Power-efficient ARQ schemes for Wireless Gaussian channels

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Abstract: In this paper, efficient power allocation strategies for ARQ protocols operating in wireless environments are studied. Power is optimally adapted by the transmitter based on channel state information (CSI) obtained through feedback, while guaranteeing quality-of-service (QOS) constraints such as average throughput or average delay. The power policies adopted for basic ARQ protocols, such as Stop-and-Wait or Go-Back-N, is characterized and a comparison of their relative performances is studied. Numerical results are presented for a Gaussian channel.

1 Introduction

With the advent of wireless networks, ubiquitous access to information is gradually becoming a reality. A key concern in wireless technologies is to conserve power, for example to extend battery life in hand-held devices. Also, in some sensor networks, the communicating nodes may be discarded once their power is drained. Power then becomes critical to the lifetime of such networks, and the need to conserve it cannot be overemphasized. However conservation of power cannot come at the cost of providing an unacceptable QOS to the user. Moreover wireless links, generally have large error rates as compared to wireline channels. Therefore, it is sensible to perform a link-level error control, in addition to any end-to-end error control that may be provided by the higher layers. In this work, we study power efficiency in the context of link-level ARQ protocols for wireless networks. Our emphasis is on standard ARQ approaches - we do not address hybrid ARQ approaches, such as code combing or incremental redundancy.

We study the performance of various ARQ protocols when physical layer parameters, such as transmission power can be adapted based in part on the available CSI. Here, CSI could be the exact or average fade level or any other meaningful description of the physical layer. This results in a stronger coupling between the physical layer and data link layer, than found in traditional wireless networks. There is a growing awareness that such coupling between layers can be beneficial in wireless settings [1],[2]. For these ARQ protocols, we investigate the trade-offs between the transmitted power and various QOS parameters, like average throughput and delay. Several other approaches have been examined along these lines. In [3],[4] and [5] power allocation schemes in ARQ protocols that minimize average power expended as well guarantee reliable communications are investigated. On the other hand, [6] studies the effect of varying packet sizes on the performance of the ARQ protocol. In our work, the optimal power policies chosen by various ARQ protocols is given and a comparison of the relative performance between the protocols is presented.

The rest of the paper is organized as follows. Section 2 describes the channel model studied in this work. The power allocation problem is formulated for ARQ protocols such as Stop-and-Wait or Go-back-N, constrained by average throughput requirements. Section 3 outlines some results for time-invariant channels. Also presented

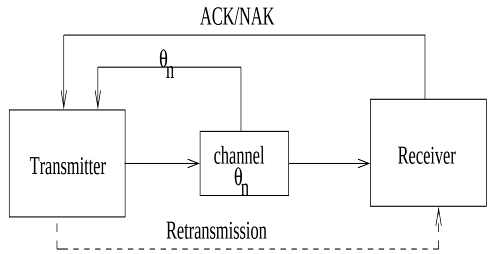

Figure 1: ARQ error control with CSI feedback to the transmitter

is a simple comparison between Stop-and-Wait and Go-Back-N protocols. In Section 4, similar results are shown for Gaussian channels in which a fixed modulation scheme is employed. Also studied is the case where communication is delay-constrained. Section 5 summarizes the contributions made.

2 System Model

We assume that each packet is sent over a narrow-band, block-fading channel with additive noise [9]. To simplify our discussion, we assume the block length is equal to the packet transmission time. We consider a discrete-time model, where each time unit corresponds to the block length. After every time step, the transmitter receives new CSI, independent of whether a transmission attempt was made or not. The CSI takes on values from a finite set $\Theta = \{\theta_1, \theta_2, \cdots, \theta_M\}$. Figure 1 shows packet transmission during the n^{th} block. The channel is assumed to have a fixed propagation delay, I. The transmitter obtains feedback from the receiver on the packet delivery status. In addition to this, the CSI during that block $\theta^{(n)}$ is also provided in the feedback. If the transmitted packet was in error, it is retransmitted according to the ARQ protocol employed. Now, the received signal $Y^{(n)}(t)$ and the transmitted signal $X^{(n)}(t)$ can be related as,

$$Y^{(n)}(t) = \sqrt{H^{(n)}} X^{(n)}(t) + Z^{(n)}(t), \tag{1}$$

where $Z^{(n)}(t)$ is the additive noise process and $H^{(n)}$ models the channel fading. The fading levels are functions of the CSI obtained. For the Gaussian channel discussed in Sec. 4, CSI is assumed to provide the exact channel realization, (i.e), $\theta^{(n)} = H^{(n)}$; this model can be extended to other cases where the CSI parameterizes the distribution of the channel realization [10].

The transmission rate is fixed at R bits per second, and the transmission power is adapted for each packet. Let P_i denote the power allocated when the CSI has value θ_i. The probability a packet arrives in error depends on the transmitted power P_i and the available CSI, θ_i. We express this via a function $\rho(P_i, \theta_i)$. This function is assumed to be decreasing and convex in P_i; a specific example is given in Sec. 4.

We consider a case where the sequence of CSI values are modelled as a stationary, ergodic Markov chain. Let $p_\theta(\cdot)$ denote the steady-state probability distribution of $\{\theta_n\}$. The steady-state average probability of a successful transmission is given by

$$q = \sum_{i=1}^{M} (1 - \rho(P_i, \theta_i))\, p_\theta(\theta_i). \tag{2}$$

Similarly, the average power $\bar{P}$ expended is found to be,

$$\bar{P} = \sum_{i=1}^{M} P_i p_\theta(\theta_i). \tag{3}$$

2.1 Problem formulation

For most common ARQ protocols, the needed success probability q can be determined given a required average throughput of R'. For instance, consider a Go-Back-N protocol with large enough window size W_{sat} so that the transmitter never idles if packets are available [8] , (i.e),

$$W_{sat} = \frac{IR}{F} + 1, \tag{4}$$

where F is the frame size including all overhead. In this case, the needed success probability is given by

$$q = \frac{W_{sat}R'}{\frac{DR}{F} + (W_{sat} - 1)R'}. \tag{5}$$

where, D is the number of data bits in each packet. Given such a relation, the power allocation problem can be formulated as,

$$\begin{aligned} \min \quad & \bar{P} = \sum_{i=1}^{M} P_i p_\theta(\theta_i), \\ \text{s.t} \quad & \sum_{i=1}^{M} (1 - \rho(P_i, \theta_i)) p_\theta(\theta_i) = K_x(R'), \\ & P_i \geq 0, \quad \forall i, \end{aligned} \tag{6}$$

where $K_x(R')$ is a function that depends on the ARQ protocol employed. For instance, $K_{gb-n}(R') = q$ is given as in (5) for a Go-Back-N protocol. For a Stop-and-wait protocol [8],

$$K_{sw}(R') = \frac{R'(F + IR)}{DR}. \tag{7}$$

For a Selective Repeat protocol with large enough window size,

$$K_{SR}(R') = \frac{FR'}{DR}.$$

Let $P_x(R')$ denote the solution to (6) as a function of the required throughput R', for a given protocol. The function, $P_x(R')$ then describes the trade-off between power and throughput for that protocol. We note that the minimum energy per bit solution investigated in [4] can be interpreted as a particular value of $P_x(R')$. The optimal power policy adopted in (6) depends on the channel model and the error function studied. These in turn are chosen to describe specific applications and/or communication environments.

3 Time-invariant channels

3.1 Stationary Power Allocations

In this section we consider some preliminary results for the case where the CSI is a constant, θ_c, for all blocks. In formulating the power allocation problem in (6), we assume that the power assignment is only a function of current CSI value. In particular, this allocation does not depend on the transmission attempt. Next we show that there is no benefit to be gained if the allocation did vary with each retransmission attempt. This analysis is carried out for the case of a Stop-and-Wait protocol, but can easily be extended for other cases as well. Consider a two-level power allocation scheme with P_1 being the power used while transmitting the frame for the first time and P_2, the power used for every retransmission. Let $\rho_c(P_i)$ be the packet error probability as a function of the transmission power P_i, for all $i = 1, 2$. The average number of transmissions can be written as

$$\begin{aligned} N &= 1 \cdot [1 - \rho_c(P_1)] + \rho_c(P_1) \sum_{n=2}^{\infty} n \rho_c(P_2)^{n-2} [1 - \rho_c(P_2)] \\ &= 1 + \frac{\rho_c(P_1)}{1 - \rho_c(P_2)}. \end{aligned} \tag{8}$$

If the total power expended is denoted by P_t, the average power $\bar{P}$ is given by,

$$\bar{P} = \frac{E(P_t)}{N} = \frac{P_1}{N} + \frac{P_2(N-1)}{N}. \tag{9}$$

Notice that for a fixed throughput, N is a constant and in order to minimize $\bar{P}$, we require that constraint (9) be satisfied. From the first order optimality conditions we have,

$$\rho_c'(P_1^*) = \rho_c'(P_2^*). \tag{10}$$

Assuming the frame error function is *concave and monotonic increasing,* (10) holds if and only if, $P_1^* = P_2^*$. Therefore, equal power allocation proves optimal in this case. This can be further extended to a N-level power allocation scheme by an induction argument.

Lemma 1. *Let P_i be the transmission power used for the i^{th} transmission, i=1,2,$\cdots$, then all P_i's need to be equal, in order that the average power is minimized.*

Intuitively, this result is to be expected, as the problem can be viewed as an average-cost Markov decision problem. Since the number of states are finite, it is known that a stationary policy is optimal.

3.2 Comparison of Stop-and-Wait and Go-back-N

In this section, we study the relative performance of the optimal power policies chosen for Stop-and-Wait and Go-Back-N to achieve a given throughput R', namely $P_{sw}(R')$ and $P_{gb-n}(R')$. However, Go-Back-N would employ on an average $P_{gb-n}(R')$ to transmit each of the W_{sat} packets in it's current window. On the other hand, Stop-and-Wait utilizes $P_{sw}(R')$ to transmit a single packet in the same time period. To ensure a fair comparison, we look at the energy expended over a window, i.e, $P_{sw}(R')$ and $W_{sat}P_{gb-n}(R')$ respectively.

Lemma 2. *While allocating power optimally to a Stop-and-Wait and a Go-back-N protocol operating over a channel with a single CSI state θ, there exists R' such that*

$$P_{sw}(R') < W_{sat}P_{gb-n}(R'), \quad \forall \quad R' < \frac{DR}{F}.$$

Proof: The Power allocation problem for the two protocols can be formulated as

Stop-and-Wait	Go-Back-N
min $\;P_{sw}(R')$,	min $\;W_{sat}P_{gb-n}(R')$,
s.t $\;1-\rho(P_{sw}(R'),\theta) = K_{sw}(R')$,	s.t $\;1-\rho(P_{gb-n}(R'),\theta) = K_{gb-n}(R')$,
$P_{sw}(R') \geq 0$.	$P_{gb-n}(R') \geq 0$.

In order that Stop-and-wait is power efficient than Go-back-N, it must be that ,

$$\rho^{-1}(1-K_{sw}(R')) < W_{sat}\rho^{-1}(1-K_{gb-n}(R')). \tag{11}$$

Since ρ^{-1} is convex we have

$$\rho^{-1}(\lambda(1-K_{gb-n}(R')) + (1-\lambda)(0)) \;<\; \lambda\rho^{-1}(1-K_{gb-n}(R')) + (1-\lambda)\rho^{-1}(0) \tag{12}$$

From (11) and (12), it is sufficient to show that

$$\rho^{-1}(1-K_{sw}(R')) \;<\; \rho^{-1}(W(1-K_{gb-n}(R')))$$

Since $\rho^{-1}(\cdot)$ is monotone increasing, from (5) and (7)

$$P_{sw}(R') \;<\; WP_{gb-n}(R'), \quad \forall \quad R' < \frac{DR}{F}, \tag{13}$$

as desired. □

Thus, for certain cases with a low enough power requirement, Stop-and-Wait will have a higher throughput than Go-Back-N. This can be contrasted with a wire-line network, in which Go-Back-N will always have a higher throughput. The reason for this is that Go-Back-N sends all packets in the current window, before sliding back. When the power is low and error rates are high, successive packets are thrown out, leading to a loss of energy. We note that as in a wireline network, a Selective Repeat protocol will always have a higher throughput than either Go-Back-N or Stop-and-Wait.

4 Gaussian channels

Now consider a model based on the error probability for Gaussian channels with fixed modulation and coding scheme. The CSI is assumed to provide the exact channel realization.When the channel realization during a particular block is h and the transmission SNR is ν, consider an error function given as

$$\rho(\nu, h) = k_1 e^{-k_2 h \nu}, \quad \forall \quad \nu \geq \bar{\nu}, \tag{14}$$

where k_1 and k_2 are constants that depend on the type of modulation scheme employed. We assume that the minimum received SNR in each state is a constant. This in turn corresponds to a minimal SNR value $\bar{\nu_i}$ that the transmitter can use in the state i. To use SNR values below $\bar{\nu_i}$ we allow the transmitter to randomly timeshare, i.e, when the transmission SNR falls below the threshold $\bar{\nu_i}$, transmission is suspended with a certain probability, or else, the power level is fixed at $\bar{\nu_i}$. If ν_i be the transmission power employed when the CSI is h_i, then the error probability is given as

$$\rho(\nu_i, h_i) = \begin{cases} 1 - \frac{\nu_i}{\bar{\nu_i}}(1 - \rho(\bar{\nu_i}, h_i)), & \text{if } \nu_i < \bar{\nu_i}, \\ k_1 e^{-k_2 h_i \nu_i}, & \text{if } \nu_i \geq \bar{\nu_i}. \end{cases} \tag{15}$$

4.1 Throughput Analysis

Consider a channel with two equally likely and independent states and gains $h_1 > h_2$. The power allocation problem in (6) can be formulated in terms of the transmission SNRs (equivalently powers) in each state. The optimal power policy is characterized below as a function of the average throughput requirement R'.

Low Power scenario

Proposition 1. *When* $K_x(R') < \frac{1-\rho(\bar{\nu_1}, h_1)}{2}$, *the powers allotted in the two channel states are*

$$\nu_1 = \frac{2K_x(R')\bar{\nu_1}}{1 - \rho(\bar{\nu_1}, h_1)} \quad ; \quad \nu_2 = 0. \tag{16}$$

Proof : For the optimal allocation, the success probability in h_1 should clearly be larger than in h_2. Hence for $K_x(R')$ in the above range we have from $\nu_i \leq \bar{\nu_i}$ for $i = 1, 2$. Therefore from (15),

$$\rho(\nu_i, h_i) = 1 - \frac{\nu_i}{\bar{\nu_i}}(1 - k_1 e^{-k_2 h_i \bar{\nu_i}}), \quad \forall \quad i = 1, 2. \tag{17}$$

If power is to be split in both channel states, then the first order optimality conditions are violated. Therefore, the strategy is to suspend transmission in the worse state. □

Proposition 2. *When* $\frac{1-\rho(\bar{\nu_1}, h_1)}{2} < K_x(R') < \left(\frac{1}{2} - \frac{1-\rho(\bar{\nu_2}, h_2)}{2k_2 h_1 \bar{\nu_2}}\right)$, *the powers allotted become*

$$\nu_1 = \frac{1}{k_2 h_1} \ln\left(\frac{k_1}{1 - 2K_x(R')}\right) \quad ; \quad \nu_2 = 0. \tag{18}$$

Proof : For $K_x(R') > \frac{1-\rho(\bar{\nu_1},h_1)}{2}$, if power is allotted only in state one, then we have $\nu_1 > \bar{\nu_1}$ and

$$\rho(\nu_1, h_1) = k_1 e^{-k_2\nu_1 h_1} \quad ; \quad \rho(\nu_2, h_2) = 1$$

This results in the power allocation form given in (18). This allocation can be shown to be optimal provided $K_x(R') < \left(\frac{1}{2} - \frac{1-\rho(\bar{\nu_2},h_2)}{2k_2h_1\bar{\nu_2}}\right)$

High Power scenario

Proposition 3. *When* $\left(\frac{1}{2} - \frac{1-\rho(\bar{\nu_2},h_2)}{2k_2h_1\bar{\nu_2}}\right) < K_x(R') < \left(\frac{2-\rho(\bar{\nu_2},h_2)}{2} - \frac{1-\rho(\bar{\nu_2},h_2)}{2k_2h_1\bar{\nu_2}}\right)$, *the powers allotted become*

$$\nu_1 = \frac{1}{k_2h_1}\ln\left(\frac{k_1k_2h_1\bar{\nu_2}}{1-\rho(\bar{\nu_2},h_2)}\right). \tag{19}$$

$$\nu_2 = \frac{2K_x(R') - 1 + \frac{1-\rho(\bar{\nu_2},h_2)}{k_2h_1\bar{\nu_2}}}{1-\rho(\bar{\nu_2},h_2)}\bar{\nu_2}. \tag{20}$$

Proof : The Kuhn-Tucker conditions yields

$$k_1k_2h_1e^{-k_2h_1\nu_1} = \frac{1}{\bar{\nu_2}}(1-\rho(\bar{\nu_2},h_2)).$$

$$k_1e^{-k_2\nu_1h_1} + 1 - \frac{\nu_2}{\bar{\nu_2}}(1-\rho(\bar{\nu_2},h_2) = 2 - 2K_x(R').$$

Therefore, the solution forms in (20) and (21) holds. □

Proposition 4. *When* $\left(\frac{2-\rho(\bar{\nu_2},h_2)}{2} - \frac{1-\rho(\bar{\nu_2},h_2)}{2k_2h_1\bar{\nu_2}}\right) < K_x(R') < 1 - \frac{\rho(\bar{\nu_2},h_2)}{2}\left(1+\frac{h_2}{h_1}\right)$, *the powers allotted are*

$$\nu_1 = \frac{1}{k_2h_1}\ln\left(\frac{k_1}{2-2K_x(R')-\rho(\bar{\nu_2},h_2)}\right). \tag{21}$$

$$\nu_2 = \bar{\nu_2}. \tag{22}$$

Proof : The solution form follows from the equality constraint in (6). □

Proposition 5. *When* $K_x(R') > 1 - \frac{\rho(\bar{\nu_2},h_2)}{2}\left(1+\frac{h_2}{h_1}\right)$, *the optimal solution is*

$$\nu_1 = \frac{1}{k_2h_1}\ln\left(\frac{k_1(1+\frac{h_1}{h_2})}{2-2K_x(R')}\right) \tag{23}$$

$$\nu_2 = \frac{1}{k_2h_2}\ln\left(\frac{k_1(1+\frac{h_2}{h_1})}{2-2K_x(R')}\right) \tag{24}$$

Proof : This follows from the first order conditions. □

Numerical results:
The Stop-and-wait protocol described in the previous sections, is assumed to operate over a 500 Khz channel. Transmission takes place at 0.25 bits per channel use and a M-PAM constellation is employed. Figure 2 shows the power policies adopted in moderately and severely fluctuating channels. The plot is shown on a logarithmic scale. The dips observed in the curve correspond to the throughput requirements where transmission power needs to be split in both the channel states. Till about 50 percent peak efficiency, transmission is suspended in the bad channel state. As throughput requirements increase, the performance of the severely fluctuating channel worsens. The savings obtained from this scheme seems appreciable as compared with an equal-power-splitting approach.

As before we compare the energy consumptions of the Go-Back-N and Stop-and-Wait protocols, i.e, $P_{sw}(R')$ and $WP_{gb-n}(R')$ respectively. Note that power is allotted only in a single channel state under Proposition 1 and Proposition 2. Therefore Lemma 2 holds in both cases. This result can be formalized as follows.

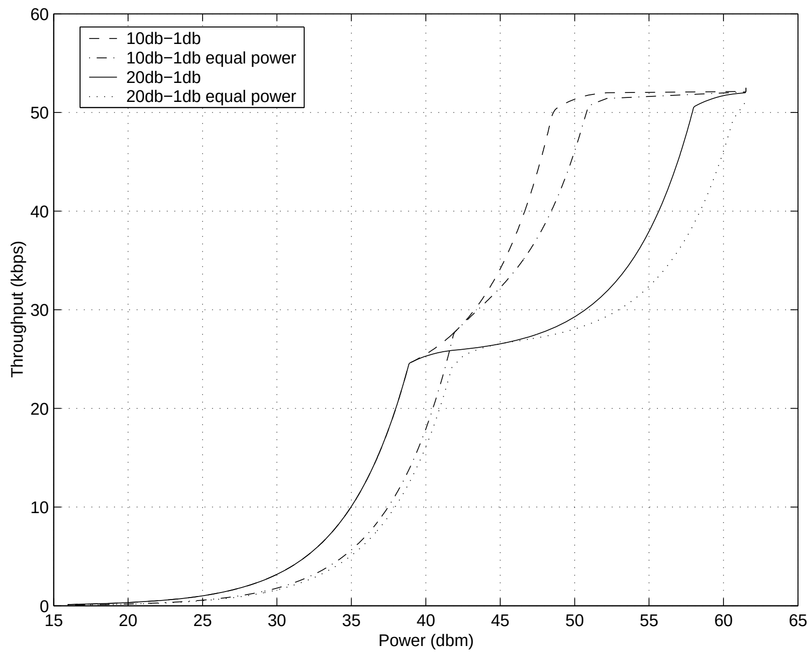

Figure 2: Fading Comparisons over Gaussian channel

Proposition 6. *While allocating power optimally to a Stop-and-Wait and a Go-back-N protocol operating over a channel with an i.i.d fading channel, there exists R' such that,*

$$P_{SW}(R') < WP_{gb-n}(R'), \quad \forall \quad K_x(R') < \min\left(\frac{1}{2} - \frac{1-\rho(\bar{\nu_2}, h_2)}{2k_2 h_1 \bar{\nu_2}}, \frac{DR}{F}\right).$$

Note that this can be extended to more general channel models as well.
Fig. 3 shows a comparative plot between Stop-and-Wait and Go-Back-N protocols. Two packets are assumed to fill the channel. The peak throughput obtained from the Stop-and-Wait protocol is about 52 Kbps. Stop-and-wait is shown to be power efficient than Go-back-N till about a throughput requirement of 26 Kbps. The plot also shows a large benefit in power over a Go-Back-N protocol that employs equal power in all channel states.

4.2 Delay Analysis

In some applications we may need to guarantee an average delay for each packet, while efficiently utilizing power. We study the case where packets arrive from a Poisson source at an average rate λ packets per time slot, (i.e) one time unit is $(\frac{F}{R} + I)$ seconds. Here each time slot is assumed to include the packet transmission time as well as round trip propagation delay. The packets are buffered at the transmitter and constrained to have an average packet delay T_p. The packet losses are assumed to be i.i.d. The transmitter's queue then can be modelled as a M/G/1 queue with the service time distribution X given as [7],

$$P\left(X = kW + 1\right) = q(1-q)^k, \quad k = 0, 1, 2 \cdots.$$

$$\text{So,} \quad \bar{X} = 1 + \frac{W(1-q)}{q}, \tag{25}$$

$$\bar{X^2} = 1 + \frac{(W^2 + 2W)(1-q)}{q}, \tag{26}$$

where q is the average probability of a successful transmission. The average packet delay is given by the Pollaczek-Khinchin formula as

$$T_p = \left(\bar{X} + \frac{\lambda \bar{X^2}}{2(1-\lambda\bar{X})}\right)\left(\frac{F}{R} + I\right). \tag{27}$$

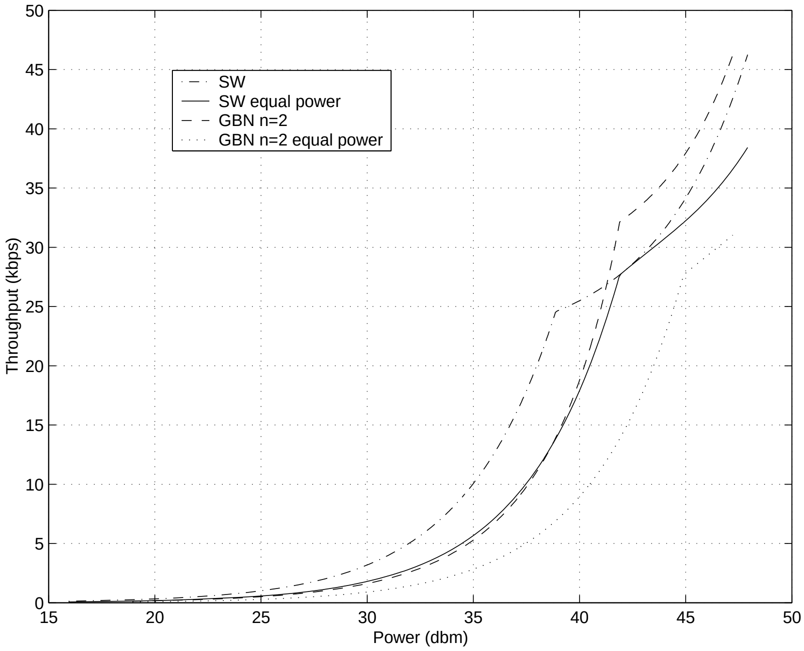

Figure 3: SW vs GBN - Gaussian channel

For Stop-and-Wait or Go-back-N operating over a Gaussian channel with two equally likely and independent states, the power allocation problem can be written as

$$\begin{aligned} \min \quad & \bar{\nu} = \frac{\nu_1 + \nu_2}{2}, \\ \text{s.t} \quad & \rho(\nu_1, h_1) + \rho(\nu_2, h_2) = 2 - 2K_{del,x}(\lambda, T_p), \\ & \nu_1 \geq 0, \quad \nu_2 \geq 0. \end{aligned} \tag{28}$$

Note that the structure of this problem is similar to (6). As in Sec. 3, we are restricting ourselves to power allocations that depend only on the channel state ; for the delay-constrained case we note that such a restriction is not optimal. Here $K_{del,x}(\lambda, T_p)$ is specific to the protocol employed and can again be interpreted as the average probability of a successful transmission. It follows that

$$0 \quad \leq \quad K_{del,gbN}(\lambda, T_p) \quad \leq \quad 1. \tag{29}$$

For a Go-Back-N protocol employing a window size W, using (27),(28) and (29) it can be shown that

$$K_{del,gbN}(\lambda, T_p) = \frac{\frac{2W}{\lambda} + W^2 - 2W + 2WT_p}{\frac{2T_p}{\lambda} + (W-1)^2 - 2T_p(W-1)}. \tag{30}$$

From (31) and (32), it follows we must have

$$\lambda \quad < \quad \frac{2T_p - 2W}{4WT_p - 2T_p - 1}. \tag{31}$$

Setting $W = 1$, the protocol constant for Stop-and-Wait is,

$$K_{del,SW}(\lambda, T_p) = \frac{2T_p\lambda + 2 - \lambda}{2T_p}. \tag{32}$$

The solution form for a two state i.i.d fading channel can be obtained as in Sec. 4.1. As before, for high delay requirements, the optimal strategy would involve suspending transmission in the bad channel. This constrains

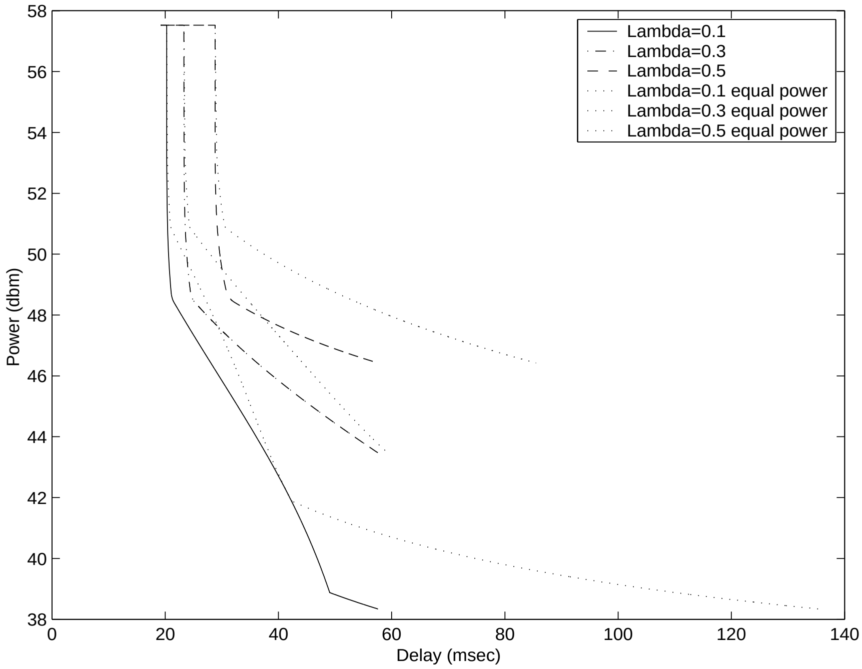

Figure 4: Effect of Arrival rate

the protocol constant to be less than 0.5. Therefore the arrival rate is bounded as

$$\lambda \quad < \quad \frac{T_p - W}{\frac{(W-1)^2}{2} - 1 + 3WT_p - T_p}. \tag{33}$$

In other words, for arrival rates larger than this, the power needs to be split in both channels for all delay requirements.

Figure 4 gives the power policy adopted by the Stop-and-Wait protocol described in the previous sections, for various arrival rates. This is compared with an equal power splitting approach. There seems to be considerable benefit in employing this scheme, especially when the delay requirement is relaxed and arrival rates are low. Power efficiency comparisons between Stop-and-Wait and Go-Back-N similar to Sec 4.1 are currently being investigated.

5 Conclusions

This paper discussed optimal power allocation schemes for ARQ protocols operating over fading channels and constrained by QOS requirements. The optimal power policy enhances performance as compared to a simple equal-power transmission scheme. The relative performance of the policies adopted by Stop-and-Wait and Go-Back-N protocols was also studied. It was shown that Stop-and-Wait is power efficient over a range of throughput requirements. This is an interesting result in the context of wireless channels, particularly because Stop-and-Wait is always less efficient in a wireline scenario. Finally, the power policy adopted while constrained by delay requirements was considered. Results similar to the throughput case were discussed.

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