Adaptive Cross-layer Optimization in Wireless Fading Channel and Limited Buffer Capacity

Zoran S. Veličković[1] and Milojko Jevtović[2]

Abstract – **Difficulties in the realization set Quality of Service (QoS) in wireless multimedia communications can be overcome by jointly optimizing the network parameters over ISO/OSI layers. This paper presents optimization algorithm that maximizes the network throughput of the wireless communication fading channel and limited capacity of transmit buffer and the available transmission power of network nodes. The applied algorithm is based on the Markov Decision Process (MDP), which requires modelling the entire communication system with Markov chain; determine the set action, transition probabilities and functions of the cost. The structures of optimal policies for different models of network traffic at the constant BER are analyzed. Numerical results obtained in the simulation environment show the reasonableness of applying MDP.**

Keywords – **Adaptive cross-layer adaptation, Markov Decision Process, Optimal transmission policy.**

I. INTRODUCTION

Adaptive network techniques have great importance in the implementation of modern wireless network systems. They provide a dynamic adaptation of wireless network like as reaction on the changes in the quality of the channel or the type of network traffic. Adaptation of network parameters is intended to improve network performance, and increasing the quality of services [1]. In addition to standard network services, modern wireless mobile communications provide attractive new services. In order to define the quality of services, ITU-T G.1010 specification standardizes its key network parameters from the perspective of users [2]. According to G.1010 parameters which affect Quality of Service (QoS) are: *delay*, *delay variation* and *information loss*. Depending on the application, according to this standard, certain levels of delay, delay variation, or loss of information can be tolerated. Thus, delay up to 150ms and delay variation up to 1ms at conversational speech can be tolerated. On the other hand, downloading content from the Web can tolerate a delay up to 10s; a variation of the delay is not specified. It is evident that different applications require a wide range of QoS, from intolerant of delay to those more tolerant of packet loss. QoS may be required in different forms, but occurs most frequently in the form of the required rate or a defined BER. The inability to guarantee the delivered QoS is a fundamental problem in wireless packet communications. This problem is particularly pronounced in mobile multimedia applications. In order to guarantee QoS and multimedia applications in wireless computer networks has been developed 802.11e standard [3]. 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. This leads to the conclusion that the solution to this problem can not be required to optimize network parameters only one ISO/OSI layer. Generally, to improve the quality of services in a wireless communication system is necessary to discuss the joint optimization of parameters with multiple ISO/OSI layers. Jointly optimization of network parameters of several ISO/OSI layers according to [4] is called *cross-layer* (CL) design. Jointly consideration of PHY and MAC-LLC layers in order to satisfy QoS is presented in [5]. In [6] cross-layer model for multimedia multicast/broadcast services to efficiently support the diverse QoS over mobile wireless networks were shown. Power/delay tradeoffs of a single user system with a finite buffer are analyzed in [7]. Optimal packet scheduling over correlated fading channels which tradeoff between minimization of three goals: average transmission power, average delay and average packet dropping probability are considered [8].

In this paper, CL is considered an optimization problem related to the maximization of flow in the wireless communication system with limited resources. First of all, restrictions are related to the level of engaged transmission power and the available buffer capacity in the communication node. Set QoS request relates to the provision of the required bit error (BER) as required by some multimedia applications. Packet traffic characteristics also significantly affect the way to achieve the required QoS. In this paper packet traffic is modeled by Poisson's distribution and by packed constant rate (CPR). The optimal transmission policy should take into account the type of packet traffic, limited buffer capacity and condition of the communication channel. This requires an optimization protocol can access the network parameters from the two layers. At the PHY layer contains information about the quality of wireless channel, until the MAC-LLC layer contains information about the state of the communication buffer in the function of the type packet traffic. Markov decision process (MDP) [9] has been applied as tools for optimization of network parameters. If MDP is used, transition probability matrices depend on the system state and actions which "the software agents" can perform in every discrete time segment in which decisions are being made (decision epoch). The software agent can achieve *rewards* or *costs* depending on the performed action and the state of the system at that decision epoch. The aim of the MDP is found

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optimal policies for defining the series of actions which should be taken in every state of the system, the utility functions that could be maximized. Adaptive techniques to PHY and MAC layer as well as the needs of their joint optimization will be presented in the following work.

Further in this paper the optimization problem of wireless communication system with one user for a constant and Poisson model of traffic has been defined. It has been developed as composite communication system model based on Markov chains of PHY and MAC layer LLC. The system model and solution of the optimization problem by using MDP is presented in section III. The obtained results and the analysis of the optimal structure policies in a simulated environment are presented in section IV. Main conclusions are summarized in the final section.

II. ADAPTIVE TECHNIQUES

A. Adaptation of the PHY layer

Adaptation of the code and modulation technique is the primary form of network parameters adjusted to new conditions in the wireless communication channel. Frame is a unit of data to the PHY layer to which the applicable code and modulation scheme. Modern wireless communication protocols at the PHY layer have a limited choice set of code and modulation scheme. However, the present protocol do not specify the way to use this scheme, they are only offer a choice. An important parameter in the choice of code and modulation scheme is the level of fading in communication channel which is determined by the SNR at the destination [10]. The quality of the communication channel can also be characterized as probability of discarded packets P_p. The level of SNR can be affected by a variation of transmitting power and adaptation of modulation parameters, which will achieve different optimization objectives. Thus, the basic mechanism of adaptation of network parameters on the PHY layer is a variation of transmission power and choice of code and modulation scheme, which adapts to flow in the wireless communication system. In real conditions they can not achieve the maximum network flows defined by the selected network parameters given the fact that there is not always data available to send. Temporary delay in sending can be optimized transmission policy in order to save transmission power, as shown in the following work.

B. Adaptation of MAC-LLC layer

The basic data unit at the MAC-LLC layer is packet, so that the maximum capacity is determined by the number of packet which can be put into it. In addition to the quality of the channel PHY layer, the size and occupancy transmitting buffer significantly affect the number of discarded packets. Since the buffer is organized on the principle of first-in-first-out, the last arrived packet is placed on top of this structure. However, if the packet arrives in the buffer when it is completed, there is a rejection of the packet.

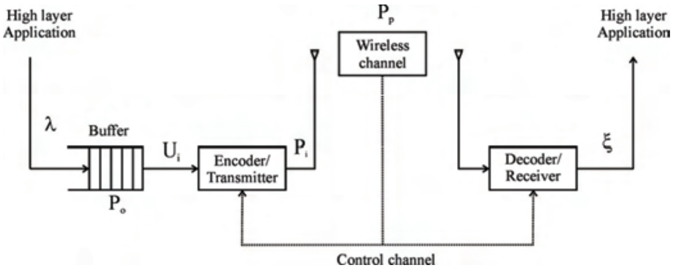


Fig. 1. Wireless communication system with one user and limited buffer capacity.

The dynamics (loading/emptying) and the current state of the buffer will depend on the number of discarded packets. The probability of discarded packets P_o due to buffer overflow depends on the dynamics of the system and the size of the buffer. Thus, the probability of rejection of the packet is reduced if the buffer capacity increases, or, if you increase the speed of emptying the buffer. As already mentioned, the adaptation of code and modulation scheme may affect the likelihood of rejection of the packets. Depending on the type of application, loading transmitting buffers with higher ISO/OSI layers can be modeled as a random process or a process with a constant rate of packets. To analyze the structure of transmission policy, a buffer loading is modeled as Poisson process, i.e. the CPR process.

C. Cross-layer optimization of PHY and MAC-LLC layer

In order to meet different QoS, it is necessary to consider optimization problem in several ISO/OSI layers. Adaptation of transmitting policy depends on the state of communication channels and buffers state in the receiving node. Taking into account the probabilities of rejection packets due to the occurrence factor in the communication channel and the probabilities of rejection packets due to overflow, packet loss rate can be expressed as:

$$\xi = 1 - \left(1 - P_o\right) \cdot \left(1 - P_p\right), \qquad (1)$$

where P_o is the buffer overflow, P_p is the packet error probability. If the application requires a constant bit error rate (BER), the maximum throughput obtained by minimization of expression (1) is equal to minimization the parameter P_o.

III. SYSTEM MODEL

The structural block diagram of the considered wireless communication system with one user is presented in Fig. 1. This communication system consists of a transmitter, which incorporates a buffer of limited capacity and encoder-modulator and of a receiver. Loading of the buffer on the transmitter side is done with packets from the higher ISO/OSI layers and is modeled by constant packed rate (CPR) and Poisson distribution. 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 as it has been presented in Fig. 1. The analysis of the work of the presented system has been considered through a series of successive time frames *i* whose duration is T_f. The mean value of the number of packets coming into the buffer while the frame lasts, λ, is calculated as, $\lambda = \mathrm{E}\{A_i\}$ where $\mathrm{E}\{\bullet\}$ 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. All the packet that arrive at the moment when the buffer is completely loaded will be rejected and regarded as lost. Another source of the rejected packets in the considered system is the wireless communication channel with correlated fading. PHY [10] and MAC-LLC models layer are based on Markov chains. The space state of the communication channels (*g*) and buffer (*b*) defines the space state of complete communication system. In order to complete Markov model, the composite transition probability matrix is determined. The resulting model of the entire communication system is complete so that you are able to join set of actions which the system can translate from one state to another. Transition probabilities of the composite communication system p_S in realization of the action *u* can be determined:

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

$$= p_G(g,g') \cdot p_B(b,b',u), \qquad (2)$$

where p_G and p_B are transition probabilities of the PHY and the MAC-LLC subsystem respectively. To complete the MDP model of the entire communication system need to determine the cost function that is implemented at each transition:

$$R = P(u,g,\overline{P}_b) + \beta \cdot L_o(b,u). \qquad (3)$$

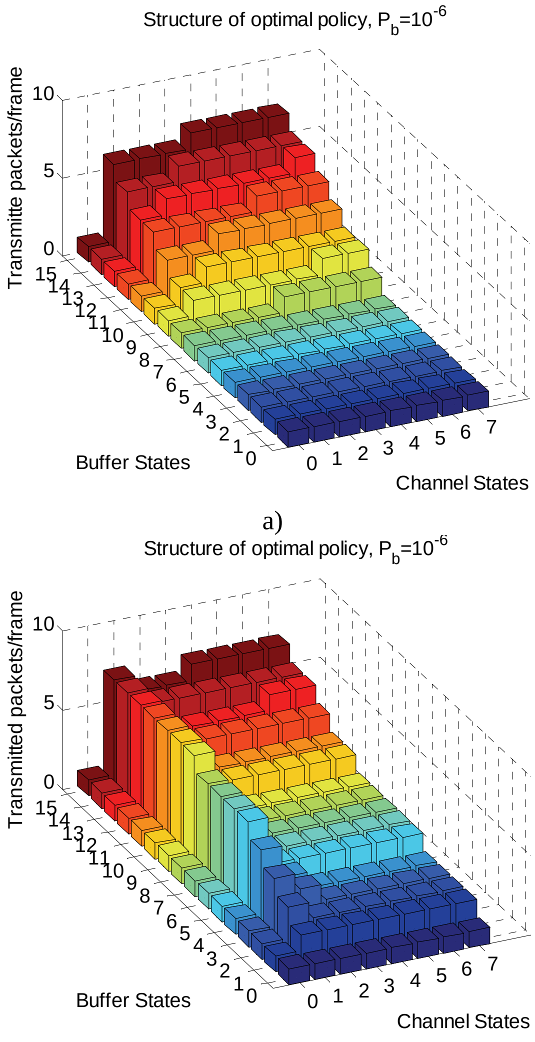
The first addendum in the weight sum of costs (3) relates to the level of the engaged power (*P*), while the second addendum relates to the number of rejected packets (L_o). By the parameter β the mutual relation between the addenda is determined and the tradeoff between the set of criteria is provided. Stationary optimal policy π^* should provide a minimum of the function (4) along with meeting the criterion of power set. The aim of MDP is minimization of the mean value of the expected discount sum:

$$\pi^* = \arg\min_{\pi} \left\{ \limsup_{T\to\infty} \frac{1}{T} \mathrm{E}\left[\sum_{i=0}^{T-1} \alpha^i R(S_i,U_i) \right] \right\},\ 0 < \alpha < 1 \cdot \qquad (4)$$

Solution of the optimization problem can be presented by following notation, $U_i = \pi^*(S_i)$ where S_i represents state of the communication system and α^i discount factor of the i-th frame. Therefore, an optimal policy relates to every frame i on the base of the state of the communication system Si and is realized with emptying the transmitting buffer in optimal number of packets U_i. By solving the optimization problem (4) for individual values of the parameter β, Pareto-optimal values $\overline{P}$ and L_o are determined.

IV. SIMULATION RESULTS

This section presents the results of the optimization of flow with limitation average transmission power and the satisfaction of a required BER. Structure of optimal transmission policy is determined for two models of loading communication buffer. The first model (CPR) involves loading the buffer at a constant rate, λ, while the second model of loading buffer is realized by Poisson distribution with mean value λ. MDP was used for the optimal solution of the problems, while the simulation parameters have the following values: $\lambda = [1100 \quad 1200 \quad 1300]$ packets/s, *L=100* bits in a packet, the buffer capacity *B=15* packets, BER $P_b = 10^{-6}$, bandwidth *W=100* kHz, noise power density $N_o=2x10^{-5}$ W/Hz, duration of the symbol is fixed to $T_s=1/W$ and the frame duration is determined with 100 symbols. In MQAM systems this parameter arrangement allows for the buffer to be emptied with the *u* packets/frame with a signal constellation $M = 2^u$. The channel with the time correlated Rayleigh fading is modeled with eight states as in [10, Table I]. For different values of the weight parameter, β, the solution of the optimization problem is the vector of the rates U_i in which the communication buffer should be emptied for every state of the communication system. On the base of the value of the vector U_i the number of rejected packets L_o is determined and the value of the engaged power $\overline{P}$. By averaging the values obtained for the engaged power and the number of rejected packets for all frames, Pareto-optimal values have been obtained. In Fig. 2 the structure of the optimal policies is shown for a) CPR and b) the Poisson model of traffic in the channel fading. For the same parameter value, λ, one can notice different structure of the optimal policy. The delay in sending packets in low occupancy of the buffer regardless of the quality of the channel is notably for the CPR traffic model, Fig. 2a. On the other hand, when it reaches certain buffer occupancy, improving quality of the channel and increasing occupancy buffer increase the speed of emptying the buffer. Figure 2b shows the structure of the optimal policy for the case Poisson's model traffic conditions in case of the same values of fading. Similar to the CPR model, withdrawal of sending in the case of the worst quality of communication channels is recommended, but we recommend sending the packets to all other conditions. Maximum transmission rate is recommended for the worst quality of the communication channel that allows you to send yet. Of course, if the buffer occupancy increases, speed of emptying the buffer increases too. However, unlike water-filing algorithm, this transmitting rate does not necessarily increase with the increase quality of the channel. With the increase of buffer occupancy, the rate of empting Poisson's model increases too. Based on the presented results, the structure of the optimal policies depends on the model of the communication channel, i.e. transition matrix of the communication channel. Fig. 3 shows Pareto-optimal values of the average engaged power and the average number of rejected packets. These parameters allow satisfying the wide palette of compromise demands.



a)

b)

Fig. 2. Structure of optimal policy: a) CPR b) Poisson's traffic model for constant BER.

From Fig. 3 it can be concluded that the CPR model of traffic can be realized by policies with lower transmission power compared to the Poisson model of traffic. Regardless of the traffic model, with an increase in the number of packets which buffer is loading, a minimum average of discarded packets is also increasing. In order to realize the optimal policies information from two layers (PHY, MAC-LLC) has been used, while realization was done only by adjusting parameters on one layer (PHY). The results obtained in simulated environment of Matlab show that the application of cross-layer design in modern wireless multimedia applications is justified.

V. CONCLUSION

Jointly optimization of network parameters with multiple ISO/OSI layers provides the satisfaction of QoS requirements set out in multimedia applications. Type of application determines the characteristics of traffic and it has a significant impact on the optimization algorithms. This paper demonstrates that the CPR traffic model in the channel with Rayleigh fading requires less transmission power compared to Poisson's traffic model. Cross-layer design provides joint optimization of application layer with the rest of the protocol stack, thereby improving network performance. For the appropriate model of network traffic parameters an optimal transmission policy can be stored in a table, where it can be used later. Optimization algorithm based on the MDP is demonstrated through simulation examples and its effectiveness is illustrated.

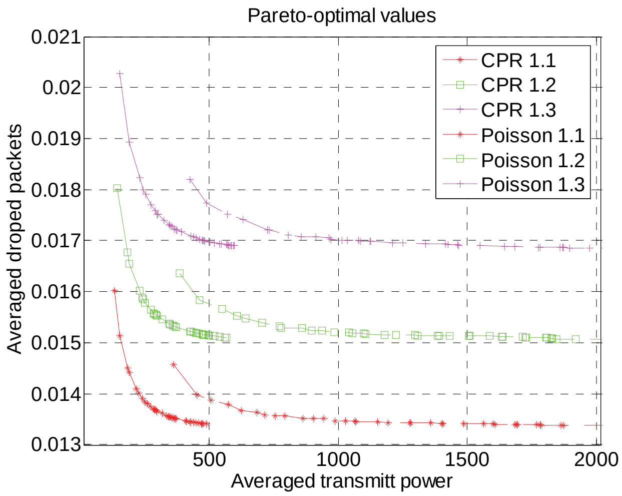


Fig. 3. Pareto-optimal values of averaged dropped packets vs. averaged transmit power for CPR and Poisson's traffic model.

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