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Analytical Study of IEEE 802.11 PCF for Regional and Metropolitan Area Networks

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Abstract: *A star-like regional wireless network under IEEE 802.11 protocol is studied: its end stations are hidden from each other and linked only with the ba-se station – the point of access to outer networks. It provides access to Internet users of cable LANs connected to its end stations.Transfer of large files through TCP/IP connections forms the main bulk of the wireless traffic. To improve the network performance, we propose and study the optional IEEE 802.11 Point Coordination Function (PCF). Specifically, we investigate different PCF implementations, which allow the achievement of high performance under various load and environment conditions.*

Keywords: *IEEE 802.11 PCF, adaptive polling policy, Markov models, throughput, MAC service time, MAC sojourn time.*

1. Introduction

A recent development in network industry is wireless data transmission networks. Wireless technology is helpful in quickly and cheaply connecting remote LANs of different organizations into a unified regional data transmission network for providing high-speed access to the Internet.

The main structural element of a typical regional wireless network is a star radio network (Fig. 1): its hub hosts a base station with omnidirectional antenna for receiving signals from end stations – the radiobridge between the wireless network and local cable networks. In a typical regional wireless network, the end stations are radio blind to each other (i.e., hidden) and are compelled to interact via the base station on a tall building or a TV tower, etc., which provides access to external networks.

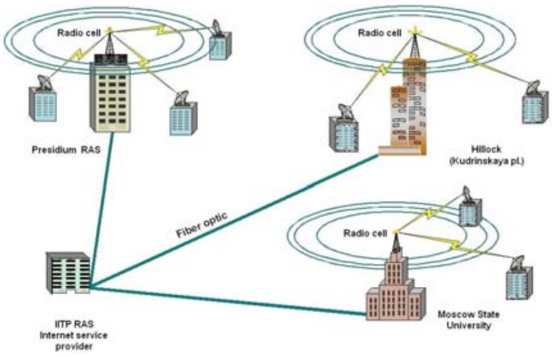

Fig. 1. Radionet: Moscow 802.11 network

IEEE 802.11 [1] being one of the most popular protocol for wireless and mobile networking, offers two different MAC mechanisms. An example of successful realization of regional wireless networks under IEEE 802.11 protocol is the Radionet [2, 10] (Fig. 2) consisting of several radio networks designed and realized by the Institute of Information Transmission Problems, Russian Academy of Science for connecting LANs of scientific organizations and educational institutions in Moscow to Internet.

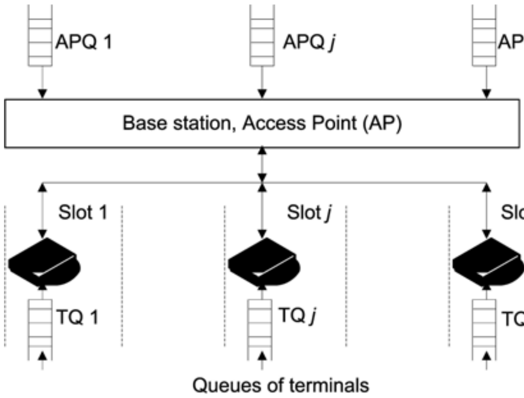

Fig. 2. PCF operation scheme

The IEEE 802.11 basic mechanism called the Distributed Coordination Function (DCF) is based on CSMA/CA scheme and allows independent and distributed channel access. The optional PCF is a centrally-controlled access scheme, according to which terminals can transmit only after receipt of prompt (a polling frame) from the point coordinator being usually the Access Point (AP) of the network.

In the majority of related papers ([3, 4], for example), the maximal throughput provided by IEEE 802.11 DCF is estimated only for local networks under the assumption that the queue at every station is never empty and there are no “hidden” stations. Prolonged measurement experiments with the Radionet [2] have shown that the “up-down” traffic, i.e., from the base station to end stations, predominates in a typical radio network (Fig. 1), because the main need is to obtain information from the Internet via the base station and the main bulk of wireless traffic handles mostly large files transmitted via TCP/IP-connections (FTP-like traffc).

Therefore, the assumption that the queue of packets for transmission is never empty (i.e., the queue is always saturated) is applicable only to the base station and the “down-up” traffic contains brief TCP-acknowledgments to TCP/IP-packets received from the base station. In [5], we studied a situation in which there are stable prolonged TCP/IP-connections between the users of local networks integrated in the Radionet and the outer world under the following assumptions:

- TCP/IP-connections are uniformly distributed over all end stations, i.e., a transferred TCP/IP-packet with equal probability, which is not dependent on the prehistory, is intended for one of the N end stations;
- packet handling time in LANs outside the wireless network is negligibly small;
- disturbance intensity defined by the bit error rate (BER) is constant and one and the same for all stations.

These assumptions were necessary since we estimated precisely the maximal intensity of the TCP/IP-traffic through a wireless network under the IEEE 802.11 protocol. In particular, they imply, first, the place in the main station buffer relieved by a packet is immediately occupied by the next TCP/IP-packet, whose destination with equal probability is one of the integrated local networks and, second, upon receipt of a TCP/IP-packet from the base station, its TCPacknowledgement is immediately put into the queue at the corresponding end station.

The results obtained in [5] allowed to conclude the following. The capacity of a wireless channel is not used efficiently if there are several hidden end stations: at a channel rate of 11 Mbps, the throughput ensuring Internet connections is not greater than 3.2 Mbps even in the absence of collisions and 2.5 Mbps under collisions due to the perceptible throughput reduction inherent in the DCF scheme and the consequent large back-off time and high collision probability. The DCF works well under low load conditions, but its performance degrades essentially with increasing the number of terminals and load. Waste of bandwidth caused by collisions and increasing back-off times becomes very high in the presence of hidden terminals.

The PCF allows avoiding the problems, since it operates on the contention-free base, and therefore achieving a much high maximum throughput than the contention-based DCF. Therefore, in the paper, we estimate the regional network considered (Fig. 1) operation efficiency under centralized control guaranteeing the point coordination function (PCF). The rest of the paper is organized as follows. In Section 2, we describe briefly the PCF. In Section 3, we propose and study various PCF implementations under high downlink load coniditions described above. In Section 4, we investigate analytically a generic polling backoff scheme providing the PCF efficiency under normal load conditions and bursty traffic. Section 5 contains some numerical results and discussion on comparing various polling back-off schemes and their optimization. Summary is given in Section 6.

2. Point coordination function

The PCF recommended in IEEE 802.11 as an alternative of the DCF mechanism requires a centralized poll by the coordinator (the base station, or the AP, in the network) for all remaining stations. The base station has a list, from which it chooses an end station and sends frames containing permission for transmission and also data packets, if any, addressed to this station.

Usually, the AP polls terminals (end stations) in the Round-Robin way. In fact, the PCF represents a TDMA scheme, where the network operation time is subdivided into polling cycles consisting of time-variable slots (Fig. 2). Slot i is designated for a frame exchange between the AP and the *i*-th terminal. In contrary to a terminal controlling the only queue of packets, the AP manages *N* AP's Queues (APQs), where *N* is the number of polled terminals, and APQ*j* contains packets to be transmitted to terminal *j*. We call the APQ*j* and the *j*-th Terminal's Queue (TQ*j*) the opposite queues. Both the APQ and TQ size are assumed unlimited in the paper.

At the beginning of the *j*-th slot, the AP sends a polling frame being either a CF-DATA frame (if APQ*j* is not empty) or a short CF-POLL frame containing no data (Fig. 3). If the AP has received a data packet in the previous slot, it acknowledges the receipt by setting the appropriate bit to one in the polling frame MAC header. Upon a correct polling frame receipt, the terminal replies with a data frame or null frame (if TQ*j* is empty) containing no payload together with possible setting the acknowledgment bit to one, after a short interval δ (called SIFS, Short InterFrame Space, in [1]). The AP starts polling the next terminal either after receiving a reply from the the current terminal, including δ closing the polling slot, or upon the expiration of the timeout PIFS (PCF InterFrame Space) that means an unsuccessful transmission of an inquiry frame.

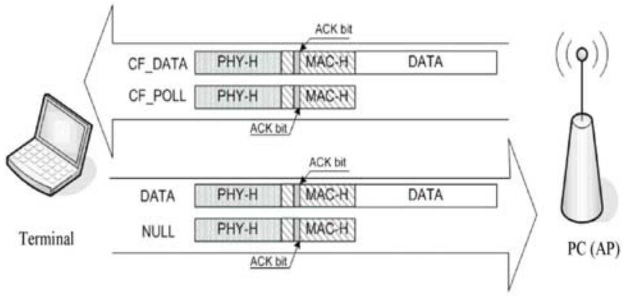

Fig. 3. Frame exchange in the PCF

3. PCF performance under high downlink load

Let us study the PCF performance under the assumptions introduced at the end of Section 1. Moreover, we assume that:

- all end stations are homogeneous, and they are polled in the Round Robin way;
- all packets transferred from the base station to an end station (that is, TCP packet) and vise versa (TCP acknowledgment) are of size r_b and r_e, respectively;
- the probabilities of disturbance-distorted data frame with a packet of length r ($\xi(r)$) depends on Bit Error Rate (BER).

In a PCF slot *j*, a TCP packet is transferred successfully with a probability $1 - \xi(r_b)$ to the end station *j*, which after verifying for duplication (ratio of duplicates obviously is equal to $\xi(r_e)$) transmits the packet at IP level. As a result of this, a TCP acknowledgement arrives at the queue (under instantaneous service discipline). Hence, the probability α_b of arrival of a new TCP acknowledgement in a PCF slot is equal to $\alpha_b^0 = [1-\xi(r_b)][1-\xi(r_e)]$. Similarly, a TCPacknowledgement is assumed to have been transmitted successfully with a probability α_e and it quits the queue at the end station in the course of a PCF slot. The probability α_e in the standard PCF scheme is $\alpha_e = \alpha_e^0 = [1-\xi(r_b)]^2[1-\xi(r_e)]$. Since $\alpha_b^0 > \alpha_e^0$ and the buffer size $L >> 1$, queues at end stations may be assumed to be saturated. Consequently, the throughput is defined by the expression

$$S = r_b \alpha_e / t_{\text{slot}}^{\text{PCF}}, \quad (1)$$

where $t_{\text{slot}}^{\text{PCF}}$ is the mean length of a PCF slot. For the standard PCF scheme, $\alpha_e = \alpha_e^0$ and

$$t_{\text{slot}}^{\text{PCF}} = t_{\text{slot}}^{\text{PCF0}} = t_{\text{DATA}}^{b} + \xi(r_b)\text{PIFS} + [1-(\xi(r_b))][t_{\text{DATA}}^{b} + 2\delta]. \quad (2)$$

Fig. 4 shows the curves of a throughput under decentralized (DCF curve) and centralized (PCF curves) control for N=3 end stations. Clearly, under weak disturbances, the PCF control is doubly superior to the DCF control in throughput. Still greater throughput can be ensured under weak disturbances by integrating sequential packets (and their TCP-acknowledgements) intended for an end station into one MAC-frame. Fig. 5 shows the curves for different PCF variants obtained under packet integration optimized for a concrete BER. It is easier to integrate packets in PCF control, because the packet queue at the base station under this scheme is not unified, but subdivided into different directed subqueues (see Fig. 2).We have used the results of [5] to plot the DCF curves and the analytical method described in this section to plot PCF curves. The values of parameters of the protocol and traffic used in modeling correspond to IEEE 802.11b (Short Preamble) and conventional sizes of TCP packets and acknowledgments. They are listed in Table 1 and determined by [1, 6].

The difference in throughputs in the DCF scheme and the main PCF variant (PCF curves in Figs. 4 and 5) under strong disturbances is not large as a result of the high probability unsuccessful exchange. In this case, the "attachment" of permission for transmission and its MAC acknowledgement to data frames may be not desirable. Therefore, we consider the following alternative PCF-schemes that are consistent with IEEE 802.11 Standard [1].

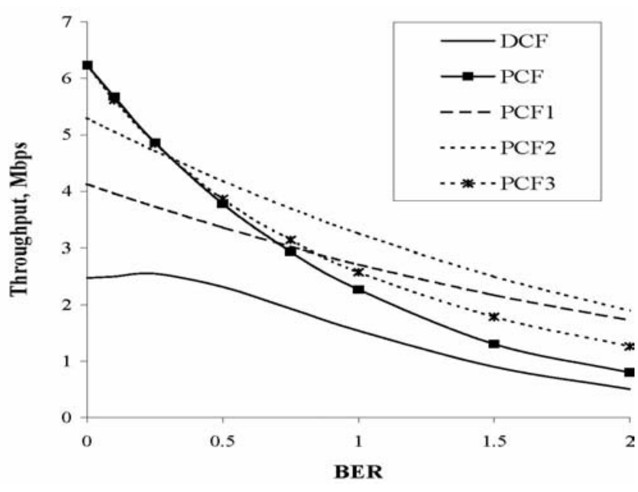

Fig. 4. Comparison of DCF and PCF for BER$\times 10^4$ and $N = 3$

Table 1. Parameter values

Parameter	Value
Channel rate, V	11 Mbps
SIFS $= \delta$	10 μs
PIFS	30 μs
MAC+PHY header, H	49 bytes
t_{ACK}	106 μs
t_0	121 μs
TCP packet size, r_b	576 bytes
t^b_{DATA}	540 μs
TCP ACK size, r_e	80 bytes
T^e_{DATA}	179 μs

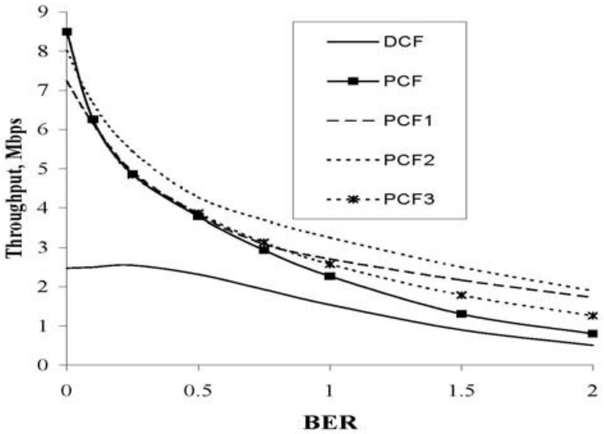

Fig. 5. Comparison of DCF and PCF with packet integration

• In the **PCF1 scheme**, permission for transmission and MAC acknowledgements are transmitted as separate frames, i.e., every PCF-slot in general contains up to five phases:

1) the base station transfers data frames to end stations;

2) an end station returns an ACK frame to every successfully received data frame;

3) the base station sends a CF-POLL frame without any data;

4) the end station replies (after δ) by a data (or NULL) frame;

5) the base station acknowledges by a CF-ACK frame.

All these phases are separated by δ. The base station awaits a reply from end stations after phases 1 and 3 for a PIFS interval.

• The **PCF2 scheme** uses a separate CF-ACK frame to confirm successful transfer of data from end stations.

• In the **PCF3 scheme**, a CF-ACK frame is used only to confirm the receipt of duplicates (from end stations).

In the PCF2 and PCF3 schemes, $\alpha_b = \alpha_b^0$ and the probability α_e is equal to

$$\alpha^2_e = [1 - \xi(r_b)][1 - \xi(r_e)](1 - \xi_0)$$

or

$$\alpha^3_e = [1 - \xi(r_b)][1 - \xi(r_e)](1 - D),$$

where ξ_0 is the probability of the CF-ACK frame distortion (and of CF-POLL and NULL frame of the same size, equal to H), and $D = \xi(r_b)/[1 - \xi_0 + \xi(r_b)]$ is the number of duplicates in the total number of TCP-acknowledgements received by the base station in the PCF3 scheme. In these schemes, queues at end stations are obviously saturated. Therefore, the throughput is defined] by (1) with $\alpha_e = \alpha_e^{\,i}$ and $t^{\mathrm{PCF}i}_{\mathrm{slot}} = t^{\mathrm{PCF}i}_{\mathrm{slot}}$ for PCF*i* schemes (i = 2, 3), where $t^{\mathrm{PCF}i}_{\mathrm{slot}}$ is computed by (2) with the addition of $[1 - \xi(r_e)](t_0 + \delta)$ for PCF2 or $[1 - \xi(r_e)]\, D(t_0 + \delta)$ for PCF3 in the last square brackets, where t_0 is the time of transmission of a CF-ACK frame (or CF-POLL and NULL frames).

In the PCF1 scheme,

$$\alpha_b = \alpha^1_b = [1 - \xi(r_b)](1 - \xi_0)$$

and

$$\alpha_e = \alpha^1_e = (1 - \xi_0)^2[1 - \xi(r_e)],$$

α^1_b is less than α^1_e if BER> 0 (because $\xi(r_b) >> \xi(r_e)$) and queues at end stations are not saturated. In one cycle, the queue of TCP acknowledgements of an arbitrary chosen end station j increases by 1 with probability $\lambda = \alpha^1_b(1 - \alpha^1_e)$ and decreases by 1 with probability $\mu = \alpha^1_e(1 - \alpha^1_b)$. Regarding the changes in the queue size ℓ as a birth-death process, we can find the probability $\rho = \lambda / \mu$ of a nonempty queue at the instant of commencement of a PCF slot related to a given end station. Thus, (1) is transformed to the form

$$S = r_b \rho_e \alpha^1_e \,/\, t^{\mathrm{PCF}i}_{\mathrm{slot}},$$

where $\rho_e = (1 - \rho)\alpha^1_b + \rho$ is the probability of a nonempty queue at the instant at the instant of poll of the end station and

$$t^{\mathrm{PCF}i}_{\mathrm{slot}} = t^b_{\mathrm{DATA}} + \xi(r_b)\mathrm{PIFS} + [1 - \xi(r_b)][t_{\mathrm{ACK}} + 2\delta] + \\ + t_0 + \xi_0\mathrm{PIFS} + \\ +(1 - \xi_0)\{\rho_e\, t^e_{\mathrm{DATA}} + (1 - \rho_e)t_0 + 2\delta + \rho_e[1 - \xi(r_e)](t_0 + \delta)]\}$$

In the absence of disturbances (BER=0), these formulas hold with $\rho_e = 1$.

The curves of the throughput S versus BER for the PCF*i* schemes plotted with the formulas of this section are also shown in Figs. 4 and 5. Clearly, the PCF2 scheme is optimal if packets are integrated (the standard PCF scheme is superior to the PCF2 scheme by less than 5% only if there are no disturbances). If packets are transferred without integration, the standard PCF scheme is optimal under weak disturbances (BER< 3×10^{-5}), but the PCF2 with a separate ACK frame is optimal under stronger disturbances. Since BER is not easy to determine, the standard PCF scheme can be switched to the PCF2 scheme when the packet duplicates received by end stations reaches a certain percentage level. According to Fig. 4 and conventional TCP packet size, this limiting ratio is 14%, i.e., on the average, 0.14 duplicate per packet at a channel rate of V = 11 Mbps.

4. Adaptive polling in the PCF

4.1. Generic adaptive polling policy

In a previous section, we have shown that the PCF is much more efficient than the DCF under high load conditions. However, with a large number of terminals and low-rate traffic, there is essential waste of bandwidth caused by unsuccessful polling attempts not replied by data transfers [7, 9]. This is the reason why the conventional PCF can be less efficient than the DCF under normal load conditions and has not been widely used up to the present.

Our paper focuses on decreasing this waste. The previous attempt to solve the problem can be found in [7], where the implicit signaling scheme was proposed, according to which a terminal indicates (setting the bit added specially to the MAC header to one) that its queue is not empty. However, this approach, firstly, leads to loss of compatibility with original 802.11 devices, and secondly, relies on the DCF with solving the problem of resuming the terminal polling.

In our paper the problem will be solved only by the PCF means. Specifically, we are going to adopt, develop, and study the polling backoff policy suggested for the Bluetooth networks in [12]. According to this adaptive policy (Fig. 6), a terminal is necessarily polled only if its backoff counter k is equal to the backoff window W_i specified for each backoff stage $i = 0, 1, \ldots, I$. At the null stage, $k = W_0 = 1$ and the terminal is polled every cycle. When the AP receives a null frame from the terminal, it understands that the terminal queue is empty and sets $i = 1$. During the next $W_i – 1$ cycles ($1 < W_i \leq W_{i+1}$ for all $0 < i < I – 1$), the AP will poll the terminal only if the appropriate APQ is not empty. (Otherwise, slots designated to the terminal will be null, that is, skipped, and the AP only increments k by 1 for a cycle.) Upon receipt of a data packet from the terminal, the AP returns it to the null stage. When $k = W_i$, the AP polls necessarily the terminal and, in case of a null reply, it increments i by 1 (if $i < I$) and sets $k = 1$. Particular forms of this backoff policy were proposed in [12] for the Bluetooth networks (with $W_i = 2i$) and in [13] for voice traffic transmission over IEEE 802.11 PCF (with the only backoff stage).

In the next Subsection 4.2, we develop Markov models describing the changes of the 802.11 PCF network queues in the case of ideal channel and the generic backoff policy. To consider both the rate and burstiness of incoming traffic, we choose a Batch Poisson fow of packets as a load for each queue, a number of packets in a batch being geometrically distributed. (That is, a batch contains h packets with probability $(1 – q)q^{h–1}$, where $q^{–1}$ is the average batch size.) In Subsection 4.3, using the models, we estimate the average MAC service time and the average MAC sojourn time for each queue, which are main performance measures in normal load conditions. Specifically, we define the average MAC service time as the mean time between either the acknowledgment receipts for consecutive packets of the queue (if the packet arrives to non-empty queue), or instances of the packet arrival and acknowledgment. Both of estimated performance measures are of great importance for transport layer protocols, such as TCP. In Section 5, we adopt the developed analytical method to compare different polling policies and to choose the optimal backoff rule.

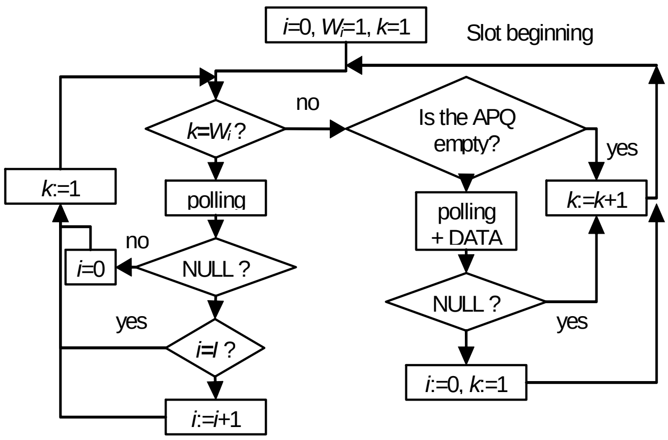

Fig. 6. Adaptive backoff-based polling strategy

4.2. Model description

We study the IEEE 802.11 PCF network consisting of the AP and N terminals. The batch arrival rate, the mean packet transmission time (including MAC and PHY headers), and the mean batch size characterizing the traffic burstiness are equal to Λ_d, T_d, and q_d^{-1}, respectively, for an APQ and to Λ_u, T_u, and q_u^{-1}, for a TQ.

Let $\ell_{dj}(t)$ and $v_j(t)=[i_j(t), k_j(t), \ell_{uj}(t)]$ be the stochastic processes representing the states of a APQ j and TQ j at time t. The APQ state is described only by the APQ length ℓ_{dj} measured in batches, while the TQ state description (with adaptive polling) includes also the backoff stage number $i_j = 0, ..., I$ and the backoff counter value $k_j = 1, ..., W_i$ (with the standard polling, the TQ state is described only by ℓ_{uj}); $\pi_d(\ell)$ and $\pi_u(i, k, \ell)$ are stationary probabilities of these states.

For both processes, we adopt a discrete time scale with a cycle as the time unit. For $\ell_{dj}(t)$, each t corresponds to the beginning of the slot intended for the j-th terminal, including the null slot case. For $v_j(t)$, each t corresponds to the end of either the terminal polling (if the slot is not null) or the previous terminal slot. We assume that all $\ell_{dj}(t)$ and $v_j(t)$ are independent. However, in fact, $v_j(t)$ depends on $\ell_{dj}(t)$, since a conditionally polled terminal can transmit only if the opposite APQ is not empty. We will try to consider the dependence by choosing appropriately the transition probabilities for $v_j(t)$. With modeling, we will adopt the following

Main Assumption. For any queue, we neglect the probability that more than one batch arrive to the queue during a cycle.

The assumption allows us the simplifying of the model form and using average transmission times instead of their distribution with calculating the transition probabilities. Moreover, with the assumption, $\ell_{dj} \le k_j$ if $i_j > 0$.

4.2.1. Access Point Queue model

Obviously, $\ell_{dj}(t)$ is a birth-and-death process, where a "birth" happens when the current batch service is not completed and a new batch arrives. That is, the "birth" probability is $\lambda^0_d = 1 - \exp\{-\Lambda_d(T_c^* + T_{sl}^d(0))\}$ (for $\ell_d = 0$), while for $\ell_d > 0$ we have

(3) $$\lambda_d = (1-q_d)[1-\exp\{-\Lambda_d(T_c^* + T_{sl}^d(\ell_d))\}],$$

where $T_{sl}^{d}(\ell_d)$ is the average j-th slot time that depends on ℓ_d, and T_c^* is the average time of other $N-1$ slots. For $\ell_d = 0$, the j-th slot is not null under condition A that the terminal is necessarily polled in the current cycle. So,

$$T_{sl}^{d}(0) = T_{sl}^{d0} = \nu_p[t_0 + 2\delta + (1-\rho_u^p)t_0 + \rho_u^p T_u],$$

where t_0 is the transmission time of CF-POLL or NULL frames, ρ_u^p is the probability of a non-empty opposite TQ under condition A, and ν_p is the condition probability, that is:

$$\nu_p = 1 - \sum_{i=1}^{I}\sum_{k=1}^{W_i-1}\sum_{\ell=0}^{k}\pi_u(i,k,\ell),$$

$$\rho_u^p = 1 - \nu_p^{-1}\sum_{i=0}^{I}\pi_u(i,W_i,0).$$

($\nu_p = 1$ and $\rho_u^p = \rho_u$ with the standard polling).

With $\ell_d > 1$, TQ j can not be in such states $\mathbf{v}_j(t)=[i_j(t) > 0,\ k_j(t),\ \ell_{uj}(t)]$ that $\ell_{uj}(t-1) > 0$, since the terminal would be polled in the previous cycle, otherwise. (Let X be the set of these states.) So,

$$T_{sl}^{d}(\ell_d > 1) = T_{sl}^{d1} = T_d + 2\delta + (1-\rho_u^1)t_0 + \rho_u^1 T_u, \tag{4}$$

where ρ_u^1 is the probability of a non-empty opposite TQ under condition $\mathbf{v}_j \notin X$. At last, for $\ell_d(t) = 1$ the j-th slot time depends on $\ell_d(t-1)$: OTj can be in any state if $\ell_d(t-1) = 0$, while $\mathbf{v}_j \notin X$ should be held with $\ell_d(t-1) > 0$. Therefore, $T_{sl}^{d}(1) = T_{sl}^{d*}$ is also determined by (4) with a substitution of ρ_d^* at will be obtained further) for ρ_u^1. Thus, $\lambda_d(1) = \lambda_d^*$ and $\lambda_d(\ell_d > 1) = \lambda_d$, where the right parts of these equations are defined, substituting T_{sl}^{d*} and T_{sl}^{d1} into (3). At last,

A "death" happens with the current batch service completion and the absence of a new batch arrival for a given cycle, so its probability is $\mu_d^* = q_d \exp\{-\Lambda_d(T_c^* + T_{sl}^{d*})\}$ with $\ell_d = 1$ or $\mu_d^* = q_d \exp\{-\Lambda_d(T_c^* + T_{sl}^{d*})\}$ with $\ell_d > 1$.

Thus, we find the stationary probabilities: $\pi_d(0) = G_d^{-1}$,

$$\pi_d(1) = G_d^{-1}\frac{\lambda_d^0}{\mu_d^*},\quad \pi_d(\ell > 1) = G_d^{-1}\frac{\lambda_d^0}{\mu_d^*}\frac{\lambda_d^*}{\mu_d}\left(\frac{\lambda_d}{\mu_d}\right)^{\ell-2}, \tag{5}$$

where the normalizing constant

$$G_d = 1 + \frac{\lambda_d^0}{\mu_d^*}\left[1 + \frac{\lambda_d^*}{\mu_d - \lambda_d}\right], \tag{6}$$

and $\rho_d = 1 - \pi_d(0)$ is the probability of a non-empty APQ.

Obviously, λ_d should be less than μ_d. Now we can find ρ_u^*. Since the probability that the APQ whose length is one was empty in the previous cycle is equal to

$$\lambda_d^0\pi_d(0)/\{\lambda_d^0\pi_d(0) + [1-\lambda_d^* - \mu_d^*]\pi_d(1) + \mu_d\pi_d(2)\} = \mu_d^*,$$
$$T_c^* = (N-1)\{\pi_d(0)T_{sl}^{d0} + \pi_d(1)T_{sl}^{d*} + [1-\pi_d(0)-\pi_d(1)]T_{sl}^{d1}\}.$$

then $\rho^*_u = \mu^*_d\rho_u + (1 - \mu^*_d)\rho^1_u$, where $\rho_u = 1 - \sum_{i=0}^{I} \sum_{k=1}^{W_i} \pi_u(i,k,0)$ is the absolute probability of non-empty opposite TQ, while ρ_u^1 will be determined with the help of TQ model analysis.

4.2.2. Terminal Queue model

With the standard polling, $l_{uj}(t)$ is also a birth-and-death process, which stationary probabilities are also defined by (5) and (6), where we substitute λ^0 for λ^0_d, λ for λ_d and λ_d^*, and μ for μ_d and μ^*_d, which are, in turn, defined by the same formulae, using Λ_u and q_u instead of Λ_d and q_d, $T_{sl}^{u1} = T_u + \delta + t^p(\rho_d)$ instead of T_{sl}^{d1} and T_{sl}^{d*}, and $T_{sl}^{u0} = t_0 + \delta + t^p(\rho_d)$ instead of T_{sl}^{d0}. (Here $t^p(\rho_d) = (1 - \rho_d)\, t_0 + \rho_d T_d + \delta$ is the average polling time.)

With an adaptive polling, the process $\boldsymbol{v}_j(t)$ can be considered as a Markov chain, which example is shown in Fig. 7. [Transitions returning the terminal to the null stage
are shown only for states (1, 2, 2) and (2, 3, 3).] Let us define the non-null one-step transition probabilities. In fact, all these transitions can be attributed to one of the following generic transitions:

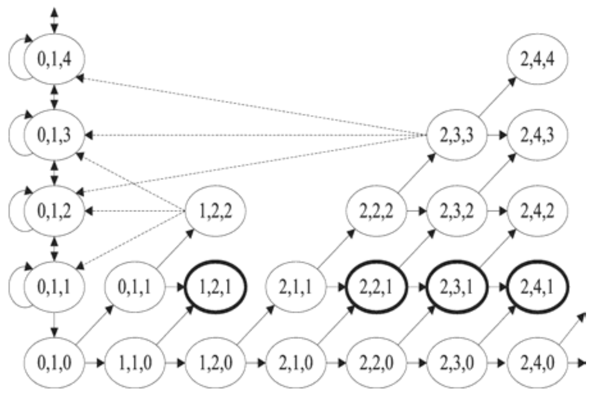

Fig. 7. Beginning of a Markov chain for a TQ with $W_1 = 2$ and $W_2 = 4$

• Backoff counter increment (for $k < W_i$) or transition to the next stage (for $k = W_i$ and $\ell = 0$) without (γ-transitions) and with (ψ-transitions) increasing the TQ length. These transition probabilities are:

$$\Gamma(\theta,\eta_1) = (1-\theta)\exp\{-\Lambda_u(T_c^* + \eta_1)\} \quad \text{and}$$

$$\Psi(\theta,\eta_1) = 1 - \theta - \Gamma(\theta,\eta_1) \quad \text{for } \ell > 0,$$

while

$$\Gamma_0(\theta,\eta_0) = \exp\{-\Lambda_u[T_c^* + \eta_0 + \theta(t_0 + \delta)]\} \quad \text{and}$$

$$\Psi_0(\theta,\eta_0) = 1 - \Gamma_0(\theta,\eta_0) \quad \text{for } \ell = 0,$$

where θ and η (with various indices) are the polling probability and the conditional average value of the next polling time, respectively. (After γ- and ψ-transitions from $(I, W_I, 0)$, the TQ appears in $(I, 1, 0)$ and $(I, 1, 1)$, respectively.)

• For states with $\ell > 0$: transitions to a null-stage state with increasing, decreasing, and without changing the TQ length (α-, φ -, and β-transitions). Their probabilities are:

$$\mathrm{A}(\theta,\eta_2)=\theta(1-q_u)[1-\exp\{-\Lambda_u(T_c^*+\eta_2+T_u+\delta)\}],$$

$$\Phi(\theta,\eta_2)=\theta q_u\exp\{-\Lambda_u(T_c^*+\eta_2+T_u+\delta)\},$$

$$\mathrm{B}(\theta,\eta_2)=\theta-\mathrm{A}(\theta,\eta_2)-\Phi(\theta,\eta_2).$$

The concrete values of θ and η are given in Table 2. By considering states (i, k >(1,1) (bold ellipses in Fig. 7), we find that the polling probability θ to be determined for such state depends on the way of reaching the state. If the TQ passed to the state from (i, k–1, 0), then $\theta = \rho_d$, since the APQ could be in any state before the transition; otherwise, $\theta = \omega = 1 - \exp\{-\Lambda_d T^*_c\}$, since the APQ was empty a cycle ago. To take into account this peculiarity and to save Markov property, we have to split each of these states into two sub-states: (i, k,1_0) and (i, k, 1_1) reached from (i, k–1, 0) and (i, k–1, 1), respectively. (The state (i, 1, 1) consists only of (i, k, 1_0).)

Table 2. Values of θ and η

i,k,ℓ	θ	η_0	η_1	η_2
$0,1,\ell>1$	1	-	-	$t^p(\rho_d)$
$i,k<W_i-1,0$	ρ_d	$t_0^p(\xi_1)$	-	-
$i,W_i-1,0$	ρ_d	$t^p(\xi_1)$	-	-
$i,W_i,0$	1	$t^p(\rho_d)$	-	-
$i,k<W_i-1,\ell>1$	ω	-	$t_0^p(\omega)$	$t^p(\xi_2)$
$i,W_i-1,\ell>1$	ω	-	$t^p(\omega)$	$t^p(\xi_2)$
$i,W_i,\ell>1$	1	-	-	$t^p(\xi_2^*)$
$i,k<W_i-1,1_0$	ρ_d	-	$t_0^p(\omega)$	$t^p(\xi_1^*)$
$i,k<W_i-1,1_1$	ω	-	$t_0^p(\omega)$	$t^p(\xi_2)$
$i,W_i-1,1_0$	ρ_d	-	$t^p(\omega)$	$t^p(\xi_1^*)$
$i,W_i-1,1_1$	ω	-	$t^p(\omega)$	$t^p(\xi_2)$
$i,W_i,1_0$	1	-	-	$t^p(\rho_d)$
$i,W_i,1_1$	1	-	-	$t^p(\xi_2^*)$

Now we can determine the probability ρ_u^1 that the opposite TQ is not empty under condition $\mathbf{v}_j \notin X$:

$$\rho_u^1=1-\sum_{i=0}^{I}\sum_{k=1}^{W_i}\pi_u(i,k,0)/$$

$$/\left\{1-\sum_{i=1}^{I}\sum_{k=2}^{W_i}\left[\pi_u(i,k,1_1)+\sum_{\ell=2}^{k}\pi_u(i,k,l)\right]\right\}.$$

In Table 2, $t^p{}_0(\omega) = \omega(T_d + \delta)$, and the probabilities ξ (with various indices) that the opposite APQ will not be empty before the next polling, are:

$$\xi_1 = \rho_d \left[1 - \frac{q_d \pi_d(1)}{\rho_d} \exp\{-\Lambda_d (T_c^* + T_d + 2\delta + t_0)\} \right] + (1-\rho_d)\omega,$$

$$\xi_1^* = 1 - \frac{q_d \pi_d(1)}{\rho_d} \exp\{-\Lambda_d (T_c^* + T_d + 2\delta + T_u)\},$$

$$\xi_2 = 1 - q_d \exp\{-\Lambda_d (T_c^* + T_d + T_u + 2\delta)\},$$

$$\xi_2^* = 1 - \exp\{-\Lambda_d (2T_c^* + t_0 + T_u + 2\delta)\} - \omega(1-\xi_2).$$

Now we can determine the stationary probabilities $\pi_u(i, k, \ell)$. These probabilities are found in turn, using global balance equations written, firstly, for states of non-null stages and then for $(0, 1, \ell)$ with $\ell = 0, ..., W_I$. Since the paper size is limited, we have to omit the final equations for $\pi_u(i, k, \ell)$ and only mention that, for states $(0, 1, \ell > W_I + 1)$,

$$\pi_u(0,1,\ell) = \pi_u(0,1,W_I+1)(\lambda/\mu)^{\ell - W_I - 1}$$

and the sum of the stationary probabilities is

$$S_\infty = \sum_{\ell = W_I + 1}^{\infty} \pi_u(0,1,\ell) = \pi_u(0,1,W_I+1) / \left(1 - \frac{\lambda}{\mu}\right).$$

Obviously, λ should be less than μ.

In fact, the calculation of the stationary probabilities is an iterative process: using some initial values of T_{sl}^{d0} , T_{sl}^{d*} , and T_{sl}^{d1} , we calculate the transition and stationary probabilities, firstly, for the APQ model, and secondly, for the TQ model. At last, we find modified values of $T_{sl}^{d}(\ell)$ and use half sums of the modified and initial values as new initial ones. We stop the calculations when the absolute differences of consecutive values $T_{sl}^{d}(\ell)$ become less than a pre-defined small threshold.

4.3. Estimation of performance measures

In the section, we estimate firstly the average MAC service time. Let us start with packets Transmitted after Queueing (TaQ packets). This is the case when either the packet is not the first in the batch, or the batch that the packet belongs to arrives to a non-empty queue. Another packet category consists of packets Transmitted without Queueing (TwQ packets). Obviously, the average TaQ packet MAC service time is equal to $D^d_{TaQ} = T^*_c + T_{sl}^{d1}$ for an APQ and $D^u_{TaQ} = T^*_c + T_{sl}^{u1}$ for a TQ.

Now let us consider TwQ packets. For an APQ, using the Main Assumption, we find that the average TwQ packet MAC service time is $D^d_{\mathrm{TwQ}} = (T^*_c + \mathrm{T}d_0\, s_1)/(2 + T_{sl}^{d1})$. The average numbers of all packets and TwQ packets arriving to a given APQ for a cycle are equal to $n^d = \Lambda_d T_c$ and $n^d_2 = \Lambda_d q_d (1 - \rho_d)(T^*_c + T_{sl}^{d0})$, where

$$T_c = T_c^* + (1-\rho_d)\left[T_{sl}^{d0} + \frac{\lambda_d^0}{\mu_d^*} T_{sl}^{d*} \right] + \left[\rho_d - \frac{(1-\rho_d)\lambda_d^0}{\mu_d^*} \right] T_{sl}^{d1}$$

is the average cycle duration. Therefore, a packet is a TwQ one with a probability

(7) $$\kappa_{TwQ}^{d} = n_{Twq}^{d}/n^{d} = q_d(1-\rho_d)(T_c^{*} + T_{sl}^{d0})/T_c,$$

and the sought average MAC service time for an APQ is

(8) $$M_d = (1-\kappa_{TwQ}^{d})D_{TaQ}^{d} + \kappa_{TwQ}^{d}D_{TwQ}^{d}.$$

For a TQ, the averageMAC service time is defined by the similar formula: $M_u = (1 - \kappa^u_{\mathrm{TwQ}})D^u_{\mathrm{TaQ}} + \kappa^u_{\mathrm{TwQ}}D^u_{\mathrm{TwQ}}$, where we need to find the TwQ probability κ^u_{TwQ} and the average TwQ packet MAC service time D^u_{TwQ}. We can write them in the form:

$$\kappa_{TwQ}^{u} = \frac{q_u \kappa_0^u}{T_c}, \quad D_{TwQ}^{u} = \frac{1}{\kappa_0^u}\sum_{i=0}^{I}\sum_{k=1}^{W_i} s_{ik0} D_{ik} \pi_u(i,k,0),$$

where

$$\kappa_0^u = \sum_{i=0}^{I}\sum_{k=1}^{W_i} s_{ik0}\pi_u(i,k,0).$$

Here s_{ikl} and D_{ik} are the average duration of cycle (i, k, ℓ), at the beginning of which the TQ is in state (i, k, ℓ), and the average service time for a TwQ packet arriving for the cycle $(i, k, 0)$, respectively. Let us find s_{ikl} and D_{ik}:

$$s_{ik\ell} = T_c^{*} + 1(\ell > 0)[\theta_{ik\ell}(T_u + \delta + \eta_2^{ik\ell}) + (1-\theta_{ik\ell})\eta_1^{ik\ell}] +$$

$$+ 1(\ell = 0)[\theta_{ik\ell}(t_0 + \delta) + \eta_0^{ik\ell}],$$

where θ_{ikl}, η^{ikl}_0, η^{ikl}_1 and η^{ikl}_2 are defined accordingly to Table 2; 1(condition) is the Boolean operator equal to one if the condition holds; and

$$D_{ik} = \frac{s_{ik0}}{2} + T_u + \delta + t_{ACK} + (1-\rho_d)\Delta_{ik},$$

where $\Delta_{ik} = F_D(W_i - k)$ with $k < W_i$, $\Delta_{i,W_i} = F_D(W_{i+1})$ with $i < I$; and $\Delta_{i,W_i} = F_D(W_I)$,

$$F_D(W) = 1(W > 2)\omega\sum_{j=0}^{W-3}[(j+1)T_c^{*} + T_d + \delta](1-\omega)^{j} +$$

$$+ 1(W > 1)(1-\omega)^{W-2}[(W-1)T_c^{*} + t^{p}(\xi_1)],$$

t_{ACK} is the average time of acknowledgment receipt that happens (in most cases) during polling the next terminal whose slot is not null. So,

$$t_{ACK} = [\rho_d T_d + (1-\rho_d)\nu_p t_0]/[\rho_d + (1-\rho_d)\nu_p].$$

Now let us estimate the average packet sojourn time for both APQ and TQ (T_d^{MAC} and T_u^{MAC}). Obviously, these measures can be found via the Little's formula: $T_d^{\mathrm{MAC}} = q_d L_d/\Lambda_d$, and $T_u^{\mathrm{MAC}} = q_u L_u/\Lambda_u$,so the main problem is to estimate the average lengths measured in packets of and APQ(L_d) and a TQ(L_u). For an APQ, we have $L_d = S^d_L/T_c$, where

$$S_L^d = \sum_{\ell} \overline{\ell}_d(\ell) t_c^d(\ell) \pi_d(\ell),$$

$$\overline{l}_d(l) = \frac{l}{q_d} + \frac{\Lambda_d}{2q_d}[T_c^* + T_{sl}^d(l)] - 1(l>0)\left[1 - \frac{T_{sl}^d(l) - \delta}{T_c^* + T_{sl}^d(l)}\right],$$

and $t^d_c(\ell) = T^*_c + T^d_{sl}(\ell)$. Therefore,

$$S_L^d = \pi_d(0) \frac{\Lambda_d}{2q_d}(T_c^* + T_{sl}^{d0})^2 +$$

$$+\pi_d(1)\left\{\frac{T_c^* + T_{sl}^{d*}}{q_d}\left[1 - q_d + \frac{\Lambda_d}{2}(T_c^* + T_{sl}^{d*})\right] + T_{sl}^{d*} - \delta\right\} +$$

$$+\frac{\pi_d(2) D_{TwQ}^d}{q_d(1 - \lambda_d/\mu_d)}\left(l_d^1 + 1 + \frac{1}{1 - \lambda_d/\mu_d}\right),$$

where $l_d^1 = \frac{\Lambda_u}{2} D_{TwQ}^d - q_d\left[1 - \frac{T_{sl}^{d1} - \delta}{D_{TwQ}^d}\right]$. For a TQ, we use the similar equation: $L_u = S^u{}_L / T_c$, where

$$S_L^u = \sum_{(i,k,\ell)} \overline{\ell}_u(i,k,\ell) s_{ik\ell} \pi_u(i,k,\ell),$$

$$\overline{l}_u(i,k,l) = \frac{l}{q_u} + \frac{\Lambda_u}{2q_u} s_{ikl}$$

$$-1(l>0)\theta_{ikl}\left[1 - \frac{T_u + \delta + t_{ACK}}{T_c^* + T_u + \delta + \eta_2^{ikl}}\right].$$

At last, we obtain after simple transformations:

$$L_u = (q_u^{-1} D_{TwQ}^u \kappa_1^* + \kappa_0^*)/T_c,$$

where

$$\kappa_1^* = \sum_{\ell=1}^{W_I}(\ell + \ell_u^1)\pi_u(0,1,\ell) + (\ell_u^1 + W_I)S_\infty +$$

$$+\pi_u(0,1,W_I+1)/\left(1 - \frac{\lambda}{\mu}\right)^2,$$

$$\ell_u^1 = \frac{\Lambda_u}{2} D_{TwQ}^u - q_u\left(1 - \frac{T_u + \delta + t_{ACK}}{D_{TwQ}^u}\right),$$

$$\kappa_0^* = s_{010} \frac{\Lambda_u}{2q_u} \pi_u(0,1,0) +$$

$$+ \sum_{(i,k,l):i>0} \bar{l}_u(i,k,l) s_{ikl} \pi_u(i,k,l).$$

5. Numerical results

Let us adopt the developed analytical method to evaluate the PCF performance, depending on parameters of traffic and network configuration, and to compare the Standard Polling (SP), the Binary Scheme (BS) with $I = 8$ and $W_i = 2^i$, and the Optimal Polling (OP). The OP form is determined, using the analytical method to find the optimalset (I, W_i) providing the minimal value M_u or $T^{MAC}{}_u$ for each point of space (N, Λ_d, Λ_u, q_d, q_u, T_d, T_u). Thus, the OP scheme requires following the change of uplink and downlink traffic parameters and correcting on-line the set (I, W_i).

The main fraction of traffic transmitted through a wireless network is related to TCP/IP protocol stack operation, when arrival rates of uplink and downlink packets are approximately the same, since each TCP packet (which mean length is assumed to be 576 bytes that corresponds to multihop connections) is followed by a TCP acknowledgement (we assume its length to be equal to 80 bytes). Therefore, we consider the case $\Lambda_d = \Lambda_u = \Lambda$ and $q_d = q_u = q$ in the numerical research. Moreover, we use the following probability distribution of packet length m: m = 576 and m = 80 bytes with probabilities 0.7 and 0.3 for the AP and with probabilities 0.3 and 0.7 for a terminal, what approximately corresponds to the case, when a third of TCP connections carries out downlink traffic. Thus, basing on this discussion and IEEE 802.11b (Long Preamble) specifications [6], we adopt the following parameter values with our numerical research: 11-Mbps channel rate, δ = 10 μs, t_0 = 217 μs, T_d = 528 μs, and T_u = 383 μs.

In Fig. 8, we show how the average service time M_u depends on the load, that is, on Λ, for different N and polling policies. The OP form has been determined for $I = 1$ with varying W_1 from 2 to $W_{max} = 256$, and the found optimal values $W_1 = W^{opt}{}_1$ versus Λ are shown in Fig. 9 by solid curves. Here and further in the numerical research, we deal only with one-stage optimal policies, since it appears that increasing the number I of backoff stages does not allow improving the network performance.

Let us look at the curves in Fig. 8. We see that both dynamic polling schemes are much better than the SP with non-saturated queues: the mean service time for the BS and OP is more than ten times less than the one for the SP with low load. Comparing to the BS, the OP decreases M_u in two-three times with moderate load. However, with a low load, it is not essential which of dynamic polling schemes is adopted, since each terminal spends most of time at the stage with window W_{max}.

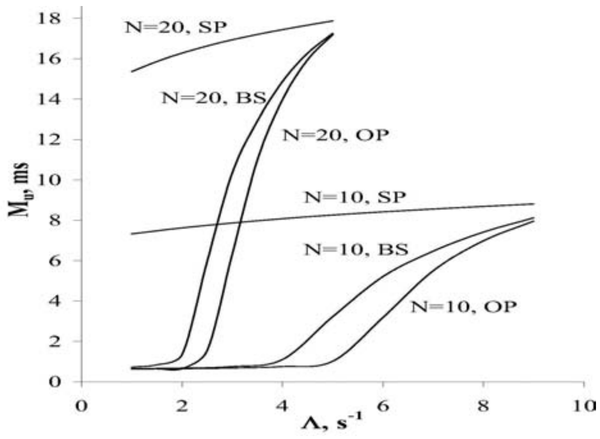

Fig. 8. Mean service time versus traffic rate with $q = 0.1$

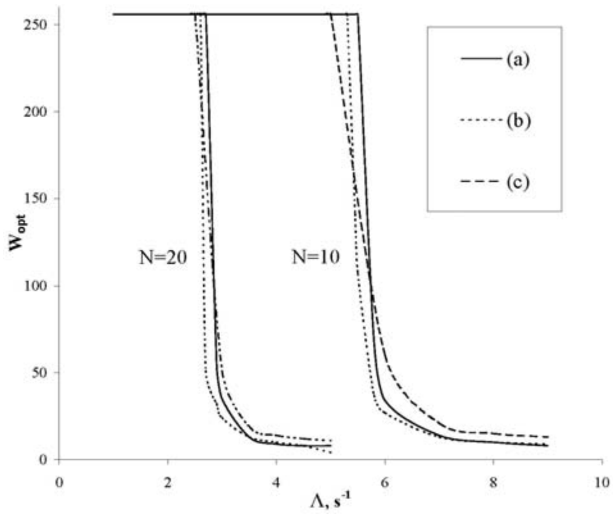

Fig. 9. Backoff window optimal for: a – M_u; b – T^{MAC}_u and c – $T^{MAC}_u + T^{MAC}_d$ versus traffic rate with $q = 0.1$

In Fig. 10 we show how the traffic burstiness characterized by q affects the mean service time. Here each curve has been obtained with constant value Λ/q equal to incoming packet rate for each queue. As Fig. 8, Fig. 10 shows that a dynamic polling is always better than the standard one, while the OP improves essentially the M_u value, comparing with the BS, for moderate values of q and Λ/q. With large Λ/q, the difference between the BS and OP performance is much less (within 10 %). Moreover, it appears (see also Fig. 8) that, in contrary to a dynamic policy, with the SP the mean service time only slightly depends on both Λ and q, and their ratio.

Fig. 11 shows the mean sojourn time T^{MAC}_u being another performance measure versus load. Here OP curves have been obtained with minimizing T^{MAC}_u , but not M_u, and the corresponding optimal windows W^{opt}_1 are shown in Fig. 9 by dotted curves. As one can expected, the relation between T^{MAC}_u values for three polling schemes under consideration is nearly the same as the relation of the corresponding M_u.

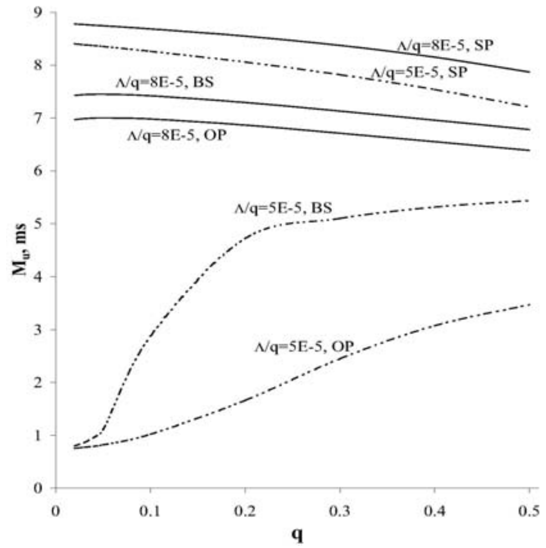

Fig. 10. Mean service time versus traffic businesss with $N = 10$

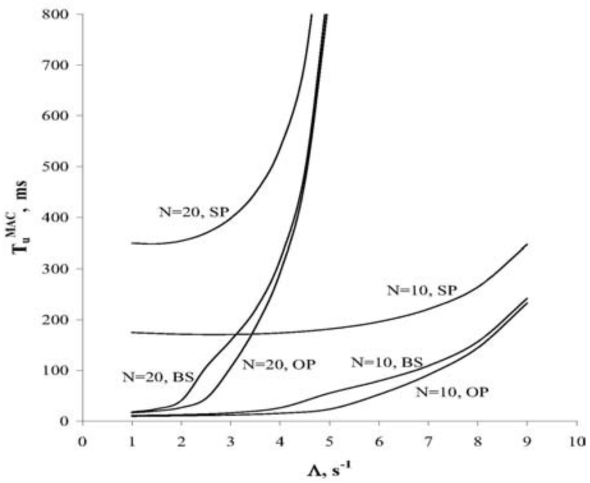

Fig. 11. Mean sojourn time versus traffic rate with $q = 0.1$

The sum $T^{MAC}_u + T^{MAC}_d$ is a very important performance index for networks with TCP traffic, because just this sum is equal to the average sojourn time of TCP segment represented firstly by a TCP packet and then by its TCP acknowledgment in the wireless network MAC queues. This time can be a determining component of such important TCP protocol parameter as Round Trip Time. Considering similar behavior of dependencies $T^{MAC}_u(\Lambda)$ and $T^{MAC}_d(\Lambda)$ (see Figs. 8 and 10), it is easy to predict the form of curves $T^{MAC}_u + T^{MAC}_d$ vs. Λ given in Fig. 11 for $N = 10$ and $N = 20$. To obtain the OP curve in the figure, we have used the optimizing W_{opt} curve shown by the dashed line in Fig. 9.

As a concluding result, we would like to point out that the optimization criterion choice is not essential. Specifically, it appears that the relative difference in M_u values obtained for the OP with W^{opt}_1 minimizing M_u and T^{MAC}_u does not exceed 5%.

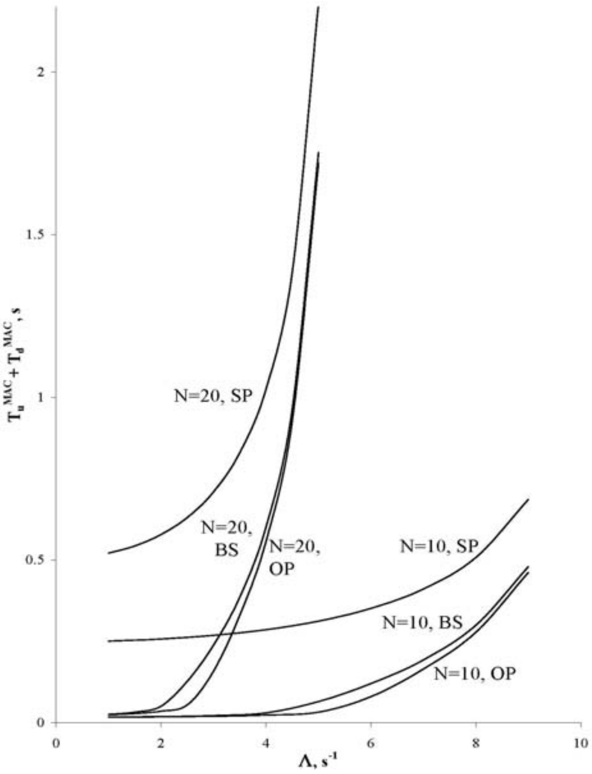

Fig. 12. Sum of sojourn times versus traffic rate with $q = 0.1$

6. Conclusion

In the paper, we have proposed and studied analytically various IEEE 802.11 implementations, which are to be efficent in different environments and under different load.

Firstly, we have studied the PCF operation under high downlink load. It has appeared that an optimally chosen PCF scheme is two-fold more efficient (and four-fold if packets are integrated or disturbances are strong) in throughput than the usual DCF scheme. Unfortunately, radio devices for realizing the PCF mechanism are not produced, at least, on mass scale, because the superseded IEEE 802.11 protocol was mostly used for designing local area networks containing no hidden stations and the DCF is far superior in throughput. Therefore, a project has been undertaken at the Institute of Information Transmission Problems on the design of a radio appliance for realizing an optimized PCF scheme on the basis of our results.

Further investigation of this scheme in the paper have been concerned with the development of new polling strategies to reduce waiting time under normal traffic rates and typical bursty TCP connection traffic.

To improve IEEE 802.11 PCF performance under normal load, we have proposed and studied a generic adaptive policy for polling terminals, depending on observed traffic parameters. The proposed policy is based on concepts of polling backoff and polling stage and allows minimizing the performance wastes related to unsuccessful

polling attempts. Describing the network queues changes by discrete-time Markov chains, we have developed an analytical method to estimate the average service time and the average sojourn time for each network queue. Accordingly to extensive numerical results, the developed method is very efficient in comparing different polling schemes as well as for choosing and optimizing the dynamic polling policy form, depending on the parameters of traffic and network configuration. We believe that the proposed adaptive polling policy and its modelling method should be useful also for
other centrally-controlled wireless protocols, such as IEEE 802.15 and 802.16.

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