Performance Analysis of UDP With Energy Efficient Link Layer on Markov Fading Channels

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***Abstract*—In this paper, we analyze the throughput and energy efficiency performance of user datagram protocol (UDP) using linear, binary exponential, and geometric backoff algorithms at the link layer (LL) on point-to-point wireless fading links. Using a first-order Markov chain representation of the packet success/failure process on fading channels, we derive analytical expressions for throughput and energy efficiency of UDP/LL with and without LL backoff. The analytical results are verified through simulations. We also evaluate the mean delay and delay variation of voice packets and energy efficiency performance over a wireless link that uses UDP for transport of voice packets and the proposed backoff algorithms at the LL. We show that the proposed LL backoff algorithms achieve energy efficiency improvement of the order of 2–3 dB compared to LL with no backoff, without compromising much on the throughput and delay performance at the UDP layer. Such energy savings through protocol means will improve the battery life in wireless mobile terminals.**

***Index Terms*—Backoff algorithms, energy efficiency, fading channels, link layer, user datagram protocol.**

I. INTRODUCTION

WIRELESS channels are typically characterized by high error rates due to multipath fading [1]. Link layer (LL) automatic repeat request (ARQ) schemes are often used on wireless fading channels to improve the error rate in order to provide wireless data services [2]. Since wireless portable devices must rely on finite battery power for their operation, judicious use of the available energy is important [3]. It has been shown that energy savings in portable devices can be sought at different layers of the wireless protocol stack [4]–[9], not necessarily at the devices/circuits level alone (e.g., low power radio frequency (RF) devices/circuits). A detailed survey of energy efficient protocols at various layers of wireless network protocol stacks is presented in [10].

In a related area of multiple access networks, backoff algorithms are employed during recovery from packet collisions. For example, a truncated binary exponential backoff scheme is employed in Ethernet [11]. The backoff delay is increased by larger and larger amounts on each successive collision, up to a finite number of retransmissions. In [12], we proposed that backoff schemes could be applied beneficially on *point-to-point* wireless links as well. The motivation arises from the potential for substantial energy savings through backoff when the wireless link experiences deep fades and bursty errors.

During channel fades, it is likely that a number of consecutive packets are received in error due to memory in the multipath fading process [1]. In [12], we proposed to exploit this channel memory for better energy efficiency, by applying backoff strategies. In particular, we proposed that a backoff scheme at the LL, which applies an appropriate backoff rule upon each LL packet error event, can leave the channel *idle* for some specified number of slots, thereby reducing the energy wastage due to packet transmissions in error. The proposed backoff algorithms are linear backoff (LBO), binary exponential backoff (BEBO) and geometric backoff (GBO). Through renewal-reward analysis, we showed that, on slowly fading channels where packet errors occur in bursts, the proposed LL backoff algorithms provided improvement in energy efficiency of the order of 3 dB, which can lead to increased battery life in portable devices. A question in this regard is whether the energy savings achieved at the link layer using the proposed backoff schemes is preserved at the transport layer as well. In this paper, we extend our performance analysis to address this question. This issue becomes important with the increasing need for real-time applications like VoIP, voice chat, etc., over wireless Internet, using transport protocols like user datagram protocol (UDP). For example, in the next generation wireless systems, a generalized multimedia service model, including voice services on UDP/Internet protocol (IP)/point-to-point protocol (PPP)/LL framework and packet data services on transmission control protocol (TCP)/IP/PPP/LL framework, is envisaged [13].

UDP is a simple, connectionless transport protocol [14]. UDP does not guarantee reliable, in-sequence delivery of packets and is suited to delay-sensitive applications (e.g., voice over Internet). Performance (including the energy efficiency aspects) of the wireless segment of systems which use UDP as the transport protocol calls for a detailed analysis. We, in this paper, analyze the throughput and energy efficiency performance of UDP on a wireless fading link which employs the energy efficient backoff algorithms at the link layer. We also study the delay and delay variation performance of voice packets when UDP is used for the transport of voice packets along with the proposed backoff strategies at the LL. We show that significant improvement in energy efficiency of the order of 2 to 3 dB are achieved at the UDP layer as well, without compromising much on the throughput and delay performance.

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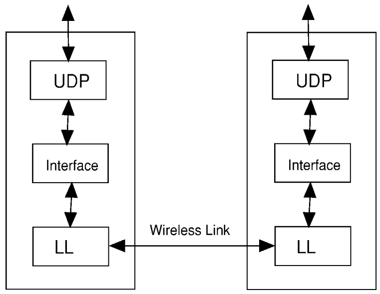

Fig. 1. UDP/LL protocol stack.

The rest of the paper is organized as follows. In Section II, the LL backoff algorithms are briefly described. In Section III, the system model and the UDP/LL performance analysis with and without energy efficient backoff are presented. Analytical and simulation results are discussed in Section IV. Section IV also presents the mean delay and delay variation performance of voice packets when the proposed backoff algorithms are used at the LL. Conclusions are presented in Section V.

II. LL Backoff Algorithms

Consider an ARQ mechanism at the LL in which recovery of erroneous LL packets is attempted through a finite number of retransmissions. Following a LL packet failure, a retransmission attempt is made after leaving few slots as idle, with an intention to improve energy efficiency. The proposed energy efficient link layer backoff algorithms are defined as follows.

Linear Backoff: In a linear backoff scheme, on ith successive failure of a LL packet, the LL leaves the channel idle for i number of subsequent LL time slots, i.e., the backoff delay grows linearly on each successive LL packet failure.

Binary Exponential Backoff: In this scheme, the LL leaves the channel idle for $2^i - 1$ number of LL time slots on ith successive failure.

Geometric Backoff: In this scheme, there is a parameter g, $0 < g \leq 1$. Following an idle or LL packet failure, the LL leaves the channel idle in the next LL time slot with probability g (or equivalently, transmits a LL packet with probability $1 - g$). In other words, the expected number of backoff slots following a failure is given by $g/(1-g)$.

III. UDP/LL Analysis

In this section, we analyze the throughput and energy efficiency performance of a generalized UDP/LL protocol stack, with and without LL backoff, operating on a point-to-point wireless link.

System Model: We consider a UDP/LL protocol stack as shown in Fig. 1. For example, one UDP end-point could be at a mobile terminal and the other at the interworking function (IWF) of a base station [13]. We consider only the wireless segment here because it is this segment which significantly influences the performance in a wireless network. In between the UDP layer and the link layer, there can be an IP layer and a PPP layer [13]. The base station IWF assigns the mobile terminal a temporary IP address upon call establishment. This IP address is unique and valid for the duration of the data call. The PPP layer is used for initial call establishment and to negotiate initial optional link capabilities like maximum PPP frame size [2]. Both IP and PPP layers add fixed number of overhead bytes (e.g., 20-B uncompressed IP header or 3-B VJ compressed IP header, 4-B PPP header [14]). Since the bulk throughput and energy efficiency performance of the stack during data transfer phase mainly depends on the ARQ mechanism at the LL, we focus mainly on UDP and LL. In particular, we ignore IP and PPP layers in our model as, from a performance view point, they will merely add their respective overheads to the UDP packet. Consequently, we assume that the UDP packet size, N_U bytes, includes IP and PPP overheads. Each UDP packet is segmented into several LL packets and transmitted. When a LL packet fails, the LL ARQ mechanism attempts to recover the lost packet.

Channel Model: As in [12], we use a first-order Markov representation of the multipath fading process. This is reasonable because, bursty errors on multipath fading channels are, with reasonable accuracy, modeled by a first-order Markov chain in most analyzes in the literature [15]–[17]. Here, we use a Markov chain representation of the wireless channel with Markov parameters p and $(1-q)$ as the probabilities that the ith LL packet transmitted is in success given the $(i-1)$th LL packet was successful and unsuccessful, respectively.

A. UDP/LL Without Backoff

In this section, we analyze UDP/LL performance without backoff. The LL is characterized by two parameters N_L and L_R, where N_L is the number of LL packets per UDP packet and L_R is the number of LL retransmissions allowed for a failed LL packet. Depending on channel error rate, LL retransmissions can increase the transmission time of UDP packets. Here, we are interested in evaluating the throughput and the energy efficiency at the UDP layer. To do that, first we will find the transition probabilities of packet success and fail at the UDP level. Define[1]

- p_n = Prob{at least one out of n LL packets fails, given the first LL attempt is a success};
- $q_n^{(k)}$ = Prob{at least one out of n LL packets fails, given first LL packet already had $k \leq L_R$ retransmissions and current LL attempt is a fail};
- u_s = Prob{current UDP packet is fail given last LL transmission of previous UDP packet is success};
- u_f = Prob{current UDP packet is fail given last LL transmission of previous UDP packet is fail}.

We can write recursive relation on p_n and $q_n^{(k)}$ with the boundary conditions $p_1 = 0$, $q_n^{(L_R)} = 1$, $1 \leq n \leq N_L$ and $q_1^{(k)} = q^{(L_R-k)}$, $0 \leq k \leq L_R - 1$. Then, for $2 \leq n \leq N_L$ and $0 \leq k \leq L_R - 1$

$$p_n = pp_{n-1} + (1-p)q_{n-1}^{(0)} \tag{1}$$

[1]In these definitions, *attempt* refers to LL transmission, i.e., a nonidle LL slot, *last LL transmission* refers to last attempt of the last LL packet, *first LL transmission* refers to the first attempt of the first LL packet. For example, denote a LL slot by a square bracket, the LL packet number by the numeral and the sequence of attempts by the alphabet inside it. Let, for this example, $N_L = 4$ and $L_R = 2$. Then, in [1a][1b][2a][3a][3b][3c][4a], every slot is an attempt, [1a] is the first LL transmission and [4a] is the last LL transmission.

$$q_n^{(k)} = (1-q)p_n + q q_n^{(k+1)} \tag{2}$$

and u_s and u_f are given by

$$u_s = p p_{N_L} + (1-p) q_{N_L}^{(0)} \tag{3}$$
$$u_f = (1-q) p_{N_L} + q q_{N_L}^{(0)}. \tag{4}$$

In the above, p and q are the Markov parameters representing the first-order Markov channel model. Now, define

- $v_{fs}^{(n)} =$ Prob{the last LL transmission of the current UDP packet of length n LL packets is success given the current UDP packet is a fail};
- $v_{ss}^{(n)} =$ Prob{the last LL transmission of the current UDP packet of length n LL packets is success given the current UDP packet is a success}.

Clearly, $v_{ss}^{(n)} = 1$, for any n. We can write recursive relation on $v_{fs}^{(n)}$, with boundary condition $v_{fs}^{(1)} = 0$, as

$$\begin{aligned} v_{fs}^{(i)} &= v_{fs}^{(i-1)} \left(p + (1-p) \sum_{j=0}^{L_R-1} q^j (1-q) \right) \\ &\quad + \left(1 - v_{fs}^{(i-1)}\right) \sum_{j=0}^{L_R} q^j (1-q) \\ &= v_{fs}^{(i-1)} (p+q-1) q^{L_R} + \left(1 - q^{L_R+1}\right). \end{aligned} \tag{5}$$

Let ϕ_{ss} and ϕ_{fs} be the probabilities that the current UDP packet is success given that the previous UDP packet is success and fail, respectively. Also, define $\phi_{sf} = 1 - \phi_{ss}$ and $\phi_{ff} = 1 - \phi_{fs}$. These transition probabilities are obtained as

$$\phi_{ss} = (1-u_s)\, v_{ss}^{(N_L)} + (1-u_f)\left(1 - v_{ss}^{(N_L)}\right) \tag{6}$$
$$\phi_{fs} = (1-u_s)\, v_{fs}^{(N_L)} + (1-u_f)\left(1 - v_{fs}^{(N_L)}\right). \tag{7}$$

1) UDP Throughput and Energy Efficiency: In [18], Zorzi *et al.*, in their study of energy constrained error control for wireless, introduced the definition of energy efficiency to be the ratio of the amount of data delivered to the total energy consumed as a more appropriate metric than just battery life. This metric has been subsequently used in several studies in the analysis of the energy performance of various protocols [4], [19]. It is assumed that the protocol evolution can be tracked by means of a Markov chain with finite state space Ω. For example, this is the case for a protocol with finite-state machine in the presence of Markovian errors, a situation which is a good approximation of reality in a number of situations [15]–[17]. By appropriately defining metrics on the transitions of this chain, renewal reward analysis allows to compute throughput and energy performance [18], [20] as follows. Let P_{ij} be the transition probability from state i to state j and let π_i be the steady-state probability of the chain being in state $i \in \Omega$. It is possible to define various semi-Markov processes in which this Markov chain is embedded [20]. In general, consider two reward functions, $R^{(1)}$ and $R^{(2)}$, where $R_{ij}^{(1)}$, $R_{ij}^{(2)}$ are quantities associated with transition ij and let $R^{(1)}(\tau)$, $R^{(2)}(\tau)$ be the cumulative values of those functions, i.e., the total reward earned through the system evolution in the time interval [0, τ]. From renewal theory [21], we have the following fundamental result:

$$\lim_{\tau\to\infty} \frac{R^{(1)}(\tau)}{R^{(2)}(\tau)} = \frac{\sum_{i\in\Omega} \pi_i \sum_{j\in\Omega} P_{ij} R_{ij}^{(1)}}{\sum_{i\in\Omega} \pi_i \sum_{j\in\Omega} P_{ij} R_{ij}^{(2)}} \tag{8}$$

which can be easily computed for a number of cases of interest. For example, let S_{ij}, C_{ij}, and D_{ij} be the average number of successfully received packets, amount of consumed energy and time delay associated with transition ij. Then, if $R^{(2)} = D$, evaluation of (8) for $R^{(1)} = S$ and $R^{(1)} = C$ gives the average throughput and energy consumption, respectively. Here, ergodicity of all processes involved is assumed. On the other hand, the choice $R^{(1)} = S$ and $R^{(2)} = C$ yields the energy efficiency of the protocol. Therefore, once the Markov chain for the protocol evolution has been found, all the relevant performance metrics can be easily computed from the above. Accordingly, the UDP throughput in our analysis can be obtained as $U_{\rm succ} N_L/(L_{\rm succ} + L_{\rm fail} + L_{\rm idle})$, where $U_{\rm succ}$ is the mean number of successful UDP packets in a UDP cycle (a UDP cycle is defined in the next paragraph), $L_{\rm succ}$, $L_{\rm fail}$ and $L_{\rm idle}$ are the mean number of successful LL packets, failed LL packets and idle LL slots, respectively, in a UDP cycle. Also, defining one energy unit as corresponding to the transmission of a LL packet at an average SNR of 0 dB, the energy efficiency can be obtained as $L_{\rm succ}/(L_{\rm succ} + L_{\rm fail})$ normalized by the average SNR.

To find the UDP throughput and energy efficiency, we need to calculate the mean number of successful and failed LL packets in a UDP cycle, where a UDP cycle is defined as a sequence of successful UDP packets followed by a sequence of failed UDP packets, which then repeats (see Fig. 2). Let l be the number of UDP packets in a cycle. In order to determine the mean number of successful and failed LL packets, define s_n and f_n as the mean successful LL packets and failed LL packets, respectively, sent for transmitting one UDP packet of length n LL packets, given that the first LL transmission is success. Let $t_n^{(k)}$ and $g_n^{(k)}$ be the mean successful LL packets and failed LL packets, respectively, sent for transmitting one UDP packet of length n LL packets, given that the first LL packet already had k ($\le L_R$) retransmissions and the current LL attempt is a fail.

With the boundary conditions, $s_1 = 1$, $t_1^{(L_R)} = 0$ and $t_1^{(k)} = \sum_{j=0}^{L_R-k-1} q^j(1-q)$, $0 \le k < L_R$, we can solve the following relations recursively, for $2 \le n \le N_L$ and $0 \le k \le L_R - 1$:

$$s_n = 1 + p s_{n-1} + (1-p) t_n^{(0)} \tag{9}$$
$$t_n^{(k)} = q t_n^{(k+1)} + (1-q) s_n \tag{10}$$

and for $k = L_R$

$$t_n^{(L_R)} = q t_{(n-1)}^{(0)} + (1-q) s_{n-1}. \tag{11}$$

Similarly, with the boundary conditions, $f_1 = 0$, $g_1^{(L_R)} = 1$ and $g_1^{(k)} = \sum_{j=1}^{L_R-k} j q^{j-1}(1-q) + (L_R - k + 1) q^{L_R-k}$, $0 \le k < L_R$, we can solve the following relations recursively, for $2 \le n \le N_L$ and $0 \le k \le L_R - 1$:

$$f_n = p f_{n-1} + (1-p) g_n^{(0)} \tag{12}$$

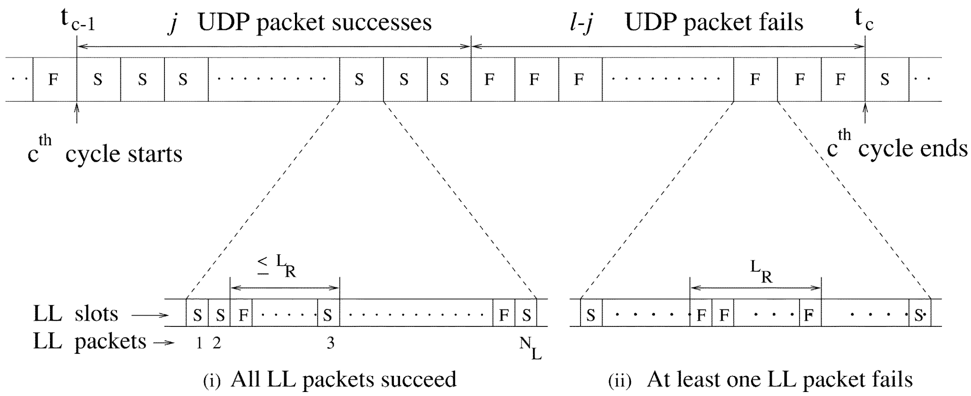

Fig. 2. UDP transmission cycle.

$$g_n^{(k)} = 1 + q g_n^{(k+1)} + (1-q) f_n \tag{13}$$

and for $k = L_R$

$$g_n^{(L_R)} = 1 + q g_{(n-1)}^{(0)} + (1-q) f_{n-1}. \tag{14}$$

Let l_{rs}, l_{rf}, and l_{ri} be the mean number of successful LL packets, failed LL packets and idle LL packets, respectively, in the current UDP packet, given that the last LL transmission of the previous UDP packet is in state r, where r can be either s, which stands for success, or f, which stands for fail. Then

$$l_{ss} = p s_{N_L} + (1-p) t_{N_L}^{(0)} \tag{15}$$
$$l_{sf} = p f_{N_L} + (1-p) g_{N_L}^{(0)} \tag{16}$$
$$l_{fs} = (1-q) s_{N_L} + q t_{N_L}^{(0)} \tag{17}$$
$$l_{ff} = (1-q) f_{N_L} + q g_{N_L}^{(0)}. \tag{18}$$

Note that $l_{si} = 0$ and $l_{fi} = 0$ in this case. Now, define S_s and S_f as the mean number of successful LL packets in the current UDP packet, given that the previous UDP packet is a success and fail, respectively. Also, define F_s and F_f as the mean number of failed LL packets in the current UDP packet, given that the previous UDP packet is a success and fail, respectively. Similarly, define I_s and I_f as the mean number of idle LL packets in the current UDP packet, given the same conditions as above.

Then, $S_s = l_{ss}$, $F_s = l_{sf}$, $I_s = l_{si}$

$$S_f = l_{ss} v_{fs}^{(L_R)} + l_{fs}\left(1 - v_{fs}^{(L_R)}\right)$$
$$F_f = l_{sf} v_{fs}^{(L_R)} + l_{ff}\left(1 - v_{fs}^{(L_R)}\right)$$
$$I_f = l_{si} v_{fs}^{(N_L)} + l_{fi}\left(1 - v_{fs}^{(N_L)}\right).$$

Let C be the random variable representing the cycle duration and let U be the random variable representing the number of UDP successes in it, then, we have

$$P\{C = l, U = j\} = \phi_{ss}^{j-1}(1-\phi_{ss})(1-\phi_{fs})^{l-j-1}\phi_{fs}. \tag{19}$$

Let L_{succ} denote the mean number of successful LL packets, L_{fail} denote the mean number of failed LL packets and L_{idle} the mean number of idle LL packets in a UDP cycle, then

$$L_{\text{succ}} = \sum_{l=2}^{\infty}\sum_{j=1}^{l-1}\left(jS_s + (l-j)S_f\right)P\{C = l, U = j\} \tag{20}$$

$$L_{\text{fail}} = \sum_{l=2}^{\infty}\sum_{j=1}^{l-1}\left(jF_s + (l-j)F_f\right)P\{C = l, U = j\} \tag{21}$$

$$L_{\text{idle}} = \sum_{l=2}^{\infty}\sum_{j=1}^{l-1}\left(jI_s + (l-j)I_f\right)P\{C = l, U = j\} \tag{22}$$

The mean number of successes, U_{succ}, in a UDP cycle is given by

$$U_{\text{succ}} = \sum_{l=2}^{\infty}\sum_{j=1}^{l-1} jP\{C = l, U = j\}. \tag{23}$$

Using the above expressions for L_{succ}, L_{fail}, L_{idle}, and U_{succ}, the UDP throughput can be obtained as $U_{\text{succ}}N_L/(L_{\text{succ}} + L_{\text{fail}} + L_{\text{idle}})$ and the energy efficiency can be obtained as $L_{\text{succ}}/(L_{\text{succ}} + L_{\text{fail}})$ normalized by the average SNR.

B. UDP/LL With LBO

In this section, the performance of UDP with LBO at the LL is analyzed. On ith successive fail of a LL packet, the LL keeps idle for i number of subsequent slots. If L_R retransmissions fail, the backoff delay is reset to zero and is as if a fresh backoff is applied to the next transmitted LL packet. The analysis for this case is similar to that without backoff. We will use all the definitions used so far for the subsequent cases also. We can write the new relations as follows.

For p_n and $q_n^{(k)}$, all boundary conditions remain same as in Section III-A, except $q_1^{(k)} = \prod_{l=2}^{L_R-k+1}\gamma_{k+l}$, $0 \le k \le L_R - 1$ and (2) becomes

$$q_n^{(k)} = \delta_{k+2}p_n + \gamma_{k+2}q_n^{(k+1)} \tag{24}$$

where δ_i and γ_i are the probabilities that LL success and failure occur, respectively, at $(m+i)$th slot given the mth slot is a failure for any $m \geq 1$ and $i \geq 1$. Observe that, for any $i \geq 1$, $\delta_i + \gamma_i = 1$. With boundary conditions $\delta_1 = 1-q$ and $\gamma_1 = q$, we can write recursive relations on δ_i and γ_i as

$$\delta_i = \gamma_{i-1}(1-q) + \delta_{i-1}p,\ i \geq 2 \tag{25}$$
$$\gamma_i = \gamma_{i-1}q + \delta_{i-1}(1-p),\ i \geq 2. \tag{26}$$

The relation on $v_{fs}^{(n)}$ can be written as

$$\begin{aligned} v_{fs}^{(i)} &= v_{fs}^{(i-1)}\left(p+(1-p)V\right) + \left(1-v_{fs}^{(i-1)}\right)((1-q)+qV) \\ &= v_{fs}^{(i-1)}\left((p+q-1)(1-V)\right) + (1-q) + qV \end{aligned} \tag{27}$$

where $V = \sum_{j=2}^{L_R+1} \delta_j \prod_{m=2}^{j-1} \gamma_m$ and $v_{fs}^{(1)} = 0$. Now, ϕ_{ss}, ϕ_{fs} and, thus, UDP throughput can be calculated using the same relations given in Section III-A.

For s_n and $t_n^{(k)}$, the boundary conditions and the recursive relations can be written as $s_1 = 1$, $t_1^{(L_R)} = 0$, $t_1^{(k)} = \sum_{j=k+2}^{L_R+1} \delta_j \prod_{m=k+2}^{j-1} \gamma_m$, $0 \leq k \leq L_R - 1$. Then, for $2 \leq n \leq N_L$ and $0 \leq k \leq L_R - 1$, (10) becomes

$$t_n^{(k)} = \gamma_{k+2} t_n^{(k+1)} + \delta_{k+2} s_n. \tag{28}$$

Similarly, for f_n and $g_n^{(k)}$, the boundary conditions and the recursive relations can be written as $f_1 = 0$, $g_1^{(L_R)} = 1$

$$\begin{aligned} g_1^{(k)} = &\sum_{j=k+2}^{L_R+1} (j-k-1)\delta_j \prod_{m=k+2}^{j-1} \gamma_m \\ &+ (L_R - k + 1) \prod_{m=k+2}^{L_R+1} \gamma_m, \qquad 0 \leq k \leq L_R - 1. \end{aligned}$$

Then, for $2 \leq n \leq N_L$ and $0 \leq k \leq L_R - 1$, (13) becomes

$$g_n^{(k)} = 1 + \gamma_{k+2} g_n^{(k+1)} + \delta_{k+2} f_n. \tag{29}$$

The remaining steps to compute UDP throughput and energy efficiency are same as that in Section III-A.

C. UDP/LL With BEBO

In the case of UDP with LL BEBO, for p_n and $q_n^{(k)}$, all boundary conditions remain same as in Section III-A, except $q_1^{(k)} = \prod_{l=1}^{L_R-k} \gamma_{2^{k+l}}$, $0 \leq k \leq L_R - 1$ and (2) becomes

$$q_n^{(k)} = \delta_{2^{k+1}} p_n + \gamma_{2^{k+1}} q_n^{(k+1)}. \tag{30}$$

The expression for $v_{fs}^{(n)}$ in (27) holds here too with $V = \sum_{j=1}^{L_R} \delta_{2^j} \prod_{m=1}^{j-1} \gamma_{2^m}$.

Similarly, for s_n and $t_n^{(k)}$, $t_1^{(k)} = \sum_{j=k+1}^{L_R} \delta_{2^j} \cdot \prod_{m=k+1}^{j-1} \gamma_{2^m}$, $0 \leq k \leq L_R - 1$ and (10) becomes for $2 \leq n \leq N_L$ and $0 \leq k \leq L_R - 1$

$$t_n^{(k)} = \gamma_{2^{k+1}} t_n^{(k+1)} + \delta_{2^{k+1}} s_n. \tag{31}$$

For f_n and $g_n^{(k)}$

$$\begin{aligned} g_1^{(k)} = &\sum_{j=k+1}^{L_R} (j-k-1)\delta_{2^j} \cdot \prod_{m=k+1}^{j-1} \gamma_{2^m} \\ &+ (L_R - k + 1) \prod_{m=k+1}^{L_R} \gamma_{2^m}, \qquad 0 \leq k \leq L_R - 1 \end{aligned}$$

and (13) for $2 \leq n \leq N_L$ and $0 \leq k \leq L_R - 1$ becomes

$$g_n^{(k)} = 1 + \gamma_{2^{k+1}} g_n^{(k+1)} + \delta_{2^{k+1}} f_n. \tag{32}$$

The UDP throughput and energy efficiency are calculated the same way as before.

D. UDP/LL With GBO

In the case of UDP with LL geometric backoff, the GBO has a stochastic backoff delay rather than deterministic delays as in LBO and BEBO. During backoff, we have four possible states, LL success, LL fail, LL idle with possible success, and LL idle with possible fail. Denote these states by 0, 1, 2, and 3, respectively. Let $\theta_n(i,j)$ be the probability that the current state is i and the nth state after the current state is j without passing through success state in between. We have the following boundary conditions: for $j = 0, 1$, $\theta_1(i,j) = (1-g)p_{kj}$ and for $j = 2, 3$, $\theta_1(i,j) = gp_{k(j-2)}$, where $k = i$ mod 2, $0 \leq i \leq 3$ and p_{lm} is the one step transition probability from the state l to m when there is no backoff. Then, for $2 \leq n \leq L_R$, the recursive relations can be written as

$$\theta_n(i,j) = \sum_{l=1}^{3} \theta_{n-1}(i,l)\theta_1(l,j). \tag{33}$$

Now, in addition to p_n and $q_n^{(k)}$, we need to define two new variables, $r_n^{s(k)}$ and $r_n^{f(k)}$ as the probabilities that at least 1 out of n LL packets fails, given the first LL packet already had $k \leq L_R$ attempts and the current attempt is idle with possible success and idle with possible fail, respectively. Now with $p_1 = 0$, $q_n^{(L_R)} = 1$, $r_n^{s(L_R)} = 1$, and $r_n^{f(L_R)} = 1$, for $1 \leq n \leq N_L$ and $q_1^{(k)} = 1 - \theta_{N-k}(1,0)$, $r_1^{s(k)} = 1 - \theta_{N-k}(2,0)$, and $r_1^{f(k)} = 1 - \theta_{N-k}(3,0)$, for $0 \leq k \leq L_R - 1$. Then, for $1 < n \leq N_L$ and $0 \leq k < L_R - 1$

$$p_n = pp_{n-1} + (1-p)q_{n-1}^{(0)} \tag{34}$$
$$\begin{aligned} q_n^{(k)} = &(1-g)(1-q)p_n + (1-g)qq_n^{(k+1)} \\ &+ g(1-q)r_n^{s(k+1)} + gqr_n^{f(k+1)} \end{aligned} \tag{35}$$
$$\begin{aligned} r_n^{s(k)} = &(1-g)pp_n + (1-g)(1-p)q_n^{(k+1)} \\ &+ gpr_n^{s(k+1)} + g(1-q)r_n^{f(k+1)} \end{aligned} \tag{36}$$
$$r_n^{f(k)} = q_n^{(k)}. \tag{37}$$

Define for $0 \leq i \leq 3$

- u_i = Prob{current UDP packet is fail given the state of last LL transmission of previous UDP packet is i};
- $v_{fi}^{(n)}$ = Prob{the last LL transmission of current UDP packet of length n LL packets is in state i given that current UDP packet is a fail};

- $v_{si}^{(n)}$ Prob{the last LL transmission of current UDP packet of length n LL packets is in state i given that current UDP packet is a success}.

Clearly, $u_2 = u_0$, $u_3 = u_1$ and $v_{sj}^{(n)} = 1$ for $j = 0$ and 0 for $j = 1, 2, 3$. We have, $v_{f0}^{(1)} = 0$ and $v_{fj}^{(1)} = \theta_{L_R}(1, j)/S$, for $j = 1, 2, 3$, where $S = \sum_{j=1}^{3} \theta_{L_R}(1, j)$. Then, with $k = l \bmod 2$ and p_{lm} defined as the one step transition probability from state l to m as before

$$v_{f0}^{(n)} = \sum_{l=0}^{3} v_{fl}^{(n-1)} \left(p_{k0} + p_{k1} \sum_{n=1}^{L_R} \theta_n(1, 0) \right) \tag{38}$$

$$v_{fj}^{(n)} = \sum_{l=0}^{3} v_{fl}^{(n-1)} p_{k1} \theta_{L_R}(1, j), \qquad 1 \le j \le 3. \tag{39}$$

Now, ϕ_{ss} and ϕ_{fs} are given by

$$\phi_{ss} = (1 - u_0) \tag{40}$$

$$\phi_{fs} = \sum_{l=0}^{3} (1 - u_l)\, v_{fl}^{(L_R)} \tag{41}$$

from which UDP throughput can be computed.

Next, to determine the energy efficiency of UDP/LL with GBO, we define $u_n^{s(k)}$ and $u_n^{f(k)}$ as the mean successful LL packets sent for transmitting one UDP packet of length n LL packets, given that the first LL packet already had $k \le L_R$ retransmissions and the current LL transmission is idle with possible success and idle with possible fail, respectively. Also, define $h_n^{s(k)}$ and $h_n^{f(k)}$ as the mean failed LL packets sent for transmitting one UDP packet of length n LL packets, given that the first LL packet already had $k \le L_R$ retransmissions and the current LL transmission is idle with possible success and idle with possible fail, respectively. With the boundary conditions $s_1 = 1$, $t_1^{(L_R)} = 0$, $u_1^{s(L_R)} = 0$, and $u_1^{f(L_R)} = 0$, we can solve the following equation recursively, for $1 \le n \le N_L$ and $0 \le k < L_R$:

$$\begin{aligned} t_n^{(k)} =& (1-g)(1-q)s_n + (1-g)qt_n^{(k+1)} \\ &+ g(1-q)u_n^{s(k+1)} + gqu_n^{f(k+1)} \end{aligned} \tag{42}$$

$$\begin{aligned} u_n^{s(k)} =& (1-g)ps_n + (1-g)(1-p)t_n^{(k+1)} \\ &+ gpu_n^{s(k+1)} + g(1-p)u_n^{f(k+1)} \end{aligned} \tag{43}$$

$$u_n^{f(k)} = t_n^{(k)} \tag{44}$$

and for $1 < n \le N_L$

$$s_n = 1 + ps_{n-1} + (1-p)t_{n-1}^{(0)} \tag{45}$$

$$t_n^{(L_R)} = qt_{n-1}^{(0)} + (1-q)s_{n-1} \tag{46}$$

$$u_n^{s(L_R)} = (1-p)t_{n-1}^{(0)} + ps_{n-1} \tag{47}$$

$$u_n^{f(L_R)} = t_n^{(L_R)}. \tag{48}$$

With $f_1 = 0$, $g_1^{(L_R)} = 1$, $h_1^{s(L_R)} = 0$ and $h_1^{f(L_R)} = 0$, we have for $1 \le n \le N_L$ and $0 \le k < L_R$

$$\begin{aligned} g_n^{(k)} =& 1 + (1-g)(1-q)f_n + (1-g)qg_n^{(k+1)} \\ &+ g(1-q)h_n^{s(k+1)} + gqh_n^{f(k+1)} \end{aligned} \tag{49}$$

$$\begin{aligned} h_n^{s(k)} =& (1-g)pf_n + (1-g)(1-p)g_n^{(k+1)} \\ &+ gph_n^{s(k+1)} + g(1-p)h_n^{f(k+1)} \end{aligned} \tag{50}$$

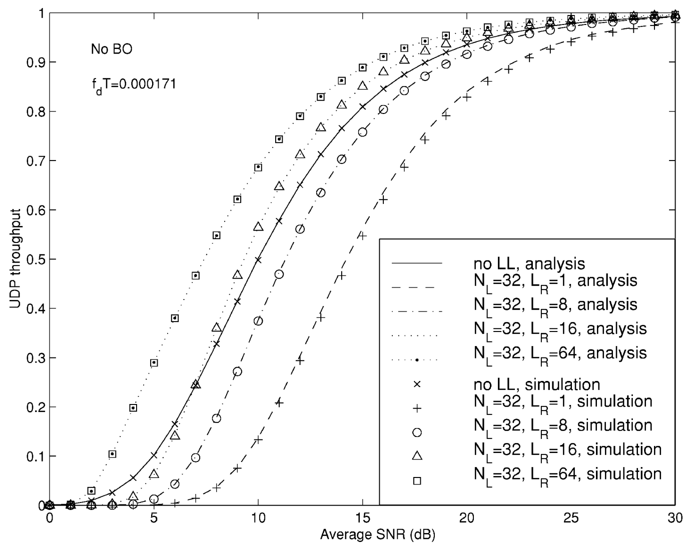

Fig. 3. UDP throughput performance with and without LL. LL has no backoff. $N_U = 1024$ B. $N_L = 32$. $L_R = 1$, 8, 16, 64. $f_dT = 0.000\,171$.

$$h_n^{f(k)} = g_n^{(k)} - 1 \tag{51}$$

and for $1 < n \le N_L$

$$f_n = pf_{n-1} + (1-p)g_{n-1}^{(0)} \tag{52}$$

$$g_n^{(L_R)} = 1 + qg_{n-1}^{(0)} + (1-q)f_{n-1} \tag{53}$$

$$h_n^{s(L_R)} = (1-p)g_{n-1}^{(0)} + pf_{n-1} \tag{54}$$

$$h_n^{f(L_R)} = g_n^{(L_R)} - 1. \tag{55}$$

Now, the equations for S_f and F_f can be rewritten as

$$S_f = l_{ss}\left(v_{f0}^{(L_R)} + v_{f2}^{(L_R)}\right) + l_{fs}\left(v_{f1}^{(L_R)} + v_{f3}^{(L_R)}\right) \tag{56}$$

$$F_f = l_{sf}\left(v_{f0}^{(L_R)} + v_{f2}^{(L_R)}\right) + l_{ff}\left(v_{f1}^{(L_R)} + v_{f3}^{(L_R)}\right) \tag{57}$$

with all other equations for calculating the energy efficiency remaining same.

IV. Results and Discussion

The UDP throughput performance with LL having no backoff is computed for different values of number of LL retransmissions, $L_R = 1$, 8, 16, 64. The following parameters are used in all the UDP/LL plots in Figs. 3–6; UDP packet size, $N_U = 1024$ B, number of LL packets per UDP packet, $N_L = 32$, normalized Doppler bandwidth, $f_dT = 0.000\,171$. This f_dT corresponds to a Doppler frequency of 1 Hz and a link speed of 1.5 Mb/s. Such low values of f_dT corresponds to high correlation in the fading process which will result in long LL error bursts. The Markov parameters p and q were obtained through correlated Rayleigh fading simulations using Jakes model [1], [17]. Note that $(1-q)^{-1}$ is the average length of the LL error burst. The performance of UDP without any LL is also plotted in Figs. 3 and 4 for comparison purposes. Note that UDP without LL corresponds to UDP/LL with $N_L = 1$ and $L_R = 0$.

From Fig. 3, it is seen that UDP/LL with $L_R = 1$ performs worse than UDP without LL. This is because, attempting retransmission only once is not adequate for recovering from LL

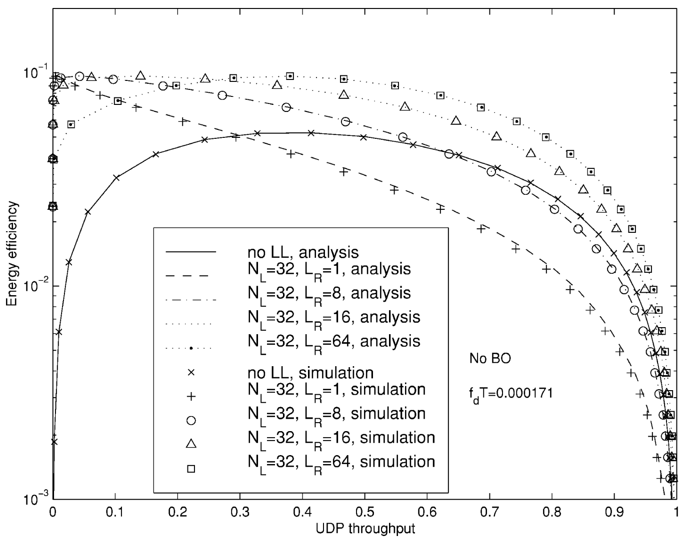

Fig. 4. Energy efficiency versus UDP throughput with and without LL. LL has no backoff. $N_U = 1024$ B. $N_L = 32$. $L_R = 1, 8, 16, 64$. $f_dT = 0.000\,171$.

errors, particularly when the channel is bad for a long time (as in the considered case of $f_dT = 0.000\,171$, where the channel correlation is high). As the number of retransmission attempts L_R is increased, UDP/LL performs better than UDP without LL. This is because the chances of UDP packet being delivered correctly improves as the LL becomes increasingly persistent (large L_R) in the LL error recovery. In other words, if the LL persists to recover an error long enough to outlast the bad channel condition (e.g., beyond the average LL burst error length, given by $1/1-q$), then the UDP throughput is expected to improve, as observed in Fig. 3. Thus, choosing a large value of L_R is preferred. Fig. 4 shows the corresponding energy efficiency versus UDP throughput performance comparison of UDP/LL NBO (no backoff) and UDP without LL. The shape of the energy efficiency curves can be explained as follows. Higher throughput may be achieved by transmitting higher power (i.e., high SNR) but may incur reduced energy efficiency due to higher energy consumption. This is evident from the plots in Fig. 4 where different points on the curves correspond to different values of average SNR. Specifically, moving along the curves toward the right-hand side of the plots corresponds to increasing SNR values. It is observed that, by choosing large values of L_R, the energy efficiency of UDP with LL is improved compared to UDP without LL. For example, for average SNRs greater than 5 dB, UDP/LL with $L_R = 64$ offers better energy efficiency than UDP without LL. Also, as we will see next (in Figs. 5 and 6), the LL backoff algorithms result in even better energy efficiency compared to UDP/LL without backoff. The analytical results in Figs. 3 and 4 are found to be in close agreement with the simulation results, thus, validating our analysis.

The UDP throughput and energy efficiency for UDP/LL with different backoff strategies are computed from respective expressions in Sections III-B, III-C, and III-D. The results are plotted in Figs. 5 and 6. In order to make a fair comparison, the L_R values for different backoff schemes are chosen in such a way that the total number of slots in the idle-retransmission slot sequence following the first failure of a LL packet (up to and including the L_Rth retransmission slot) is the same in all

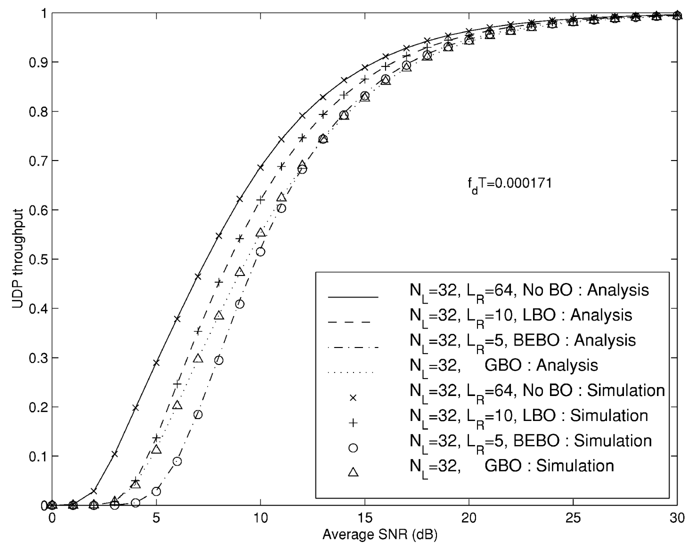

Fig. 5. Comparison of UDP throughput performance versus average SNR for no BO, LBO, BEBO, and GBO at the LL. $f_dT = 0.000\,171$. $g = 0.8$ for GBO.

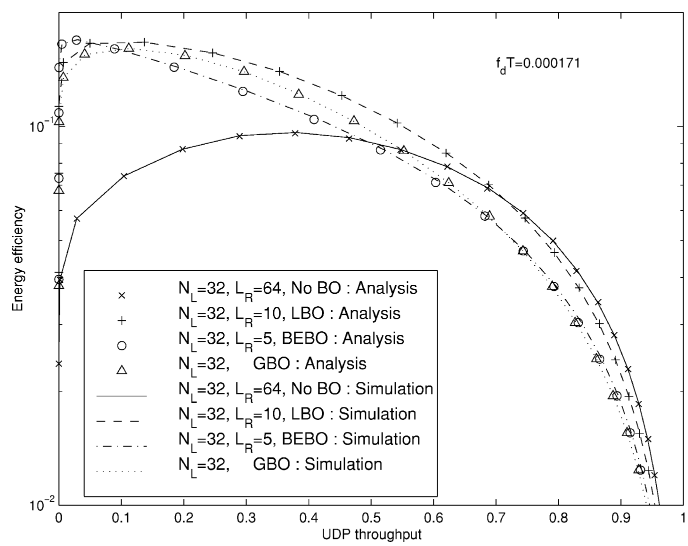

Fig. 6. Energy efficiency versus UDP throughput performance for no BO, LBO, BEBO and GBO. $f_dT = 0.000\,171$. $g = 0.8$ for GBO.

the schemes. For example, in the case of LL with no backoff, $L_R = 64$ means that retransmission can be attempted in up to 64 consecutive slots following the first failure of a LL packet. Whereas in the case of LBO scheme, 10 retransmission attempts can be made over 65 consecutive slots following the first failure of a LL packet and the slots in between these retransmission attempts are left idle as per the linear backoff rule. Hence, an L_R value of 10 is chosen for LBO. In a similar way, the L_R value for BEBO is chosen to be five. In GBO, up to 64 slots following the first failure of a LL packet are allowed for the LL to attempt retransmission with probability $(1-g)$ in each slot. The value of g for GBO is chosen to be 0.8.

From Fig. 5, it is seen that at high SNR values ($>$ 20 dB) UDP/LL with and without backoff perform almost similar. In the moderate SNR range of 5–15 dB, UDP/LL without backoff offers better UDP throughput than UDP/LL with backoff strategies. This is expected because, by possibly remaining idle in

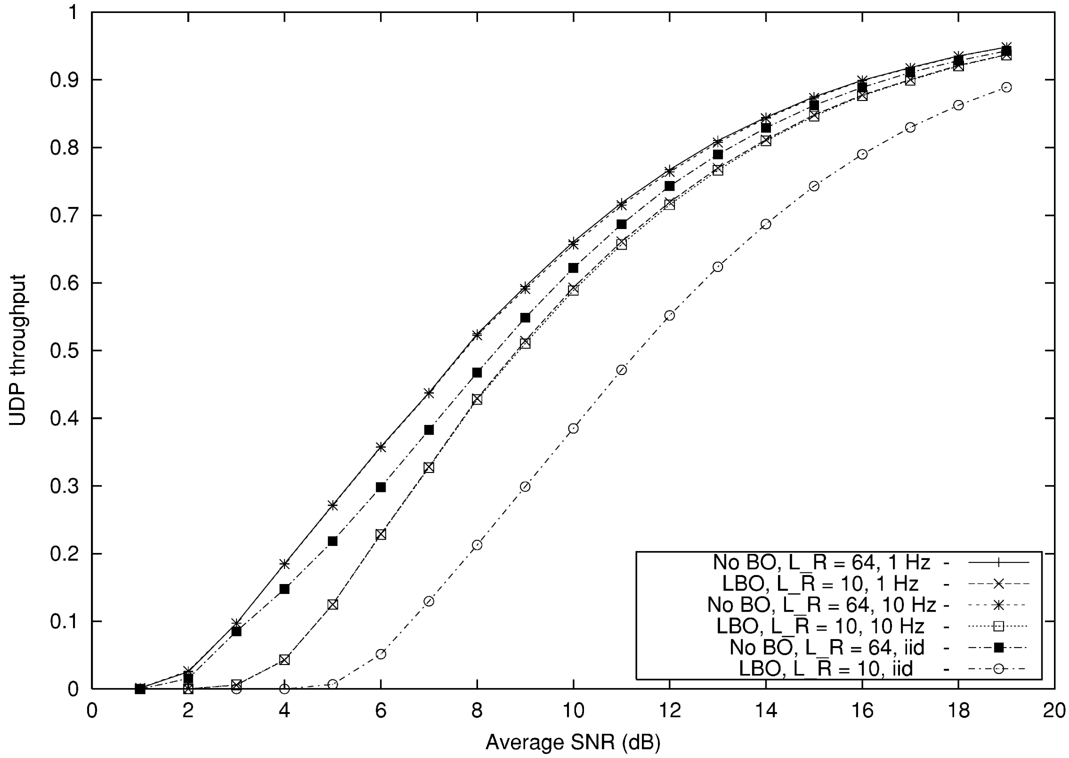

Fig. 7. UDP throughput versus average SNR performance with and without backoff for varying fading correlations. $f_d = 1$ Hz, 10 Hz, i.i.d. $L_R = 10$ for LBO. $L_R = 64$ for no BO.

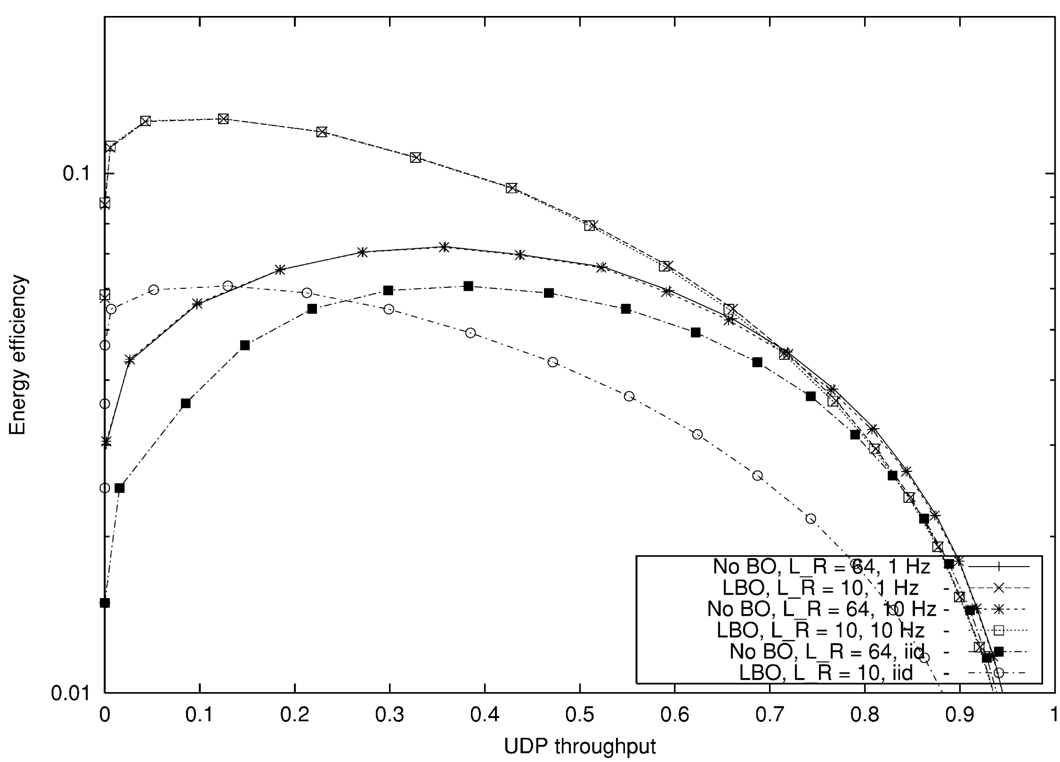

Fig. 8. Energy efficiency versus UDP throughput performance with and without backoff for varying fading correlations. $f_d = 1$ Hz, 10 Hz, i.i.d. $L_R = 10$ for LBO. $L_R = 64$ for no BO.

some good slots, the backoff schemes would sacrifice some throughput. However, note that the throughput loss is not severe. On the other hand, for UDP throughputs up to 0.5, the energy efficiencies achieved with the backoff schemes are higher than the scheme with no backoff, as seen from Fig. 6. For example, at a UDP throughput of 0.5, the UDP/LL with LBO gives nearly 1-dB energy efficiency improvement compared to UDP/LL with no backoff. At a UDP throughput of 0.3, the LBO gives nearly

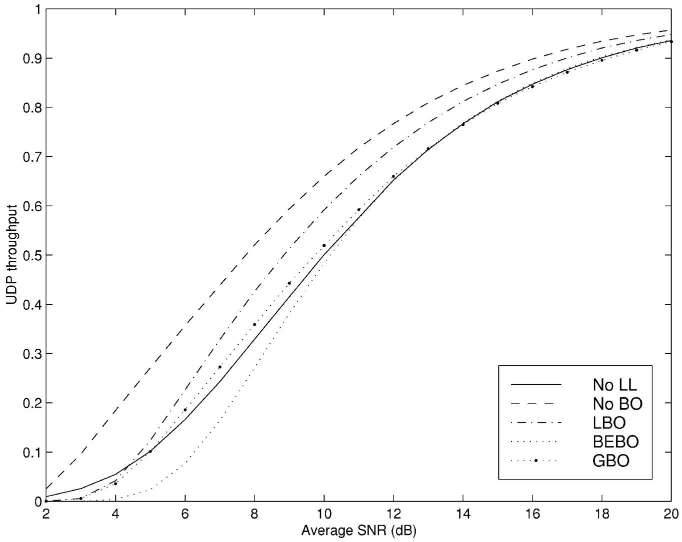

Fig. 9. UDP throughput versus average SNR performance for no LL, LL with no BO, LL with LBO, BEBO and GBO. $f_d T = 0.000\,171$. $L_R = 64$ for No BO. $L_R = 10$ for LBO, $L_R = 5$ for BEBO. $g = 0.8$ for GBO.

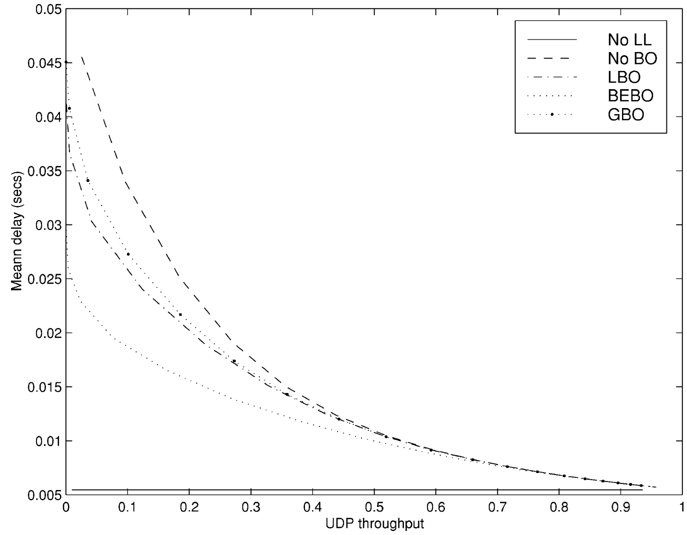

Fig. 10. Mean Delay of voice packets versus UDP throughput performance for no LL, LL with no BO, LL with LBO, BEBO and GBO. $f_d T = 0.000\,171$. $L_R = 64$ for No BO. $L_R = 10$ for LBO, $L_R = 5$ for BEBO. $g = 0.8$ for GBO.

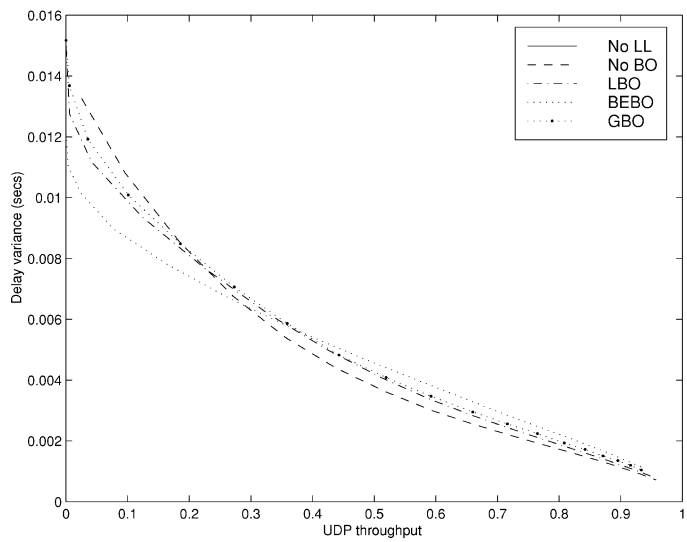

Fig. 11. Delay variance of voice packets versus UDP throughput performance for no LL, LL with no BO, LL with LBO, BEBO and GBO. $f_d T = 0.000\,171$. $L_R = 64$ for No BO. $L_R = 10$ for LBO, $L_R = 5$ for BEBO. $g = 0.8$ for GBO.

2-dB improvement while GBO and BEBO give nearly 1.7 and 1.2 dB, respectively. Thus, the proposed LL backoff algorithms are seen to provide noticeable improvement in energy efficiency, particularly when the channel undergoes long and deep fades (e.g., due to shadows).

Fig. 7 shows the UDP throughput performance with and without backoff under varying fading correlations [for $f_d = 1$ Hz, 10 Hz, and i.i.d. (independent and identically distributed)]. Fig. 8 shows the corresponding energy efficiency versus UDP throughput performance. From Fig. 7, it is observed that no BO gives better throughput than LBO, indicating some loss in throughput due to LBO. This loss in throughput due to LBO compared to no BO is less when the channel is correlated (i.e., when $f_d = 1$ Hz, 10 Hz) than when the channel is uncorrelated (i.i.d.). Also, throughputs for $f_d = 1$ Hz, 10-Hz cases are better than i.i.d. case. This observation is similar to previously reported observations that some protocols can perform better in correlated errors than in i.i.d. errors [22]. From Fig. 8, it is observed that when the channel errors are correlated ($f_d = 1$ Hz, 10 Hz), for a given UDP throughput (< 0.7), LBO results in better energy efficiency than no BO. When the channel errors becomes more and more uncorrelated (i.i.d.), the energy efficiency benefit of BO over no BO manifests only when the channel error rate is high (for throughputs < 0.3). When the channel error rates are very low and the errors are uncorrelated then BO is not beneficial, which is expected.

A. Delay Performance of Voice Packets

In this section, we consider the mean delay and delay variation performance of voice packets and the associated energy efficiency performance over a wireless link that uses UDP for transport of voice packets and the proposed backoff algorithms at the LL.

In terms of traffic characteristics, voice streams have low data rates (in the order of tens of kb/s) and exhibit low burstiness. The traditional voice encoder uses pulse code modulation which generates 8-b samples every 125 μs, leading to a rate of 64 kb/s (G.711). Newer voice coding schemes which use code book excited linear prediction techniques result in significant reduction in bit rates (e.g., 8 kb/s for G.729A) at the cost of additional encoding delay. Taking into account the headers that correspond to each of the protocol layers, the rate of packetized voice streams remain in the order of tens of kb/s. Here, we take the data rate of the voice source to be 16 kb/s. In addition, speech consists of an alternation of talk-spurts and silence periods. Here, we consider the voice source as an ON-OFF source, where voice packets are generated during ON periods and no packet gets generated during OFF periods. We assume that the ON and OFF periods are exponentially distributed with mean ON period of 400 ms and mean OFF period of 600 ms [23]. Delay and delay jitter performance requirements are stringent for voice. The requirement of maintaining good real-time voice quality limits the maximum

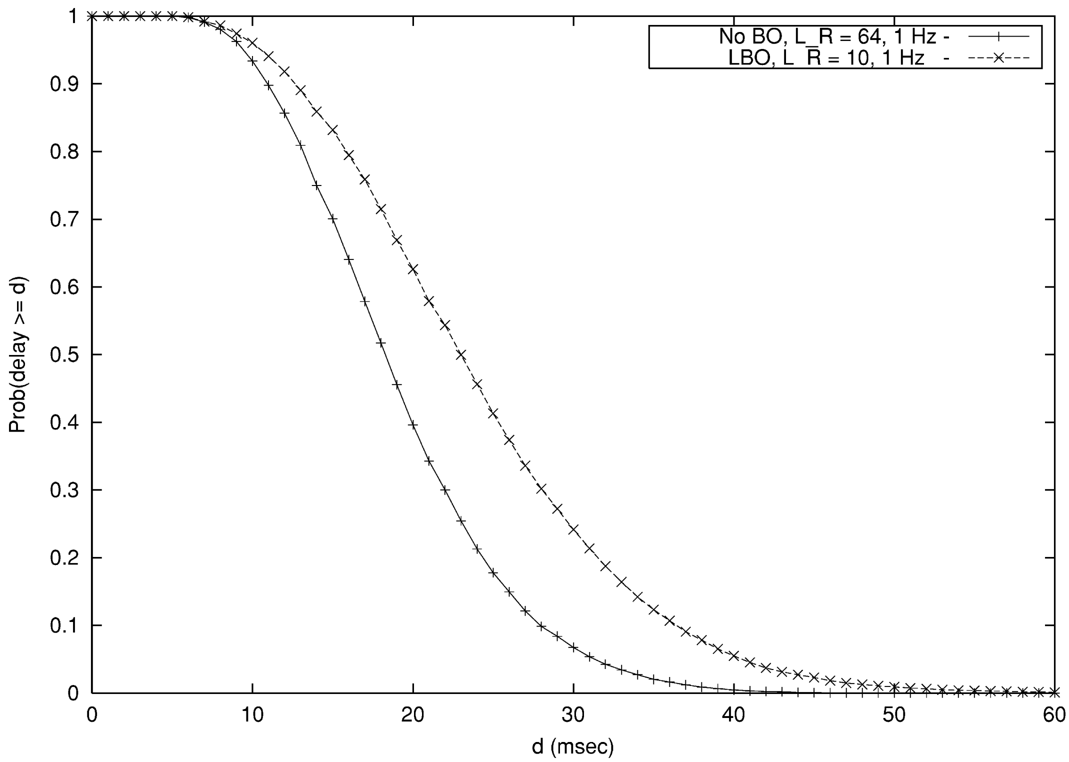

Fig. 12. Prob(delay $\geq d$) versus d (ms) with and without BO. $f_d = 1$ Hz. $\mathrm{SNR} = 5$ dB. $L_R = 64$ for no BO. $L_R = 10$ for LBO.

tolerable round-trip delay to 200–300 ms and delay jitter to less than 50 ms [24]. It is of interest then to understand how the proposed LL backoff algorithms on wireless links affect the delay and delay jitter performance of voice packets and the corresponding energy efficiency performance.

We evaluated the mean delay and delay variation of voice packets at the UDP layer and the energy efficiency performance through simulations using ns [25]. We considered a single 1.5 Mb/s wireless link undergoing flat Rayleigh fading. The LL packet size is 32 B and the UDP packet size is 1024 B. The L_R values for different BO schemes are: $L_R = 64$ for no BO, $L_R = 10$ for LBO, $L_R = 5$ for BEBO and $g = 0.8$ for GBO. We incorporated the LL backoff algorithms and the correlated fading channel model characterized by the Markov parameters, in ns. The performance results from the various simulation experiments are shown in Figs. 9–13.

Fig. 9 shows the UDP throughput performance as a function of average SNR at $f_d = 1$ Hz for: 1) UDP without LL; 2) UDP with LL and no backoff; and 3) UDP with LL backoff including LBO, BEBO, and GBO. Figs. 10 and 11 show the corresponding mean delay and delay variance of voice packets, respectively, as a function of UDP throughput. From Figs. 9 and 10, it is observed that UDP without LL performs poorer in terms of throughput but performs the best in terms of delay. This is because, without any LL, there is no retransmission and recovery of erroneous packets, resulting in a constant delay of about 6 ms (which is due only to UDP packet size and propagation delay on the wireless link) irrespective of the error rate on the channel. On the other hand, UDP with LL performs error recovery through LL retransmissions and, hence, it performs best in terms of throughput. Also, the mean delay increases because of LL retransmissions. Note, however, that the mean delay with LL retransmission is less than 20 and 10 ms for UDP throughput values better than 0.3 and 0.6, respectively. The delay variance for different LL backoff algorithms also do not exceed 4 ms for UDP throughput values better than 0.6 (see Fig. 11). Since 200–300 ms round-trip delay and less than 50 ms delay jitter are adequate to maintain good quality voice [24], the additional 20 ms mean delay and 4 ms delay variation due to the proposed LL retransmission and backoff can be acceptable.

In Fig. 12, we plot the probability that the packet delay exceeds a certain delay threshold, d, with and without BO for $f_d = 1$ Hz, SNR =5 dB, with $L_R = 64$ for no BO and $L_R = 10$ for LBO. It is observed that even with BO, the probability that the packet delay is in excess of 50 ms is less than 1%. In other words, with a delay threshold of d =50 ms, the voice packet drop probability due to delay exceeding the threshold is less than 1% even with BO. The mean and variance of the delay corresponding to this LBO plot is about 22 and 6 ms, respectively. In Fig. 13, we plot the energy efficiency as a function of this packet drop probability at a delay threshold of $d = 20$ ms [i.e., prob(delay $\geq$ 20 ms)], with and without BO for $f_d = 1$ Hz, 10 Hz, and i.i.d. The prob(delay $\geq$ 20 ms) value on the x axis is parameterized by varying the average SNR on the link. It is observed that the LBO gives about 2–3 dB more energy efficiency than no BO, particularly when the link experiences deep fades (high error rates) and bursty errors (f_d =1, 10 Hz).

In [26], based on actual measurements on wireless network cards (AT& T Wavelan card, Metricom wireless modem), it has been shown that the power drained by network interface cards in

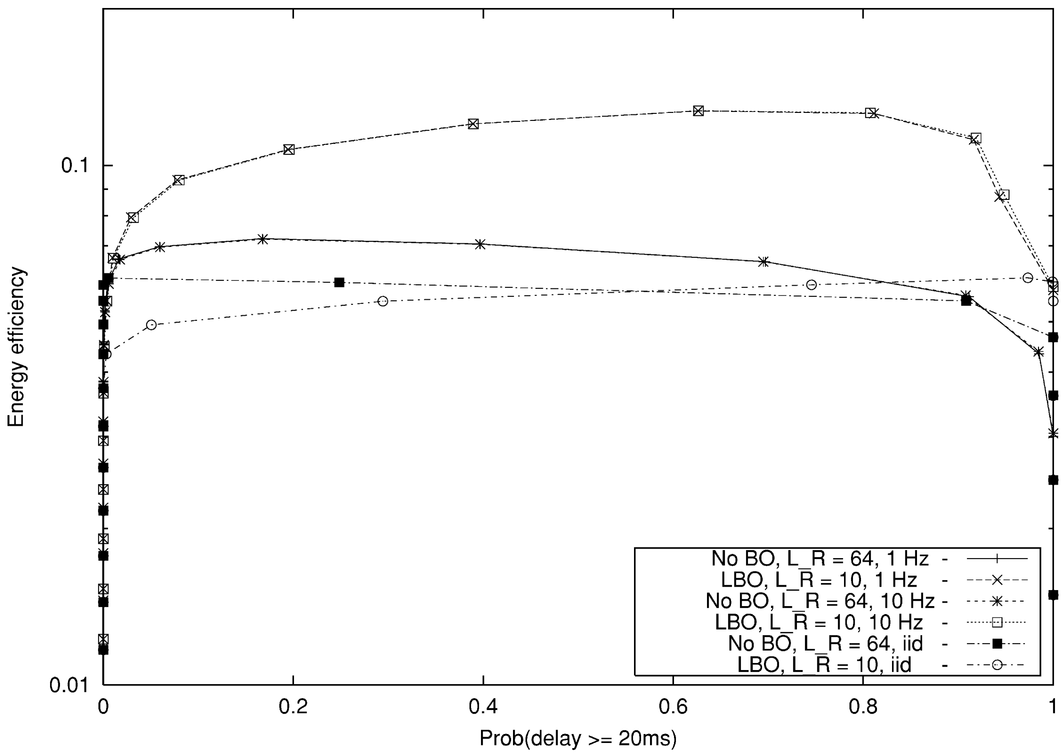

Fig. 13. Energy efficiency versus Prob(delay $\geq$ 20 s) with and without BO. $f_d = 1$ Hz, 10 Hz, i.i.d. $L_R = 10$ for LBO. $L_R = 64$ for no BO.

wireless mobile devices constitute a larger fraction of the total power used by these devices. It has also been pointed out that the cost of sending packets is much more (double in the case of Metricom modem) than the cost idling or receiving packets. In the context of the above, our proposed LL backoff strategies which attempt to avoid sending packets during bad channel conditions is a simple and effective way to increase energy savings in wireless mobile devices through protocol means. Further, the proposed LL backoff algorithms are easily implemented without much increase in complexity and they could be easily incorporated within the framework of link layers defined in recent wireless standards.

V. Conclusion

We analyzed the throughput and energy efficiency performance of UDP with linear, binary exponential and geometric backoff algorithms at the link layer on point-to-point wireless fading links. The multipath fading channel was modeled as a first-order Markov chain. The analytical results were verified through simulations. We also evaluated the mean delay and delay variation performance of voice packets and energy efficiency performance over a wireless link that uses UDP for transport of voice packets and the proposed backoff algorithms at the LL. We showed that the proposed LL backoff algorithms achieved improvement in energy efficiency of the order of 2–3 dB compared to LL with no backoff, without compromising much on the throughput and delay performance. Such energy savings through protocol means will improve the battery life in wireless mobile terminals.

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