IEEE 802.11 PCF Improvement under Normal Load

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Abstract - Point Coordination Function (PCF) of the IEEE 802.11 protocol providing a centrally-controlled polling-based multiple access to a wireless channel is very efficient in high load conditions. However, its performance degrades with increasing the number of terminals and decreasing the load, because of wastes related to unsuccessful polling attempts. To solve the problem, we propose and study analytically the generic adaptive polling policy using backoff concept. For this aim, we develop Markov models describing the network queues changes, what allows us to estimate such performance measures as the average MAC service time and the average MAC sojourn time, to show the efficiency of the adaptive polling policy and to tune optimally the backoff rule.

Keywords—**IEEE 802.11 PCF, adaptive polling policy, Markov models, MAC service time, MAC sojourn time**

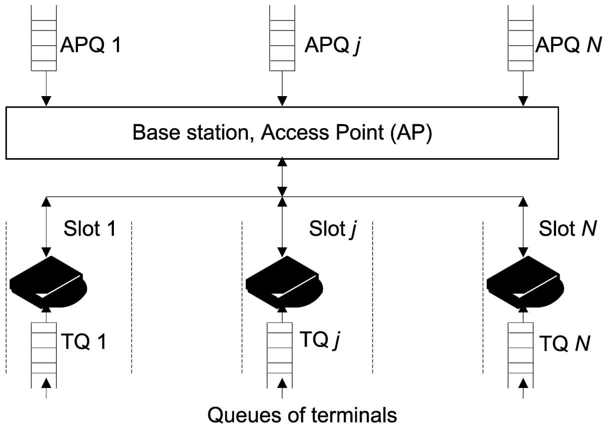

Fig. 1. PCF operation scheme

I. Introduction

IEEE 802.11 [1] being one of the most popular protocol for wireless and mobile networking offers two different MAC mechanisms. The basic mechanism called the Distributed Coordination Function (DCF) is based on the CSMA/CA scheme and allows for 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. 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 backoff 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 [2-5]. Usually, the AP polls terminals 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. 1). 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. If the AP 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 the 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. Having received the frame, the AP waits for δ and starts polling the next terminal. (This standard polling policy has been studied in [6].)

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 [2, 4]. 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 [2], 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, we will solve the problem only by the PCF means. Specifically, we are going to adopt, develop, and study the polling backoff policy suggested for the Bluetooth networks in [7]. According to this adaptive policy (Fig. 2), 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's queue is empty and sets i=1. During the next W_i-1 cycles ($1 < W_i \le W_{i+1}$ 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 $k = 1$. The particular form of this backoff policy (with $W_i = 2^i$) was proposed in [7] for the Bluetooth networks.

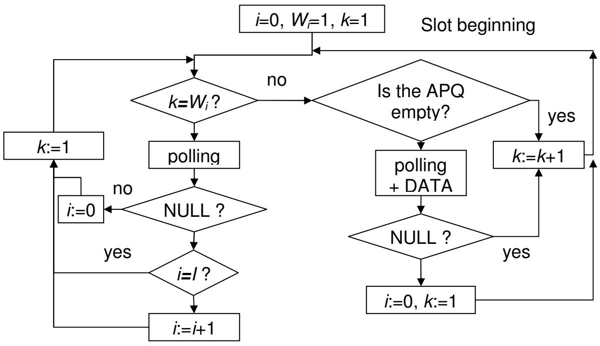

Fig. 2. Adaptive backoff-based polling strategy

In the next section II, 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 flow 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 section III, 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 IV, we adopt the developed analytical method to compare different polling policies and to choose the optimal backoff rule. In the last section, we give a brief conclusion.

II. 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 $\boldsymbol{\nu}_j(t)$=$[i_j(t), k_j(t), \ell_{uj}(t)]$ 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 $i_j = 0 \ldots I$ and the backoff counter value $k_j = 1 \ldots W_i$. (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 $\boldsymbol{\nu}_j(t)$, each t corresponds to the end of either the terminal polling (if the slot is not null) or the previous terminal's slot. We assume that all $\ell_{dj}(t)$ and $\boldsymbol{\nu}_j(t)$ are independent. However, in fact, $\boldsymbol{\nu}_j(t)$ 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 $\boldsymbol{\nu}_j(t)$. 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 simplifying the model form and using average transmission times instead of their distribution with calculating the transition probabilities. Moreover, with the assumption, $\ell_{uj} \le k_j$ if $i_j > 0$.

A. *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 new batch arrives. That is, the "birth" probability is $\lambda_d^0 = 1-\exp\{-\Lambda_d(T_c^* + T_{sl}^d(0))\}$ (for $\ell_d = 0$), while for $\ell_d > 0$ we have

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

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 $\mathcal{A}$ 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 non-empty opposite TQ under condition $\mathcal{A}$, 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 $\boldsymbol{\nu}_j(t)$=$[i_j(t) > 0, k_j(t), \ell_{uj}(t)]$ that $\ell_{uj}(t-1) > 0$, since the terminal would be polled in the previous cycle, otherwise. (Let $\mathcal{X}$ be the set of these states.) So

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

where ρ_u^1 the probability of non-empty opposite TQ under condition $\boldsymbol{\nu}_j \notin \mathcal{X}$. At last, for $\ell_d(t) = 1$ the j^{th} slot time depends on $\ell_d(t-1)$: OT j can be in any state if $\ell_d(t-1) = 0$, while $\boldsymbol{\nu}_j \notin \mathcal{X}$ should be hold with $\ell_d(t-1) > 0$. Therefore, $T_{sl}^d(1) = T_{sl}^{d*}$ is also determined by (2) with substitution of ρ_u^* (that will be obtained further) for ρ_u^1. Thus, $\lambda_d(1) = \lambda_d^*$ and $\lambda_d(\ell_d > 1) = \lambda_d$, where right parts of these equations are defined, substituting T_{sl}^{d*} and T_{sl}^{d1} into (1). At last,

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

A "death" happens with the current batch service completion and the absence of 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 $\mu_d = q_d \exp\{-\Lambda_d(T_c^* + T_{sl}^{d1})\}$ with $\ell_d > 1$. Thus, we find the stationary probabilities: $\pi_d(0) = G_d^{-1}$,

$$\pi_d(1) = G_d^{-1}\frac{\lambda_d^0}{\mu_d^*}, \quad \pi_d(\ell > 1) = G_d^{-1}\frac{\lambda_d^0}{\mu_d^*}\frac{\lambda_d^*}{\mu_d}\left(\frac{\lambda_d}{\mu_d}\right)^{\ell-2}, \quad (3)$$

where the normalizing constant

$$G_d = 1 + \frac{\lambda_d^0}{\mu_d^*}\left[1 + \frac{\lambda_d^*}{\mu_d - \lambda_d}\right] \quad (4)$$

and $\rho_d = 1 - \pi_d(0)$ is the probability of 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

$$\lambda_d^0\pi_d(0)/\{\lambda_d^0\pi_d(0) + [1-\lambda_d^*-\mu_d^*]\pi_d(1) + \mu_d\pi_d(2)\} = \mu_d^*,$$

then $\rho_u^* = \mu_d^*\rho_u + (1-\mu_d^*)\rho_u^1$, 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 TQ model analysis.

B. Terminal Queue model

With the standard polling, $\ell_{uj}(t)$ is also a birth-and-death process, which stationary probabilities are also defined by (3) and (4), where we substitute λ^0 for λ_d^0, 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.]

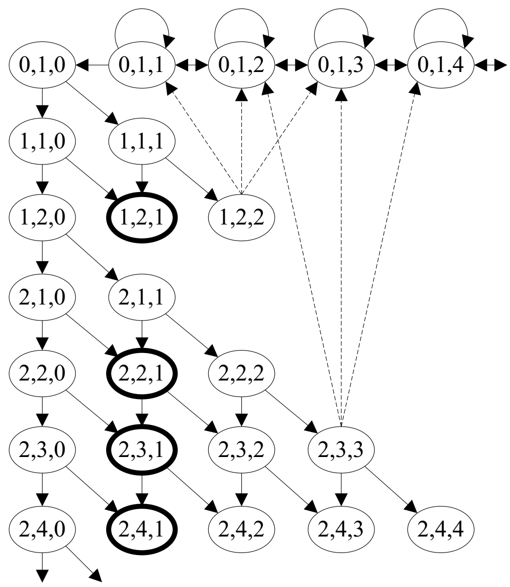

Fig. 3. Beginning of Markov chain for a TQ with $W_1 = 2$ and $W_2 = 4$

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

- 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:

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

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

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

Concrete values of θ and η are given in Tab. 1. With considering states (i,k >1,1) (bold ellipses in Fig. 3), 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 of 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).]
Now we can determine the probability ρ_u^1 that the opposite TQ is not empty under condition $\boldsymbol{v}_j \notin \mathcal{X}$:

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

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

TABLE I
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	-	-	$t^p(\xi_2^*)$

In Tab. 1, $t_0^p(\omega) = \omega(T_d + \delta)$, and 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 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 $\ell = 0, \dots, W_I$. Since the paper size is limited, we have to omit 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, calculation of stationary probabilities is an iterative process: using some initial values of T_{sl}^{d0}, T_{sl}^{d*}, and T_{sl}^{d1}, we calculate 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 calculations when absolute differences of consecutive values $T_{sl}^{d}(\ell)$ become less than a pre-defined small threshold.

III. 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 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 $D_{TaQ}^d = T_c^* + T_{sl}^{d1}$ for an APQ and

$D_{TaQ}^u = T_c^* + T_{sl}^{u1}$ 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 $D_{TwQ}^d = (T_c^* + T_{sl}^{d0})/2 + T_{sl}^{d1}$. 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 $n_2^d = \Lambda_d q_d (1 - \rho_d)(T_c^* + T_{sl}^{d0})$, 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 probability

$$\kappa^d_{TwQ} = n^d_{Twq}/n^d = q_d(1-\rho_d)(T^*_c + T^{d0}_{sl})/T_c, \quad (5)$$

and the sought average MAC service time for an APQ is

$$M_d = (1-\kappa^d_{TwQ})D^d_{TaQ} + \kappa^d_{TwQ}D^d_{TwQ}. \quad (6)$$

For a TQ, the average MAC service time is defined by the similar formula: $M_u = (1-\kappa^u_{TwQ})D^u_{TaQ} + \kappa^u_{TwQ}D^u_{TwQ}$, 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:

$$\kappa^u_{TwQ} = \frac{q_u\kappa^u_0}{T_c}, \quad D^u_{TwQ} = \frac{1}{\kappa^u_0}\sum_{i=0}^{I}\sum_{k=1}^{W_i} s_{ik0}D_{ik}\pi_u(i,k,0),$$

where

$$\kappa^u_0 = \sum_{i=0}^{I}\sum_{k=1}^{W_i} s_{ik0}\pi_u(i,k,0).$$

Here $s_{ik\ell}$ 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}:

$$s_{ik\ell} = T^*_c + 1(\ell>0)[\theta_{ik\ell}(T_u+\delta+\eta^{ik\ell}_2) + (1-\theta_{ik\ell})\eta^{ik\ell}_1]$$

$$+1(\ell=0)[\theta_{ik\ell}(t_0+\delta)+\eta^{ik\ell}_0],$$

where $\theta_{ik\ell}$, $\eta^{ik\ell}_0$, $\eta^{ik\ell}_1$, and $\eta^{ik\ell}_2$ are defined accordingly to Tab. 1; $1(\text{condition})$ 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^{MAC}_d and T^{MAC}_u). Obviously, these measures can be found via the Little's formula: $T^{MAC}_d = q_d L_d/\Lambda_d$ and $T^{MAC}_u = q_u L_u/\Lambda_u$, so the main problem is to estimate the average lengths measured in packets of an APQ (L_d) and a TQ (L_u). For an APQ, we have $L_d = S^d_L/T_c$, where

$$S^d_L = \sum_{\ell} \bar{\ell}_d(\ell)t^d_c(\ell)\pi_d(\ell),$$

$$\bar{l}_d(l) = \frac{l}{q_d} + \frac{\Lambda_d}{2q_d}[T^*_c + T^d_{sl}(l)] - 1(l>0)\left[1 - \frac{T^d_{sl}(l)-\delta}{T^*_c + T^d_{sl}(l)}\right],$$

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

$$S^d_L = \pi_d(0)\frac{\Lambda_d}{2q_d}(T^*_c + T^{d0}_{sl})^2 +$$

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

$$+\frac{\pi_d(2)D^d_{TwQ}}{q_d(1-\lambda_d/\mu_d)}\left(l^1_d + 1 + \frac{1}{1-\lambda_d/\mu_d}\right),$$

where $l^1_d = \frac{\Lambda_u}{2}D^d_{TwQ} - q_d\left[1 - \frac{T^{d1}_{sl}-\delta}{D^d_{TwQ}}\right]$. For a TQ, we use the similar equation: $L_u = S^u_L/T_c$, where

$$S^u_L = \sum_{(i,k,\ell)} \bar{\ell}_u(i,k,\ell)s_{ik\ell}\pi_u(i,k,\ell),$$

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

$$-1(l>0)\theta_{ikl}\left[1 - \frac{T_u + \delta + t_{ACK}}{T^*_c + T_u + \delta + \eta^{ikl}_2}\right].$$

At last, we obtain after simple transformations:

$$L_u = (q_u^{-1}D^u_{TwQ}\kappa^*_1 + \kappa^*_0)/T_c,$$

where

$$\kappa^*_1 = \sum_{\ell=1}^{W_I}(\ell + \ell^1_u)\pi_u(0,1,\ell) + (\ell^1_u + W_I)S_\infty +$$

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

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

$$\kappa_0^*=s_{010}\frac{\Lambda_u}{2q_u}\pi_u(0,1,0)+\sum_{(i,k,l):i>0}\bar{l}_u(i,k,l)s_{ikl}\pi_u(i,k,l).$$

IV. 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 optimal set (I,W_i) providing the minimal value M_u or T_u^{MAC} for each point of space $(N,\Lambda_d,\Lambda_u,q_d,q_u,T_d,T_u)$. 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 specifications, we adopt the following parameter values with our numerical research: 11-Mbps channel rate, $\delta=10$ μs, $t_0=217$ μs, $T_d=528$ μs, and $T_u=383$ μs.

In Fig. 4, 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 $W_1=W_1^{opt}$ versus Λ are shown in Fig. 5 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 curves in Fig. 4. 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 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 $W_{\max}$.

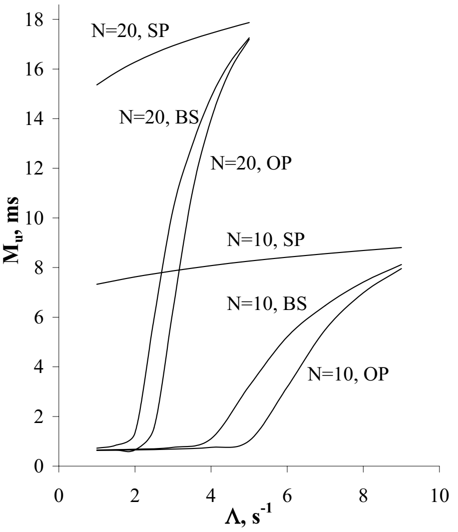

Fig. 4. Mean service time versus traffic rate with $q=0.1$

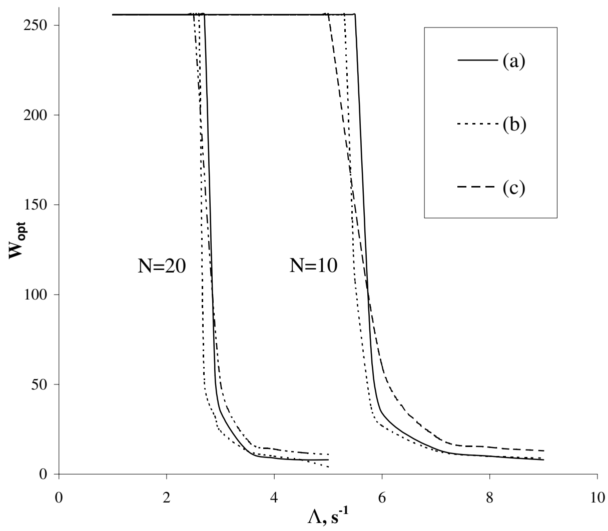

Fig. 5. Backoff window optimal for (a) M_u, (b) T_u^{MAC}, and (c) $T_u^{MAC}+T_d^{MAC}$ versus traffic rate with $q=0.1$

In Fig. 6 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. 4, Fig. 6 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. 4) 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.

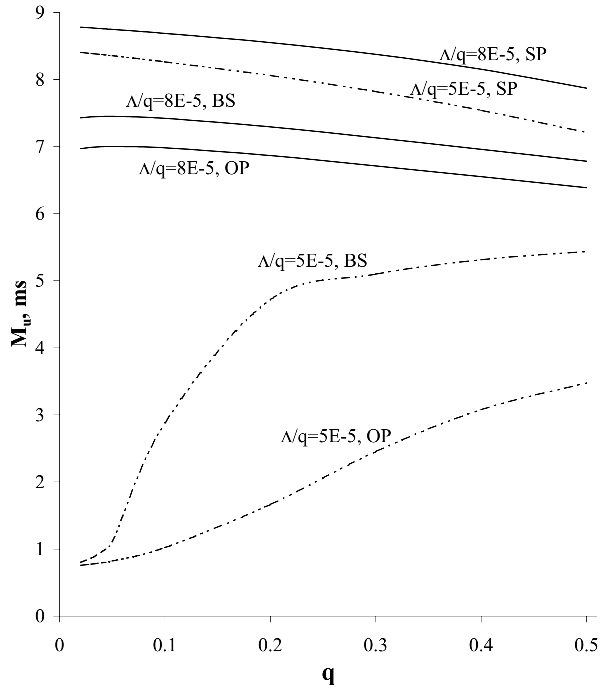

Fig. 6. Mean service time versus traffic burstiness with $N = 10$

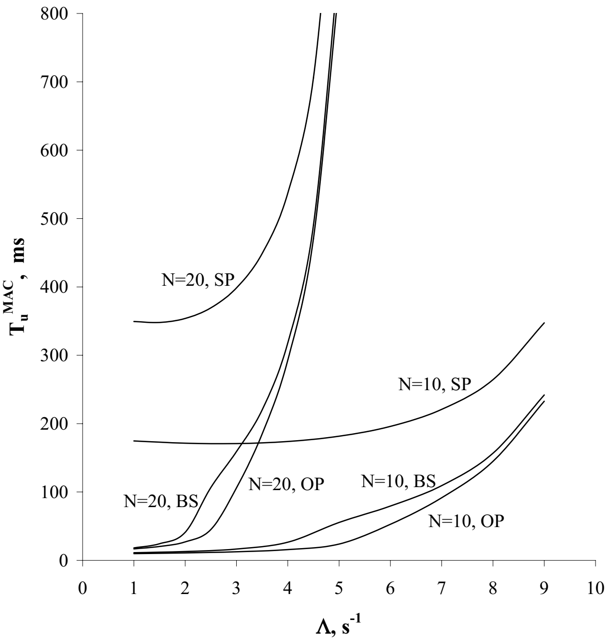

Fig. 7. Mean sojourn time versus traffic rate with $q = 0.1$

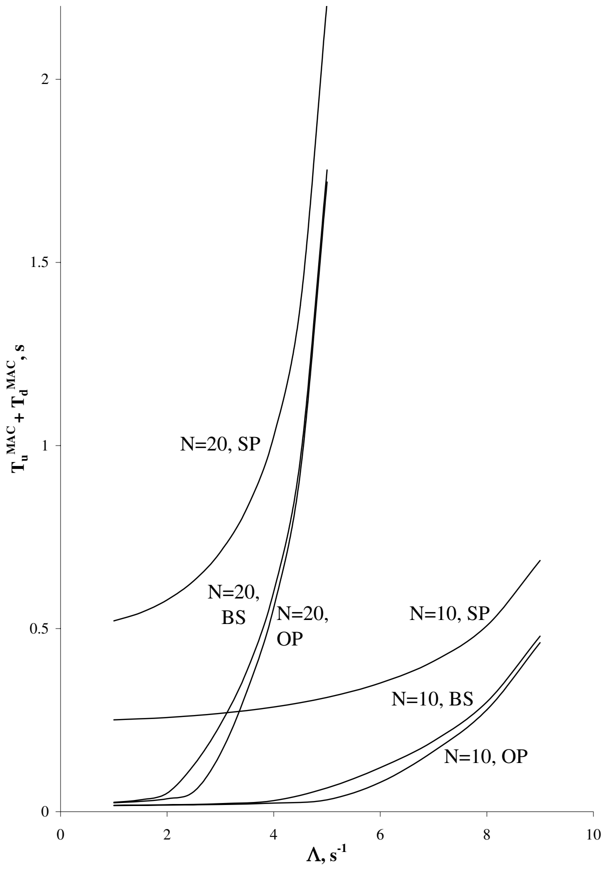

Fig. 8. Sum of sojourn times versus traffic rate with $q = 0.1$

Fig. 7 shows the mean sojourn time T_u^{MAC} being another performance measure versus load. Here OP curves have been obtained with minimizing T_u^{MAC}, but not M_u, and the corresponding optimal windows W_1^{opt} are shown in Fig. 5 by dotted curves. As one can expected, the relation between T_u^{MAC} values for three polling schemes under consideration is nearly the same as the relation of the corresponding M_u.

Sum $T_u^{MAC} + T_d^{MAC}$ is 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 $T_u^{MAC}(\Lambda)$ and $T_d^{MAC}(\Lambda)$ (see Figs. 4 and 6), it is easy to predict the form of curves $T_u^{MAC} + T_d^{MAC}$ vs. Λ given at Fig. 7 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. 5.

As a concluded 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_1^{opt} minimizing M_u and T_u^{MAC} does not exceed 5%.

V. Conclusion

To improve IEEE 802.11 PCF performance under normal load, we propose and study 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 with comparing different polling schemes as well as for choosing and optimizing the dynamic polling policy form, depending on 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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