Throughput Maximization in Wireless Fading Channel based on Markov Decision Process

Zoran Veličković[1], Milojko Jevtović[2] and Vlastimir Pavlović[3]

***Abstract* – To guarantee the quality of service (QoS) in wireless communication systems is a very challenging task which can be solved through joint optimization of network parameters on many ISO/OSI layers. In this paper the optimizing cross-layer algorithm is presented which minimizes long-term average packet dropping, average packet delay and average transmission power of single user wireless channel. The optimization problem is defined as Markov decision process (MDP) and the composite state space of the communication system with transition matrices of probabilities is determined. For solution of MDP problem the cost function is formed whose minimization allows for getting the optimal transmission policy for given criteria. The structure of the obtained optimal policies for Rayleigh and independent and identically distributed (i.i.d.) fading channel is taken into consideration. Simulation results confirm that the proposed cross-layer algorithm provides adaptation of network parameters and makes it possible for satisfying QoS in a wide range according to application demands. Through simulations it has been confirmed that the obtained solutions are Pareto-optimal, so that through adaptation of one QoS parameter it can be influenced on all the others. Application of MDP in multicriteria optimization problems has proved to be justified.**

***Keywords* – Adaptive cross-layer adaptation, Markov Decision Process, Optimal transmission policy, Quality of Services (QoS).**

I. INTRODUCTION

Extraordinary interest of users for the access to wireless communication systems can be justified by attractive multimedia services they support. The support of wireless multimedia services implies provision of a great network throughput as well as certain level of QoS (Quality of Services). Independently of networks they are applied in, ITU-T has standardized key parameters which influence on QoS of multimedia applications [1]. Without taking technical aspects into consideration, in specification G.1010, ITU-T has standardized QoS parameters. These parameters are classified into eight categories according to the type of application and include voice, video, image and text transfer. Thus, delay up to 150 *ms* and delay variation up to 1 *ms* at conversational speech can be tolerated with maximum 3% packet los rate. On the other hand, Web-browsing can tolerate a delay up to *4 s* and a variation of the delay is not specified with information loss zero. It is evident that different applications require a wide range of QoS, from intolerant of delay to those more tolerant of packet loss. In wireless communication systems, along with the standard assembly of QoS, demand for minimization of transmit power is very important. In this way the efficient using of battery supplying the mobile users is secured. Considering the limited radio recourses, dynamic network structure, time changeable characteristics of a communication medium, appearance of fading, as well as dynamic network traffic, meeting QoS in wireless communication systems is not a simple task. For this reason in some wireless networks the *soft QoS* is defined or the *best effort* service where time period when QoS is not satisfied can be tolerated. On the other hand, the *hard QoS* is defined which is sometimes hard to satisfy even in the wired IP networks. Reason for this lies in the standard ISO/OSI stack of protocols which is not projected to guarantee QoS. In order to guarantee QoS and multimedia applications in wireless computer networks the standard 802.11e has been developed [2]. Under this standard, depending on the type of application is given priority before the packets delivery to MAC layer. In this way, better system performance can be got in low traffic, but the higher traffic they will degrade.

Optimization of network resources in wireless communication systems demands consideration of many networks ISO/OSI layers, in order to satisfy QoS defined by the application. Joint optimization of network parameters of many ISO/OSI layers is called *Cross-Layer* (CL) design [3]. Three basic architectures are usually applied for an undisturbed access to network parameters: the architecture with the direct communication between layers, the architecture with divided data base, and the modular architecture of CL design. CL design of stack of communication protocols in the wireless environment is a method which could improve satisfying QoS. Optimal CL protocols which fulfill the intended QoS can be realized by joint adaptation of parameters through many ISO/OSI layers. This actually means that network parameters which relate to all aspects of wireless communications can be adapted by CL design. In this way at the same time parameters of PHY layer (transmission power, modulation type, bit error rate - BER), MAC layer (access scheme, buffer size of transmitter) and APP layer (source coding, permitted delay) can be at the same time optimized. Generally, all layers from the stack of protocols can be included into CL design, but this is often not practical. Increase of the number of optimizing network parameters demands provision of considerable processing resources which complicates realization of these protocols. Optimization CL algorithms which consider network resources with PHY, MAC and APP layers are most often realized.

[1]Zoran S. Veličković is with the High Technical School, A. Medvedeva 20, 18000 Niš, Serbia, E-mail: zoran.velickovic@vtsnis.edu.rs.

[2]Milojko Jevtović is with the Serbian Engineer Academy, L.Ribara 7, 11000 Beograd, Serbia, E-mail: vladmijev@ptt.rs

[3]Vlastimir D. Pavlović is with Faculty of Electronic Engineering Niš, A. Medvedeva 14, 18000 Niš, Serbia, E-mail: vlastimir.pavlovic@elfak.ni ac.rs

CL algorithm which makes adaptation of network parameters in function of varying the quality of communication channel (fading level) [4], total capacity of the transmitting buffer and the type of network traffic in the network node is taken into consideration in this paper. A mathematical model based on Markov Decision Process (MDP) which optimizes network parameters is applied in order to satisfy QoS [5]. The communication system is modeled by the composite discrete Markov process which describes behaving of the wireless communication system in various working conditions. The system modeled in this way can be solved numerically if dynamic programming is applied [6], wherewith optimal transmission policy for the set objective function is determined. Various objective functions can as a solution have various optimal transmition policies. The aim of this paper is maximization of average long-term network throughput along with limitation of the average transmission power, constant BER satisfying, minimization of the number of rejected packets and minimization of packets delay. The composite model of the wireless single-user communication system which consists of Markov chains PHY and MAC-LLC layers is developed in Section II. The optimization problem and its solution are presented in Section III. The obtained results are presented in Section IV. Certain conclusions are given and directions for further investigations are suggested in Section V.

II. Model Of Wireless Communication System

A. Dynamics and Throughput

Considered wireless communication system consists of a transmitter, which incorporates a buffer of the limited capacity and encoder-modulator and of a receiver. Loading of the buffer is done with packets from the higher ISO/OSI layers and is modeled by Poisson distribution. Transmission rate out of the buffer is adaptive, and it sustains the realization of optimization CL algorithms. The connection between the transmitter and the receiver is realized in Rayleigh fading channel, while information about the quality of the channel and the buffer state are being interchanged through the control channel. The analysis of the work of the presented system has been considered through a series of successive time frames whose duration is T_f. Frame i comprises the time period of $[i \cdot T_f, (i+1) \cdot T_f]$ for which the number of incoming packets into the buffer A_i is specified. Only after the expiration of the time frame i to the existing state of the buffer, the number of the arrived packets A_i can be added. The mean value of the number of packets coming into the buffer while the frame lasts, λ, is calculated as $\lambda = E\{A_i\}$, where E{•} is the operator of the mathematical expectation. It has been supposed that all the packets are of equal length and that the buffer is of limited capacity and that it can receive only B packets. Each the packet that arrives at the moment when the buffer is completely loaded will be rejected and regarded as lost. However, in the case when the buffer is not completely loaded, it will be complemented with the arrived packets until the full capacity has been reached (B), and all the rest packets are rejected and considered lost. Another source of the rejected packets in the considered system is the wireless communication channel with fading. Each error created during packets transmission will have as a consequence rejecting of that packet and it will be regarded as lost. The average number of packets η which will be delivered to the application on a higher layer of the receiver can be determined in the following way:

$$\eta = \left(\lambda T_f\right) \cdot \left(1 - P_o\right) \cdot \left(1 - P_p\right), \tag{1}$$

where P_o is the buffer overflow and P_p is the packet error probability. The expression (1) binds two independent subsystems of the wireless communication system on two ISO/OSI layers: the subsystem of the transferring medium (PHY layer) and the subsystem of the buffer in the network node (MAC-LLC layer).

B. Composite Markov Model of the Communication System

The state space of the communication system (S) is composite, determined by states of the communication channel g and the buffer in the communication node $\mathcal{B}$:

$$S = g \times \mathcal{B} \tag{2}$$

where {×} represents an operator of Cartesian product. On the base of (2), the state space of Markov chain of the communication system is determined in the expression:

$$S = \left\{s_1, s_2, ..., s_Q\right\}, \tag{3}$$

where

$$Q = K \cdot \left(B + 1\right). \tag{4}$$

Therefore, state of the communication system for frame i, S_i, is determined by two components: state of the buffer B_i and state of the communication channel G_i:

$$S_i = \left(B_i, G_i\right). \tag{5}$$

The packet number for empting the buffer when the communication system is in the state S_i is marked with U_i. CL optimization algorithm described in the following section implies that both transmitting and receiving sides have information about the state of the communication system for every frame i. To complete determination of Markov chain it is necessary to determine transition probability for the whole communication system. It is important to mention here that there is not only one probability for transition from the system state S_i into the system state S_{i+1}, but that the number of possible transitions determined by adaptive possibilities of unloading the buffer in the communication node. Therefore, set of actions A_s, which can be performed for every state of the system is determined by adaptive possibilities of coding and choice of modulation techniques in the communication system. For the observed communication system the set of actions represents the number of packets through which the buffer in the communication node can be emptied during one frame. By fixing the symbol rate and adaptation of parameters of signal constellation in MQAM modulator the rate of emptying the communication buffer can be adapted. Transition probabilities of the communication system p_S in realization of the action u can be determined in the following way:

$$p_S(s,s') = P_r\{s_{i+1} = s' | s_i = s, U_i = u\} \tag{6}$$

$$= p_G(g,g') \cdot p_B(b,b',u), \tag{7}$$

where p_G and p_B are transition probabilities of the subsystem which describe the communication channel, that is, state of the communication buffer, respectively. The quadrate matrix of transition probabilities for the whole communication system for one value of the parameter u is given in (8).

$$P^{(S)} = \begin{bmatrix} p_{0,0}^{(S)} & p_{0,1}^{(S)} & \cdots & \cdots & \cdots & p_{0,Q}^{(S)} \\ p_{1,0}^{(S)} & p_{1,1}^{(S)} & \cdots & \cdots & \cdots & p_{1,Q}^{(S)} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{Q-1,0}^{(S)} & p_{Q-1,1}^{(S)} & \cdots & \cdots & \cdots & p_{Q-1,Q}^{(S)} \\ p_{Q,0}^{(S)} & p_{Q,1}^{(S)} & \cdots & \cdots & \cdots & p_{Q,Q}^{(S)} \end{bmatrix} \tag{8}$$

III. Optimization Problem

If P_i marks the necessary transmit power of the i-th frame, it is extremely important for wireless communication systems to limit the maximum of the long-term average transmission power:

$$\lim_{T\to\infty} \sup \frac{1}{T} \mathrm{E}\left\{\sum_{i=0}^{T-1} P_i\right\} \le \overline{P}. \tag{9}$$

On the other hand, the important parameter in multimedia applications is the maximum of the permitted delay of packets. Delay of packets is defined as the buffer occupancy via Little's theorem:

$$D_i = \frac{B_i}{\lambda(1-P_p)} \tag{10}$$

where B_i is the number of packets in the buffer during the frame i. The maximum long-term average delay of packets can be defined in the following way:

$$\lim_{T\to\infty} \sup \frac{1}{T} \mathrm{E}\left\{\sum_{i=0}^{T-1} D_i\right\}. \tag{11}$$

One of the goals of this paper is minimization of the long-term average packets delay. An algorithm which is going to be presented in the next section will minimize the mean time of packets delay simultaneously with satisfying the demanded BER and limiting the average transmission power. In this paper, protocols which keep BER constant (P_b = const) will be considered, so that it will result in constant PER. Increasing of network throughput for the case of constant PER can be realized through minimization of the number of rejected packets produced by the buffer overflow in the communication node. The average number of rejected packets depends on the capacity, dynamics and fulfillment of the buffer:

$$L_o(b,u) = \mathrm{E}\{\max(0, A + b - u - B)\}, \tag{12}$$

where B is the capacity of the buffer in packets, b the number of packets in the buffer which is unloading with u packets and loading with A packets per frame. The expectation is with respect to the number of packets arriving in frame. The maximum long-term average number of rejected packets can be presented in the following way:

$$\lim_{T\to\infty} \sup \frac{1}{T} \mathrm{E}\left\{\sum_{i=0}^{T-1} L_o(B_i, U_i)\right\}. \tag{13}$$

Through previous expressions (9), (11) and (13) conflict network demands are defined regarding limiting long-term average transmit power, delay and the number of rejected packets. Namely, minimization of the average transmit power will influence on the average delay and average dropping packet. Therefore, optimization of one parameter is nor possible without influence on the other. Finally, the optimization problem can be defined as minimization problem in the following way:

Minimize the maximum of long-term average rejected packets L_o and average packet delay $\overline{D}$ of the wireless communication system subject to an average transmission power constraint $\overline{P}$.

We are interested in three objectives, minimizing the average packet delay, average packet loss over the average transmission power. All of these criteria can not be minimized at the same time. One of the solutions of the multi-objective minimization problem is, instead of the original problem, to minimize the weight function of all of three criteria. In this way the minimization problem is defined as the long-term average cost MDP.

$$\lim_{T\to\infty} \sup \frac{1}{T} \mathrm{E}\left\{\sum_{i=0}^{T-1} C_I(B_i, G_i, U_i)\right\}, \tag{14}$$

where C_I is immediate cost incurred in state (b, g) when control action (u, P) is taken, i.e.:

$$C_I(b,g,u) = P(u,g,P_b) + \beta_1 \cdot L_o(b,u) + \beta_2 \cdot D(b). \tag{15}$$

The weight factors β_1 and β_2 are positive numbers with the role of Lagrangian multipliers and indicate the relative importance of average packet lost and average buffer delay over the average power. The dynamic programming is recursion procedure for MDP solution by *value function*.

IV. Simulation Results

The results are obtained for the following simulation parameters. On APP layer packets are generated which arrive in buffer according to a Poisson distribution with λ=3000 packets/s. On MAC-LLC layer it is supposed that all the packets consist of $L=100$ bits and that the capacity of the transmitting buffer is limited to $B=15$ packets. On the physical layer the following parameters are supposed: the channel bandwidth is $W=100$ kHz, noise power density $N_o=2\cdot10^{-5}$ W/Hz and bit error rate is fixed on $P_b=10^{-6}$. MQAM modulator is used in the transmitter where through varying the constellation of the signal M adaptation of the transmission rate can be realized. Duration of the symbol is fixed to $Ts=1/W$ and the frame duration T_f is determined with *100* symbols. With the supposed parameters the buffer is to be emptied with u packets/frame when signal constellation is $M = 2^u$. Adaptation of transmission rate U_i is performed for every frame i.

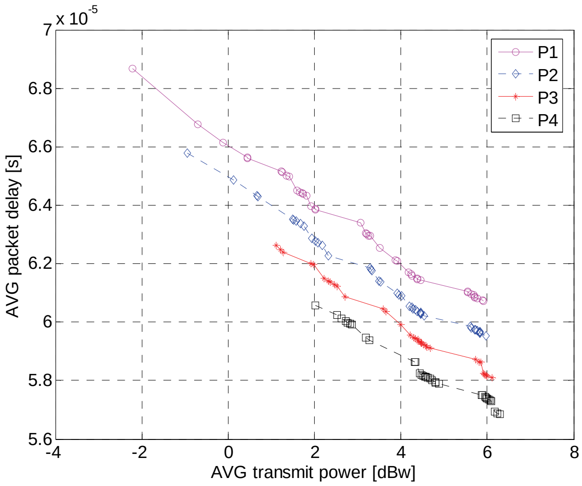

Fig. 1. Pareto-optimal AVG long-term packet delay as function of long-term AVG transmit power

Fig. 1 and Fig. 2 were obtained by variation of parameters β_1 and β_2 which is determined by the optimal policy. There are shown results for different optimal transmission policy labeled P1 to P4. Graph relating to policy P1 is obtained for constant values of β_1, while the parameter β_2 varied in the range $100\cdot10^4>\beta_2>1\cdot10^4$. Parameter β_1 corresponding to the considered policy is: β_1 = [$1\cdot10^4$ $20\cdot10^4$ $50\cdot10^4$ $100\cdot10^4$]. As a solution to the MDP, we get the vector U_i, by which it determines the number of packets dropped and the L_o level transmitting power P. Averaging obtained values of the transmitting power, number of dropped packets and packet delay for all frames are Pareto-optimal values. With the graphics shown in Fig. 1 can be concluded that the average packet delay increases with reduction of the AVG long-run transmit power.

On the graphs in Fig. 2, the results of long-term AVG number of rejected packets as a function of long-term AVG time delay of packet are shown. It is clear that there is great number of the optimal policy, and which of them will be chosen depends on the desired QoS parameters.

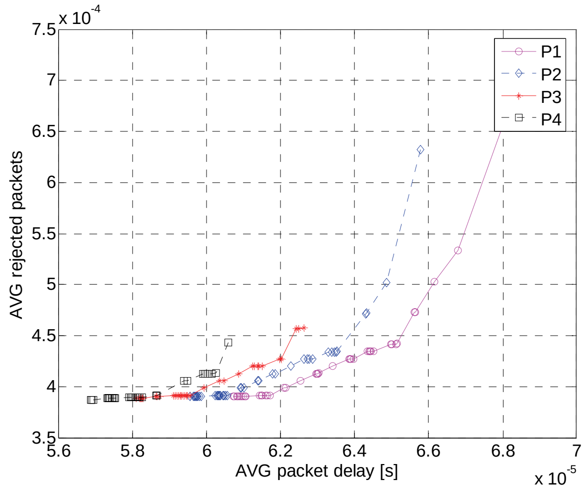

Fig. 2. Pareto-optimal AVG long-term rejected packets as function of long-term AVG packet delay

V. Conclusion

In this paper it was shown that simultaneous optimization of network parameters with many ISO/OSI layers allows for satisfying the set QoS demands for multimedia wireless applications. If wireless multimedia application set the demanded QoS in the form of MDP problem, it is possible to find effectively an optimal transmission policy. The application type, quality of the communication channel and resources of the network node determine the choice of the optimal transmission policy. The wireless communication channel with Rayleigh is considered in this paper. The channel with i.i.d. fading demands considerably less transmission power in relation to the wireless communication channel with Rayleigh fading. The cross-layer design provides joint optimization of the application layer with other layers from the protocol stack, which improves performances of the wireless communication system and provides support for the wide set of multimedia applications.

References

[1] ITU-T Recommendation G. 1010: End-user multimedia QoS categories – ITU-T, 2001.

[2] IEEE 802.11e WG. 2005. Wireless LAN MAC and PHY specifications amendment 8: MAC quality of service enhancements, http://standards.ieee.org.

[3] V. Srivastana, M. Motani, "Cross-layer design: a survey and the road ahead", IEEE Commun. Mag., vol. 43, no. 12, pp. 112–119, Dec. 2005.

[4] Z. Veličković, M. Jevtović, "Adaptive Cross-Layer Optimization in Wireless Fading Channel and Limited Buffer Capacity," ICEST Proceedings vol. 1, pp. 61–64, 2010.

[5] M. L. Puterman, *Markov Decision Processes: Discrete Stochastic Dynamic Programming*, New York, NY: John Wiley & Sons, 1994.

[6] Z. Veličković, M. Jevtović, "Adaptive Cross-Layer Optimization Based on Markov Decision Process", Journal Electronics and Electrical Engineering, No. 2 (108), pp. 39–42, Feb. 2011.