0.0024	0.998
S_2	0.63	0.37	S_{L+2}	0.0033	0.997
S_3	0.66	0.34	S_{L+3}	0.0071	0.993
S_4	0.67	0.33	S_{L+4}	0.015	0.985
S_5	0.71	0.29	S_{L+5}	0.023	0.977
S_6	0.72	0.28	S_{L+6}	0.040	0.960
S_7	0.77	0.23	S_{L+7}	0.064	0.936
S_8	0.80	0.20	S_{L+8}	0.11	0.89
S_9	0.82	0.18	S_{L+9}	0.18	0.82
S_{10}	0.86	0.14	S_{L+10}	0.29	0.71
S_{11}	0.89	0.11	S_{L+11}	0.45	0.55
S_{12}	0.92	0.080	S_{L+12}	0.66	0.34
S_{13}	0.95	0.051	S_{L+13}	0.84	0.16
S_{14}	0.99	0.013	S_{L+14}	1	-

$$p_{j+1,j} = p_{j+L,j}, \tag{4}$$

must be true for every S_j with $0 \le j \le L-2$ of the lower row. As it can easily be seen the two models describe different processes.

B. State Holding Time Distribution

The probability density $f_{T_c|S}(t|S_i)$ of the state holding time T_C in state S_i is determined with the SRCM. The shape of the state holding time histogram extracted from a large number of realizations of $h(t,\tau)$ can be approximated by an Erlang distribution of second order. The same distribution has already been used in [4] for a finite state model based on quantization. The Erlang distribution of order n is defined as

$$f_n(\tau) = \lambda \frac{(\lambda\tau)^{n-1}}{(n-1)!} e^{-\lambda\tau} \tag{5}$$

and it has an expectation value of $E(\tau) = n/\lambda$. In Figure 3 the distribution of the state holding time for S_{22} is compared with the Erlang distribution of order two. The parameter λ of the distribution for every state is given in Table 2.

C. Bit Error Rate

Until now the semi-Markov model is independent of modulation schemes and receiver characteristics. The state transition probabilities and the state holding time distribution are derived from the wireless channel model (SRCM). The last step needed for a complete model is the mapping of every state to a bit error rate for a given average SNR [7].

The power spectral density of the received signal $\Phi_{RX}(\omega)$ can be calculated from the power spectral density of the transmitted signal $\Phi_{TX}(\omega)$ as follows [3]:

$$\Phi_{RX}(\omega) = \Phi_{TX}(\omega) \cdot |H_t(\omega)|^2 \tag{6}$$

Table 2
Parameter λ of the Erlang distribution.

state S_n	λ_n	state S_n	λ_n
S_0	378	S_L	1319
S_1	800	S_{L+1}	1035
S_2	670	S_{L+2}	842
S_3	552	S_{L+3}	672
S_4	450	S_{L+4}	521
S_5	384	S_{L+5}	413
S_6	317	S_{L+6}	319
S_7	272	S_{L+7}	249
S_8	227	S_{L+8}	189
S_9	192	S_{L+9}	144
S_{10}	166	S_{L+10}	111
S_{11}	144	S_{L+11}	88
S_{12}	126	S_{L+12}	74
S_{13}	112	S_{L+13}	69
S_{14}	101	S_{L+14}	73

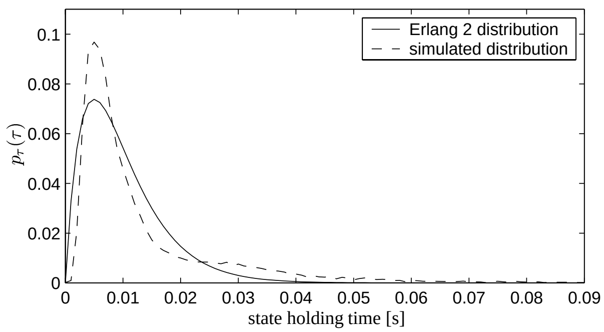

Fig. 3. Distribution of the state holding time $p_\tau(\tau)$.

Where $H_t(\omega)$ is the Fourier transform of $h(t,\tau)$. For modulation schemes like classical OFDM with a nearly constant spectral density $\Phi_{TX}(\omega)$ in the observed frequency band the received signal power is $P_{RX}(t) = P_{TX}(t) \cdot \int_{-\infty}^{\infty} |H_t(w)|^2 d\omega$. By applying Parsevals theorem we get the received power

$$P_{RX}(t) = P_{TX}(t) \cdot 2\pi \int_0^\infty |h(t,\tau)|^2 d\tau. \qquad (7)$$

Therefore $P_{RX}(t)$ is proportional to the CIR energy $E_h(t)$. For modulation schemes with a non constant power spectral density $\Phi_{TX}(\omega)$ in the observed frequency band the above calculation is an approximation. For channels which are wide sense stationary with uncorrelated scattering (WSSUS) the expectation $E[P_{RX}(t)]$ is proportional to the expectation of the CIR energy $E[E_h(t)]$ [8]. The average SNR is influenced by transmit power, path loss and receiver/antenna gain. As mentioned above only scenarios with constant path loss are considered. The current SNR at the receiver is calculated by the average SNR and the current value of the CIR energy $E_h(t)$.

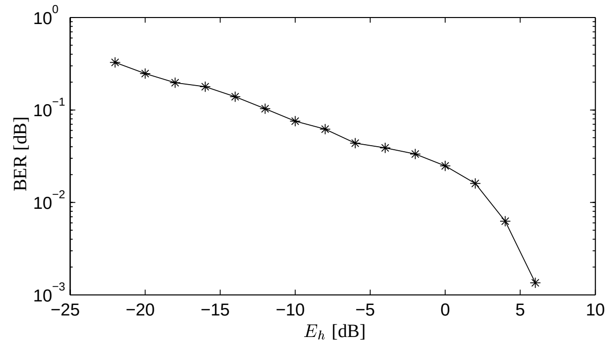

Fig. 4. Bit error rate for discrete CIR energy states ($\overline{SNR}$=20 [dB]).

For normalized CIR energy $E[E_h(t)] = 1$ and a given average $\mathrm{SNR} = 20$ dB, the BER for every state is simulated. The physical layer described in the proposals for the IEEE standard 802.15.3 [1] is used here for the evaluation of the BER. The modulation scheme is QPSK with a symbol length of $T_s = 90.9\mathrm{ns}$. The receiver is assumed to work with perfect channel estimation, zero forcing equalization, hard decision detection and no coding. The resulting bitrate is 22 Mbit/s. Figure 4 shows the mean BER for every state pair with the same CIR energy.

V. CHANNEL MODEL EVALUATION

In this section the dynamic behavior of the new model is compared with the pure quantization model. For simulation purposes the higher complexity of the new model doesn't result in higher computational effort. Only the needed memory for the state space is higher and the size of the probability matrices increases. The parameters for the new model are estimated by similar procedures like for existing models.

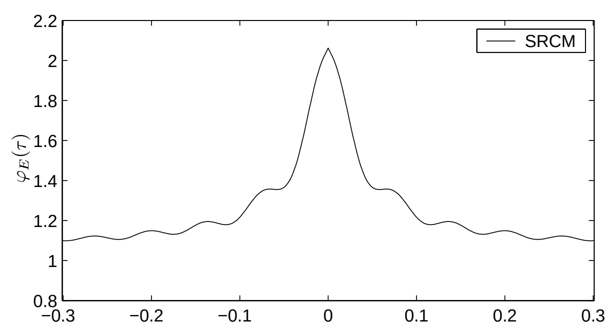

Fig. 5. Autocorrelation of the CIR energy using the SRCM.

One of the main drawbacks of simple quantization models [6] is the autocorrelation properties. Deep fades are often caused by the superposition of dominant incident waves, resulting in a strong tendency of CIR energy variation. The new model reproduces the typical fading behavior better by adding higher order statistics.

Figure 5 shows the simulated autocorrelation $\varphi_E(\tau) = E[E_h(t) \cdot E_h(t+\tau)]$ of the CIR energy $E_h(t)$ for the SRCM model. Because the channel is WSSUS the autocorrelation only depends on τ.

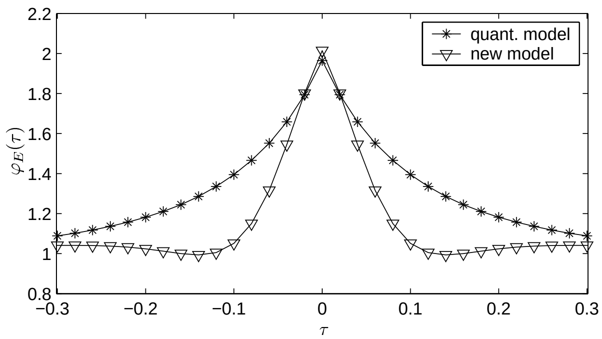

Fig. 6. Autocorrelation of the CIR energy for finite state models.

By comparing the autocorrelation $\varphi_E(\tau)$ of the SRCM model in Figure 5 with the autocorrelation of the two semi-Markov models in Figure 6 the time variant behavior can be evaluated. The quantization model tends to be still correlated for $\tau > 0.1\,\mathrm{s}$. This is mainly caused by the fact that the choice of the next state only depends on the current state which leads to a direction-less behavior. The autocorrelation $\varphi_E(\tau)$ for the new model decays faster and therefore it is closer to the autocorrelation of the original model.

An other way to compare the time variant behavior of the new model with the quantization model is the evaluation of the time while the semi-Markov process stays in lower energy states. This corresponds to fade periods with high BER. For a given CIR energy level $E_6 = -11\,\mathrm{dB}$ relative to $\overline{SNR}$ the fade-time is simulated. The mean time the CIR energy stays below E_6 is $\overline{t_f} = 18\,\mathrm{ms}$ for both channel models. This is not surprising because the semi-Markov models provide a good approximation of the stationary state probabilities as shown in [4]. The variance for the quantization model is $\sigma_{tq}^2 = 8.1 \cdot 10^{-4}\ \mathrm{s}^2$ and for the new model $\sigma_{tn}^2 = 1.6 \cdot 10^{-4}\ \mathrm{s}^2$. The variance of the new model is closer to the SRCM model with $\sigma_{ts}^2 = 2.4 \cdot 10^{-4}\ \mathrm{s}^2$.

VI. CONCLUSIONS

A discrete state channel model for wireless personal area networks (WPAN) is presented. Like in the previous approach [4] the channel impulse response (CIR) energy is discretized and mapped to a finite number of states of a semi-Markov model. In addition to pure quantization, the new model includes the tendency of CIR energy variations in order to improve the time variant behavior. Based on a complex stochastic radio channel model (SRCM) [6] the state transition probabilities and the distribution of the state holding times are determined. Finally a BER value is mapped to every state given an average SNR. The physical layer signaling is similar to a proposal for the IEEE 802.15.3 standard for high rate WPANs.

The autocorrelation property of the two semi-Markov models are compared in Figure 6. Due to the modeling of the fading tendency in the new approach the correlation decays faster than in the quantization model. If the fading tendency is not included the resulting process shows a direction-less behavior and therefore correlation to past values is stronger. Different evaluations show that the new model approximates the original fading process better. It can be used for example for simulation of adaptive DLC/MAC protocols which are dynamically reacting to channel conditions. An accurate channel model is important for the evaluation of protocols which exploit the variation of the BER.

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