Cross-layer analytical modeling of wireless channels for accurate performance evaluation

Dmitri Moltchanov, Yevgeni Koucheryavy, Jarmo Harju

Institute of Communication Engineering,
Tampere University of Technology,
P.O.Box 553, Tampere, Finland
{moltchan,yk,harju}@cs.tut.fi

Abstract. An intention to adopt IP protocol for future mobile communication and subsequent extension of Internet services to the air interface calls for advanced performance modeling approaches. To provide a tool for accurate performance evaluation of IP-based applications running over the wireless channels we propose a novel cross-layer wireless channel modeling approach. We extend the small-scale propagation model representing the received signal strength to IP layer using the cross-layer mappings. Proposed model is represented by the IP packet error process and retains memory properties of initial signal strength process. Contrarily to those approaches developed to date, our model requires less restrictive assumptions regarding behavior of the small-scale propagation model at layers above physical. We compare results obtained using our model with those, published to date, and show that our approach allows to get more accurate estimators of IP packet error probabilities.

1 Introduction

While next generation (NG) mobile systems are not completely defined, there is a common agreement that they will rely on IP protocol as a consistent end-to-end transport technology. The motivation is to introduce a unified service platform for future 'mobile Internet' known as 'NG All-IP' mobile systems.

To date only a few studies devoted to IP layer performance evaluation at the air interface have been published. Survey of literature has shown that most studies were devoted to analysis of the data-link layer protocols [1, 2]. Additionally, approaches developed to date, adopt quite restrictive assumptions regarding the performance of wireless channels at layers above physical. As a result, they may lead to incorrect estimation of IP layer performance parameters.

In this paper we propose a novel cross-layer wireless channels modeling approach. We extend the small-scale propagation model representing the received signal strength to IP layer using the cross-layer mappings. The proposed model is represented by the IP packet error process, retains memory properties of initial signal strength process and captures specific peculiarities of protocols at layers below IP. We show that our approach allows to get more accurate estimators of IP packet error probabilities compared to those approaches used to date.

Our paper is organized as follows. In Section 2 we overview propagation characteristics of wireless channels and models used to capture them. In section 3 we propose our extension to IP layer and define model that provides IP packet error probabilities. In Section 4 we provide numerical comparison of our approach with that one widely used in literature. Conclusions are drawn in the last section.

2 Propagation characteristics of wireless channels

The propagation path between the transmitter and a receiver may vary from simple line-of-sight (LOS) to very complex ones due to diffraction, reflection and scattering. To represent performance of wireless channels propagation models are used. We distinguish between large-scale and small-scale propagation models [3].

When a mobile user moves away from the transmitter over large distances the local average received signal strength gradually decreases. This signal strength is predicted using the large-scale propagation models. However, such models [4–6] do not take into account rapid variations of the received signal strength. As a result, they cannot be effectively used in performance evaluation studies. Indeed, when a mobile user moves over short distances the instantaneous signal strength varies rapidly. The reason is that the received signal is a sum of many components coming from different directions. Propagation models characterizing rapid fluctuations of the received signal strength over short time duration are called small-scale propagation models. In the presence of dominant non-fading component the small-scale propagation distribution is Rician. As the dominant component fades away Rician distribution degenerates to Rayleigh one.

The small-scale propagation models capture characteristics of wireless channel on a finer granularity than large-scale ones. Additionally, these models implicitly take into account movements of users over short travel distances [7, 8]. In what follows, we restrict our attention to the small-scale propagation models.

2.1 Model of small-scale propagation characteristics

Assume a discrete-time environment, i.e. time axis is slotted, the slot duration is constant and given by $\Delta t = (t_{i+1} - t_i)$, $i = 0, 1, \dots$. We choose Δt such that it equals to the time to transmit a single symbol at the wireless channel. Hence, the choice of Δt depends on properties of the physical layer.

Small-scale propagation characteristics are often represented by the stochastic process $\{L(n), n = 0, 1, \dots\}$ modulated by the discrete-time Markov chain $\{S_L(n), n = 0, 1, \dots\}$, $S_L(n) \in \{1, 2, \dots, M\}$ each state of which is associated with conditional probability distribution function of the received signal strength [9, 10]. The underlying modulation allows to take into account autocorrelation properties of the signal strength process. Since it is allowed for the Markov process $\{S_L(n), n = 0, 1, \dots\}$ to change state in every time slot, every bit may experience different received signal strengths.

An illustration of such a model is shown in the Fig. 1 where states are associated with conditional distribution functions $F_L(k\Delta f|i)(\Delta f) = Pr\{L(n) =$

$k\Delta f|S_L(n) = i\}$, $k = 1, 2, \dots, N$, $i = 1, 2, \dots, M$, where N is the number of bins to which the signal strength is partitioned and Δf is the discretization interval. Let D_L and $\boldsymbol{\pi_L} = (\pi_1, \pi_2, \dots, \pi_M)$ be the one-step transition probability matrix and the stationary probability vector of $\{S_L(n), n = 0, 1, \dots\}$ respectively. Parameters M, D_L, $F_L(k\Delta f|i)(\Delta f)$, must be estimated from statistical data [9, 10]. For the ease of notation we will use $F_L(k|i)$ instead of $F_L(k\Delta f|i)(\Delta f)$.

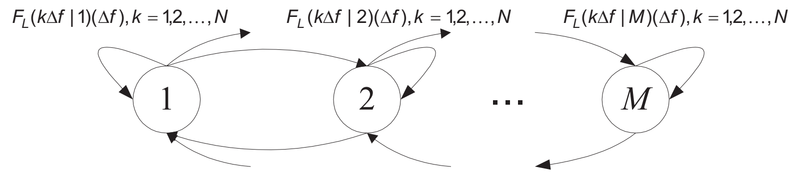

Fig. 1. An illustration of the Markov model for small-scale propagation characteristics.

3 Wireless channel model at IP layer

The small-scale propagation model of the received signal strength defined in the previous section cannot be directly used in performance evaluation studies and must be properly extended to IP layer at which QoS usually is defined. To do so we have to take into account specific peculiarities of layers below IP including modulation schemes at the physical layer, data-link error concealment techniques and possible segmentation procedures between different layers. As a result, the IP layer wireless channel model must be a complex cross-layer function of underlying layers and propagation characteristics.

In the following subsections we define models of incorrect reception of the protocol data units (PDU) at different layers. For this purpose we implicitly assume that these PDUs are consecutively transmitted at corresponding layers.

3.1 Bit error process

Consider a certain state i of the Markov chain $\{S_L(n), n = 0, 1, \dots\}$ associated with the conditional probability distribution function $F_L(k|i)$, $k = 1, 2, \dots, N$, of the received signal strength. Since the probability of a single bit error is the deterministic function of the received signal strength [3], all values of $F_L(k|i)$ that are less or equal to a computed value of the so-called bit error threshold B_T cause bit error. Those values which are greater than B_T do not cause bit error. So that each state i, $i = 1, 2, \dots, M$ of the Markov process $\{S_L(n), n = 0, 1, \dots\}$ can be now associated with the following bit error probability $p_{E,i}$:

$$p_{E,i} = Pr\{E(n) = 1|S_E(n) = i\} = \sum_{k=1}^{B_T} Pr\{L(n) = k|S_L(n) = i\}, \qquad (1)$$

where $\{E(n), n = 0, 1, \dots\}$, $E(n) \in \{0, 1\}$ is the bit error process for which 1 denotes an incorrectly received bit, 0 denotes a correctly received bit, $\{S_E(n), n = 0, 1, \dots\}$ is the underlying Markov chain of $\{E(n), n = 0, 1, \dots\}$. Note that $\{S_L(n), n = 0, 1, \dots\}$ and $\{S_E(n), n = 0, 1, \dots\}$ are actually the same and $\boldsymbol{\pi_E} = \boldsymbol{\pi_L}$, $D_E = D_L$, where D_E and $\boldsymbol{\pi_E}$ are one-step transition probability matrix and stationary distribution vector of $\{S_E(n), n = 0, 1, \dots\}$ respectively. B_T must be estimated based on a modulation scheme and other specific features of physical layer utilized at a given wireless channel [3].

Let us denote by $d_{E,ij}(k) = Pr\{E(n) = k, S_E(n) = j | S_E(n-1) = i\}$, $k = 0, 1$, the transition probability from the state i to state j with correct ($k = 0$) and incorrect ($k = 1$) bit reception respectively. These probabilities can be represented in a compact form using matrices $D_E(1)$ and $D_E(0)$ such that $D_E(1) + D_E(0) = D_E$. In our case the state from which the transition occurs completely determines the bit error probability. The state to which transition occurs is used for convenience of matrix notation useful in the following.

3.2 Frame error process without FEC

Assume that the length of the frame is constant and equals to m bits. The sequence of consecutively transmitted bits, denoted by gray rectangles, is shown in the Fig. 2, where $(l-1)$, l, $(l+1)$ denote time intervals whose length equals to the time to transmit a single frame; k, i, j, denote the state of the Markov chain $\{S_E(n), n = 0, 1, \dots\}$ in the beginning of these intervals.

Consider the stochastic process $\{N(l), l = 0, 1, \dots\}$, $N(l) \in \{0, 1, \dots, m\}$, describing the number of incorrectly received bits in consecutive bit patterns of the length m. This process is doubly stochastic one modulated by the underlying Markov chain $\{S_N(l), l = 0, 1, \dots\}$. $\{N(l), l = 0, 1, \dots\}$ and can be completely defined via parameters of the bit error process.

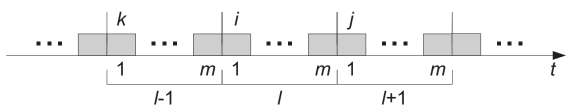

Fig. 2. Sequence of consecutively transmitted bits at the wireless channel.

Let us denote the probability of going from the state i to the state j for the Markov chain $\{S_N(l), l = 0, 1, \dots\}$ with exactly k, $k = 0, 1, \dots, m$ incorrectly received bits in a bit pattern of the length m by $d_{N,ij}(k) = Pr\{N(l) = k, S_N(l) = j | S_N(l-1) = i\}$. These transition probabilities can be found using $D_E(k)$,

$k = 0, 1$ and $\boldsymbol{\pi_E}$:

$$
\begin{aligned}
&d_{N,ij}(0) = \boldsymbol{\pi_E} D_E^m(0)\boldsymbol{e}, \\
&d_{N,ij}(1) = \boldsymbol{\pi_E} \sum_{k=m-1}^{0} D_E^{m-k-1}(0) D_E(1) D_E^k(0)\boldsymbol{e}, \\
&\dots \\
&d_{N,ij}(m) = \boldsymbol{\pi_E} D_E^m(1)\boldsymbol{e},
\end{aligned} \tag{2}
$$

where $\boldsymbol{e}$ is the vector of ones of appropriate size.

Let us now introduce the frame error process $\{F(l), l = 0, 1, \dots\}$, $F(l) \in \{0, 1\}$, where 0 indicates the correct reception of the frame, 1 denotes incorrect frame reception. Process $\{F(l), l = 0, 1, \dots\}$ is modulated by the underlying Markov chain $\{S_F(l), n = 0, 1, \dots\}$. Note that $\{S_F(l), l = 0, 1, \dots\}$ and $\{S_N(l), l = 0, 1, \dots\}$ are the same. Let us denote the probability of going from the state i to the state j for the Markov chain $\{S_F(l), l = 0, 1, \dots\}$ with exactly k, $k = 0, 1$ incorrectly received frames by $d_{F,ij}(k)$. Process describing the number of bit errors in consecutive frames can be related to the frame error process $\{F(l), l = 0, 1, \dots\}$ using the so-called frame error threshold F_T:

$$
d_{F,ij}(0) = \sum_{k=0}^{F_T-1} d_{N,ij}(k), \qquad d_{F,ij}(1) = \sum_{k=F_T}^{m} d_{N,ij}(k). \tag{3}
$$

Expressions (3) are interpreted as follows: if the number of incorrectly received bits in the frame is greater or equal to a computed value of the frame error threshold ($k \geq F_T$) the frame is incorrectly received and $F(l) = 1$, otherwise ($k < F_T$) the frame is correctly received and $F(l) = 0$.

Assume that FEC is not used at the data-link layer. It means that every time a frame contains at least one bit error, it is received incorrectly ($F_T = 1$). Thus, the probabilities (3) of the frame error process take the following form:

$$
d_{F,ij}(0) = d_{N,ij}(0), \qquad d_{F,ij}(1) = \sum_{k=1}^{m} d_{N,ij}(k) = 1 - d_{F,ij}(0). \tag{4}
$$

The slot durations of $\{N(l), l = 0, 1, \dots\}$ and $\{F(l), l = 0, 1, \dots\}$ are the same $\Delta t'$ and related to the slot duration of the received signal strength process $\{L(n), n = 0, 1, \dots\}$ as $\Delta t' = nl\Delta t$, $n = 0, 1, \dots$.

3.3 Frame error process with FEC

The frame error threshold F_T depends on FEC correction capabilities. Assume that the number of bit errors that can be corrected by a FEC code is l. Then, $F_T = (l + 1)$ and the frame is incorrectly received when $k \geq (l + 1)$. Otherwise, it is correctly received. Thus, the transition probabilities (3) of the frame error process take the following form:

$$d_{F,ij}(0) = \sum_{k=0}^{l} d_{N,ij}(k), \qquad d_{F,ij}(1) = \sum_{k=l+1}^{m} d_{N,ij}(k). \tag{5}$$

3.4 IP packet error process

Assume that IP packet is segmented into z frames of equal size at the data-link layer.[1] The sequence of consecutively transmitted frames, denoted by gray rectangles, is shown in the Fig. 3, where $(h-1)$, h, $(h+1)$ denote time intervals whose length equals to the time to transmit a single packet; k, i, j, denote the state of the Markov chain $\{S_F(n), n = 0, 1, \dots\}$ in the beginning of intervals.

Consider the stochastic process $\{M(h), h = 1, 2, \dots\}$, $M(h) \in \{0, 1, \dots, z\}$, describing the number of incorrectly received frames in a consecutive frame patterns of the length z. This process is modulated by the Markov chain $\{S_M(h), h = 0, 1, \dots\}$ and can be defined via parameters of the frame error process.

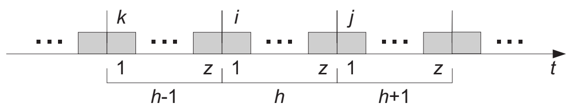

Fig. 3. Sequence of consecutively transmitted frames at the wireless channel.

Let us denote the probability of going from state i to state j for the Markov chain $\{S_M(h), h = 0, 1, \dots\}$ with exactly k, $k = 0, 1, \dots, z$ incorrectly received frames in a frame pattern of length z by $d_{M,ij}(k) = Pr\{M(h) = k, S_M(h) = j | S_M(h-1) = i\}$. These transition probabilities can be found using $D_F(k)$, $k = 0, 1$ and $\boldsymbol{\pi_F}$ of $\{F(l), l = 0, 1, \dots\}$ as follows:

$$\begin{aligned} d_{M,ij}(0) &= \boldsymbol{\pi_F} D_F^z(0)\boldsymbol{e}, \\ d_{M,ij}(1) &= \boldsymbol{\pi_F} \sum_{k=z-1}^{0} D_F^{z-k-1}(0) D_F(1) D_F^k(0)\boldsymbol{e}, \\ &\dots \\ d_{M,ij}(z) &= \boldsymbol{\pi_F} D_F^z(1)\boldsymbol{e}, \end{aligned} \tag{6}$$

where $\boldsymbol{\pi_F}$ is the stationary distribution vector of $\{S_F(l), l = 0, 1, \dots\}$.

Let us now introduce the packet error process $\{P(h), h = 0, 1, \dots\}$, $P(h) \in \{0, 1\}$, where 0 indicates the correct reception of the packet, 1 denotes incorrect

[1] Assumption of the constant frame size does not restrict the generality of the results as long as only one traffic source is allowed to be active at any instant of time for which only data-link error concealment techniques are possible (e.g., IP telephony).

packet reception. Process $\{P(h), h = 0, 1, \dots\}$ is modulated by the underlying Markov chain $\{S_P(h), h = 0, 1, \dots\}$. Note that $\{S_P(h), h = 0, 1, \dots\}$ and $\{S_M(h), h = 0, 1, \dots\}$ are the same. Let us denote the probability of going from the state i to the state j for the Markov chain $\{S_P(h), h = 0, 1, \dots\}$ with exactly k, $k = 0, 1$ incorrectly received packets by $d_{P,ij}(k)$. Process $\{M(h), h = 0, 1, \dots\}$ describing the number of incorrectly received frames in consecutively transmitted packets can be related to the packet error process $\{P(h), h = 0, 1, \dots\}$ using the so-called packet error threshold P_T:

$$d_{P,ij}(0) = \sum_{k=0}^{P_T-1} d_{M,ij}(k), \qquad d_{P,ij}(1) = \sum_{k=P_T}^{z} d_{M,ij}(k) = 1 - d_{M,ij}. \tag{7}$$

Expressions (7) are interpreted as follows: if the number of incorrectly received frames in a packet is greater or equal to a computed value of the packet error threshold ($k \geq P_T$) the packet is incorrectly received and $P(h) = 1$. Otherwise, it is correctly received and $P(h) = 0$. Since no error correction procedures are defined for IP layer, $P_T = 1$ and only $d_{M,ij}(0)$ must be computed in (6). That is, every time a packet contains at least one incorrectly received frame, the whole packet is received incorrectly.

The slot durations of $\{P(h), h = 0, 1, \dots\}$ and $\{M(h), h = 0, 1, \dots\}$ are the same $\Delta t''$ and related to the slot duration of the received signal strength process $\{L(n), n = 0, 1, \dots\}$ as $\Delta t'' = nlh\Delta t$, $n = 0, 1, \dots$.

3.5 Illustration of the proposed extension

An illustration of proposed cross-layer mapping is shown in Fig. 4 where time diagrams of $\{L(n), n = 0, 1, \dots\}$, $\{E(n), n = 0, 1, \dots\}$, $\{N(l), l = 0, 1, \dots\}$, $\{F(l), l = 0, 1, \dots\}$, $\{M(h), h = 0, 1, \dots\}$, $\{P(h), h = 0, 1, \dots\}$ are shown. Error thresholds B_T, F_T and P_T must estimated as outlined previously and then used to compute transition probabilities of error processes at different layers.

To define models of the incorrect reception of PDUs at different layers we implicitly assumed that appropriate PDUs are consecutively transmitted at corresponding layers. Hence, the IP packet error process is conditioned on the event of consecutive transmission of packets.

4 Comparison of the proposed approach

Let us now compare the proposed approach with that one developed and used to date. We consider two cases: (1) the signal strength is assumed to be constant during the frame transmission time (2) the signal strength is mapped to the IP layer model in accordance with our approach. In what follows, we use subscripts 1 and 2 to denote performance estimators obtained using corresponding approach.

Assume that the wireless channel at the physical layer is represented by the Markov chain with $M = 4$, $p_{E,i} = 0$, $i = 1, 2, 3$, $p_{E,4} \neq 0$ and the following

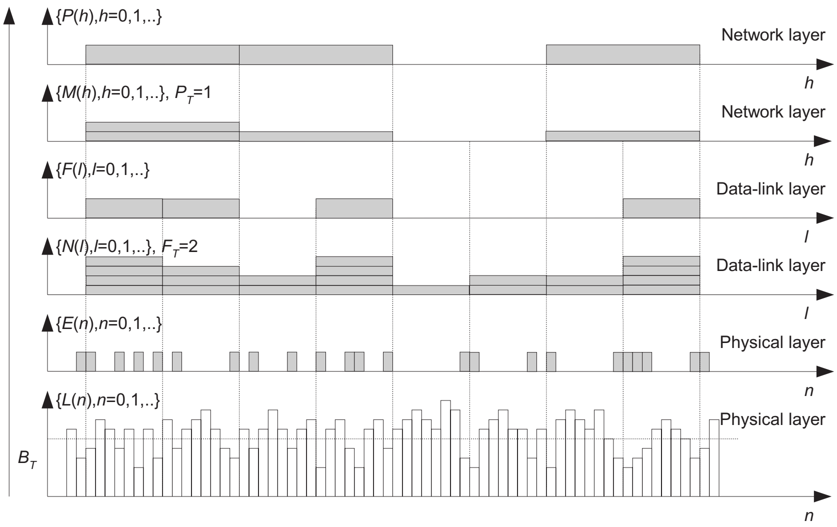

Fig. 4. Illustration of proposed cross-layer mapping.

transition probability matrix:

$$P_E = \begin{pmatrix} 0.42 & 0.18 & 0.24 & 0.16 \\ 0.18 & 0.42 & 0.04 & 0.36 \\ 0.07 & 0.03 & 0.54 & 0.36 \\ 0.03 & 0.07 & 0.09 & 0.81 \end{pmatrix}. \quad (8)$$

We also assume that exactly one IP packet is mapped into one frame at the data-link layer. It can be easily shown that this assumption provides the best possible conditions at the IP layer.

4.1 Packet error processes without FEC

Assume that the length of the frame is m bits and FEC is not used at the data-link layer. Then, the conditional mean of the incorrectly received packets[2] is given by the following expressions:

$$E_1[P] = \sum_{i=1}^{4} \pi_{E,i} \sum_{k=0}^{m-1} (1 - p_{E,i})^k p_{E,i}, \qquad E_2[P] = 1 - \boldsymbol{\pi_E} D_E^m(0)\boldsymbol{e}. \quad (9)$$

The estimated values of the conditional mean of the incorrectly received IP packets for different values of m and $p_{E,4}$ are shown in the Table 1. Comparing

[2] This performance parameter can be interpreted as the mean number of the incorrectly received IP packets given that packets are generated according to Bernoulli process with probability of a single arrival set to 1.

obtained results we note that the assumption of the same received signal strength during the frame transmission time significantly overestimates the actual performance of wireless channels when the channel coherence time is comparable with the time to transmit a single symbol.

Table 1. Conditional mean number of incorrectly received packets (no FEC)

m	$p_{E,4} = 0.3$		$p_{E,4} = 0.1$	
	$E_1[P]$	$E_2[P]$	$E_1[P]$	$E_2[P]$
100	0.622	1.000	0.622	0.998
500	0.622	1.000	0.622	1.000
2000	0.622	1.000	0.622	1.000

4.2 Packet error processes with FEC

Consider now the effect of FEC. Assume that the FEC code may correct up to l bit errors i.e. $F_T = l + 1$. Then, the conditional mean of the incorrectly received packets is given by the following expressions:

$$E_1[P] = \sum_{i=1}^{4} \pi_{E,i} \sum_{k=F_T}^{m} \binom{k}{m} (1 - p_{E,i})^k p_{E,i}^{m-k},$$
$$E_2[P] = \sum_{i=1}^{4} \pi_{E,i} \sum_{k=F_T}^{m} d_{N,ij}(k)\boldsymbol{e}. \tag{10}$$

Results for different values of l, m and $p_{E,4}$ are shown in the Table 2. For illustrative purposes some non-realistic values of (m, l) are also included. Comparing obtained results we note that the assumption of the same received signal strength during the frame transmission time significantly underestimates or overestimates the actual performance of wireless channel depending on correction capabilities of FEC code. Our approach provides exact values of conditional mean of the incorrectly received packets when the channel coherence time is comparable with the time to transmit a single symbol at the wireless channel.

5 Conclusions and future work

We extended the small-scale propagation model representing the received signal strength of the wireless channel to IP layer using the cross-layer mappings. Our model is represented by the IP packet error process and retains memory properties of the initial signal strength process. We compare results obtained using our model with those presented in literature and show that our approach allows to

Table 2. Conditional mean number of incorrectly received packets (FEC)

(m, l)	$p_{E,4} = 0.3$		$p_{E,4} = 0.1$	
	$E_1[P]$	$E_2[P]$	$E_1[P]$	$E_2[P]$
(100,5)	0.622	1.000	0.622	0.587
(100,10)	0.622	0.976	0.622	0.054
(100,20)	0.622	0.328	0.622	8E-8
(500,20)	0.622	1.000	0.622	0.975
(500,40)	0.622	1.000	0.622	0.052
(500,100)	0.622	0.233	0.622	<10E-10
(2000,100)	0.622	1.000	0.622	0.986
(2000,200)	0.622	1.000	0.622	4E-6
(2000,300)	0.622	1.000	0.622	<10E-10

get more accurate estimators of IP packet error probabilities when the channel coherence time is comparable with the time to transmit a single symbol.

The proposed model entirely relies on classic small-scale propagation model and does not take into account the signal strength attenuation caused by movements of the user over the large distances. The aim of our further work is to extend our approach to mobility-dependent propagation characteristics.

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