Channel Adaptive Stop-and-Wait ARQ Protocols for Short-Range Wireless Links

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Abstract

In the link layer frame retransmission strategies, the short-term variation of physical channel properties has not been fully exploited. To combat the negative impact of fading, channel memory can be used to make intelligent predictions about the upcoming channel state and frame retransmission timings can be adapted based on these predictions. In this paper, two variants of simple yet efficient channel-adaptive stop-and-wait retransmission schemes are proposed for short-range wireless networks, wherein the transmitter node learns about the channel condition from the immediate past response of the receiver to adapt the next frame retransmission timing. Using Markov channel model, performance of the competitive stop-and-wait protocols are captured. It is shown that, with a suitably chosen frame retransmission timing, the proposed schemes fair better than the existing stop-and-wait retransmission schemes in terms of reduced energy consumption with a nominal data delivery rate trade-off. The performance gain is significant particularly in the harsh fading conditions.

Index Terms

Stop-and-wait ARQ, fading, channel probing, channel adaptive transmission, energy saving

I. Introduction

The features unique to the communication between wireless nodes are high error rates, randomly time varying link characteristics, and limited battery life of communicating nodes. To deal with all these constraints, we need to have error control strategies which are energy efficient and channel adaptive. The classical error control schemes fall in two categories: automatic repeat request (ARQ) and forward error correction (FEC). ARQ scheme, is preferred where a return channel is available and the delay requirements are not stringent. Conventional ARQ protocols, namely, stop-and-wait (SW), go-back-n (GBN), and selective repeat (SR), are channel unaware. In the event of an error, they continue to retransmit the erroneously received frames regardless of the channel condition, until the frames are received correctly.

In GBN and SR protocol studies by Lu and Chang [1], error dependency was studied for Markovian-k channel and gap error based channel. In a time varying channel, SR protocol performance was studied by Kim and Krunz in [2] by accounting queuing, transmission, and resequencing delays. Chakraborty et al. [3] studied adaptive GBN protocol, where time varying channel was characterized using Gilbert-Elliot model. A similar approach of sending multiple copies of a frame was studied for SW protocol by Benelli [4]. Efficiency of GBN protocol reduces sharply with high error rate, whereas SR is much complex and requires theoretically infinite resequencing buffer at the receiver. Hence, there is also a need for the SW protocol in applications with low complexity requirements.

Delay performance of SW protocol was studied by De Vuyst et al. [5] where the channel errors were modeled using a two-state Markov chain. In [6], Li and Zhao studied the resequencing buffer behavior of SW protocol with multiple parallel channels. To efficiently adopt SW protocol in systems with large propagation delay, Benelli and Garzelli [7] proposed dividing a frame into small codewords and retransmit only the uncorrectable ones. The additional delay and memory overheads and energy efficiency in view of frame splitting, individual codeword processing, and re-sequencing were not studied. Also, usefulness of this approach in short-range communications with slow fading channel is expected to be limited. All the above link layer approaches waste the energy in blind retransmissions during ‘bad’ channel states.

In order to increase link layer throughput in presence of wireless channel fading, adaptive modulation and coding (AMC) scheme was studied at the physical layer in [8]–[13]. In AMC, in deep fading states there is a provision for not sending data payload (known as mode 0). Yet, under severe channel condition, mode 0 transmission still wastes energy. To improve system reliability and throughput over dynamic wireless channels, a combination of FEC and ARQ – called hybrid ARQ (HARQ) [14] – is commonly used. HARQ is used for packet retransmission, modulation adaptation, and transmit antenna selection process incorporated in an adaptive modulation system combined with selection transmit diversity [15]–[17]. In these schemes also, under severe channel condition, nodal energy is wasted in blind retransmissions.

Some research studies have addressed channel awareness in link layer retransmissions [18]–[21]. The main principle of these protocols is to adapt transmissions with the past success rate. Guth and Ha [18] proposed an error feedback dependent frame size adaptation in SW ARQ protocol with the intuitive understanding that a smaller frame has a higher probability of successful reception over an error-prone channel. In this protocol, after a certain number of retransmission attempts the frame size is reduced to the next smaller size, and similarly after a certain number of consecutive successes the frame size is increased to the next higher size. A probing based data frame retransmission approach in GBN and SR was proposed by Zorzi and Rao in [19], where in the event of a negative acknowledgment (NAK) for a data frame, the transmitter starts sending short probing frames until an ACK (acknowledgment) is received. The count of successive ACKs or NAKs was considered by Minn et al. [20] to determine the channel state - ‘good’ or ‘bad’, and accordingly the channel coding was switched between ‘low error rate’ mode and ‘high error rate’ mode. In the channel adaptive approach by Kumar et al. [21], a stochastic learning control algorithm was used to determine the transmission probability of data frames, where, at any time the next frame transmission probability is increased (respectively, decreased) if an ACK (respectively, a NAK) for the previous frame is received.

In short-range wireless communication environments, e.g., wireless local area networks and sensor networks, propagation delays among communicating nodes are relatively very small. In such networks, a SW retransmission scheme is more appropriate than GBN and SR schemes because of its simplicity, which is important for wireless nodes with rudimentary capabilities. In this work we investigate the channel aware SW ARQ strategies under correlated channel error conditions with a view of energy saving. We note that, given a wireless communication environment, the channel parameters may be known a priori and a waiting time could be suitably chosen in bad channel states, which was not considered in the prior approaches. Particularly, although the probing approach in [19] aims at energy saving by refraining from data frame transmission in the bad channel states, it did not characterize the probing periodicity with respect to the channel properties. Similarly, while the adaptive learning approaches adjust the frame size (in [18]) or the transmission timing (in [21]) with the reception rate, these protocols do not have a direct influence of the channel fading state. In contrast, our proposed adaptive ARQ approaches adjust the next transmission timing instant deterministically by exploiting partially or fully the channel state information.

We propose two variants of channel adaptive SW ARQ schemes, namely, channel-aware probing (CAP) and channel-aware stop-and-wait (CASW), wherein the transmitter senses the fading channel condition by received ACK/NAK frames and refrains from transmitting when the channel is possibly impaired. Taking Rayleigh distributed slow fading channel as an example of wireless channel with memory, performance of the proposed schemes are analyzed and contrasted with that of the conventional SW, channel oblivious probing (COP) scheme [19], as well as stochastic learning based approach [21]. We show that, when only binary feedback (ACK/NAK) about the channel condition is available at the transmitter, waiting for an average fading duration (AFD) before sending the probing frames or retransmitting a data frame helps in significant energy saving. Additionally we show that, if the received signal strength information is available at the transmitter via the NAK frames, by appropriately reducing the probing intervals in CAP, the data frame success rate can be increased without compromising on the energy saving performance. A preliminary simulation based study on CAP protocols was presented in [22]. In the current work, besides modifying the CAP protocols to address the implementation feasibility, the CASW protocol is introduced and detailed mathematical analyses of the proposed protocol variants are provided.

II. Channel Model

We consider the envelope of the received signal over the wireless channel is Rayleigh distributed. Following the observations in [23]–[25] on first-order Markov approximation of block fading channel and packet-level binary error characterization over Rayleigh fading channel in [19], in this paper the wireless channel fading envelope is modeled as a two-state binary Markov process, as shown in Fig. 1.* The channel is in 'good' state (state '1') if the received signal-to-noise ratio (SNR) is above a certain

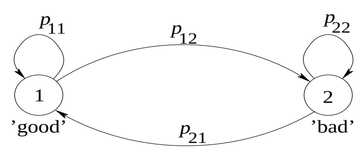


Fig. 1. System state transition diagram for wireless channel.

threshold during a frame reception time. This is true when an ACK is received on the reverse channel. If a NAK is received, or if the ACK/NAK frame is corrupted or lost, the channel is considered to be in 'bad' state (state '2'). In our model, for simplicity we assume a reliable feedback channel, i.e., for a short ACK/NAK frame transmission, the reverse channel is error-free. Accommodating the effect of unreliable reverse channel can be done similarly as in [19]. The patterns of the frame errors is described by the transition matrix $M(x) = M(1)^x$ with

$$M(x) = \begin{bmatrix} p_{11}(x) & p_{12}(x) \\ p_{21}(x) & p_{22}(x) \end{bmatrix} \text{ and } M(1) = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix},$$

where $p_{11}(x) = 1 - p_{12}(x)$ (respectively, $p_{21}(x) = 1 - p_{22}(x)$) is the probability that slot i is 'good' given that slot $i - x$ was 'good' (respectively, 'bad').

*As in [26], a two-state Gilbert-Elliot model can also be used to characterize the burst error process, where each state has an associated error probability.

For Rayleigh fading channel, p_{21} and steady state error probability in a slot ε (and hence p_{11}) were computed in [23] in terms of fading margin F (ratio between the average received SNR and the SNR threshold for a 'good' state), Doppler frequency f_D, and time slot duration s, which are given by:

$$\varepsilon = 1 - e^{-\frac{1}{F}},\ p_{11} = 1 - \frac{p_{21}\varepsilon}{1-\varepsilon},\ \text{and}\ p_{21} = \frac{Q(\theta, \sigma\theta) - Q(\sigma\theta, \theta)}{e^{\frac{1}{F}} - 1},$$

where $Q(\cdot,\cdot)$ is the Marcum Q function, $\theta = \sqrt{\frac{2}{F(1-\sigma^2)}}$, $\sigma = J_0(2\pi f_D|s|)$ is the correlation coefficient of two successive samples of the complex amplitude of a fading channel with Doppler frequency f_D, observed at time interval s, and $J_0(\cdot)$ is the Bessel function of the first kind and zeroth order.

III. Analysis of Stop-and-Wait ARQ Protocols

General assumptions are: the data transfer is one-way, frames are always available for transmission, the communication is slotted, and as per the basic SW ARQ principle, every data frame is acknowledged.

The duration of a data frame T_f is considered such that it is smaller than the coherence time of the fading channel. Accordingly, following [12], [13], [19], [27], [28], to simplify the analytical expressions without loss of generality, in this paper we consider $T_f = s$ sec, i.e., the data frame is of constant size, single slot long. The ACK/NAK as well as probing frame duration T_p is very small compared to T_f, i.e., $T_p = \eta T_f$ where $\eta \ll 1$. The interval between two data frame transmission attempts is m slots, where $m \geq 1$. Hence, the ACK/NAK frame transmission interval is m slots.

Performance of an ARQ protocol is defined in terms of *data throughput* $\mathcal{R}$ and *energy consumption* $\mathcal{E}$. $\mathcal{R}$ is defined as the long-term average number of successfully delivered data frames per second:

$$\mathcal{R} \triangleq \lim_{t\to\infty} \frac{E\{\text{number of data frames successful in time } t\}}{t}. \tag{1}$$

$\mathcal{E}$ is the consumption per successful data frame, defined in terms of battery energy consumed (in Joules), including transmit and receive energy per data frame e_d, transmit and receive energy per ACK/NAK frame e_a, per slot idling energy e_w, and per slot total energy consumption e_p per probing frame.

A. Basic SW

Here, a data frame is transmitted in every m slots. m-step transition probabilities are obtained as:

$$p_{11}(m) = \frac{[p_{21} + (1 - p_{21} - p_{12})^m p_{12}]}{p_{21} + p_{12}}, \qquad p_{21}(m) = \frac{p_{21}\,[1 - (1 - p_{21} - p_{12})^m]}{p_{21} + p_{12}}.$$

Definition 1: (*SW cycle*) The length of a cycle in basic SW protocol is defined as the duration starting from an unsuccessful frame to the end of its successful transmission.

Thus, in a SW cycle all but the last transmission attempt are unsuccessful. Denote the number of frame transmissions in one cycle by the random variable (RV) $\mathbf{K}$. The average $E\{\mathbf{K}\}$ is given by:

$$E\{\mathbf{K}\} = \sum_{\kappa=1}^{\infty} \kappa \cdot \Pr[\mathbf{K} = \kappa], \tag{2}$$

in which only one frame is successful. $\Pr[\mathbf{K} = \kappa]$ in (2) is obtained as:

$$\Pr[\mathbf{K} = \kappa] = \begin{cases} p_{11}(m) & \text{for } \kappa = 1 \\ p_{12}(m)\,[p_{22}(m)]^{\kappa-2}\,p_{21}(m) & \text{for } \kappa \geq 2. \end{cases} \tag{3}$$

Hence, substituting (3) in (2) and simplifying, we obtain,

$$E\{\mathbf{K}\} = \frac{p_{12}(m) + p_{21}(m)}{p_{21}(m)}.$$

Since a SW cycle has only one successful data frame, by (1) and (2), the throughput of basic SW is:

$$\mathcal{R}_{SW} = \frac{1}{E\{\mathbf{K}\} \cdot m \cdot s}.$$

The energy consumed per successful data frame in basic SW approximately given by:

$$\mathcal{E}_{SW} = E\{\mathbf{K}\}\left[e_d + e_a + (m-1)e_w\right], \tag{4}$$

where, in accounting idling energy consumption, time taken due to ACK transmission is considered negligibly small, since $T_p \ll s$.

B. Channel Oblivious Probing (COP) based SW

In this approach, once a NAK is received, the transmitter enters into probing mode, with a periodicity independent of the fading margin [19]. The probing frames are continued until a probing ACK is received.

Let t_p be the probing periodicity in number of slots, and the number of probing frames (a RV) per probing cycle be $\mathbf{P}$. The average number $E\{\mathbf{P}\}$ in a set of contiguous probing is:

$$E\{\mathbf{P}\} = \sum_{\phi=1}^{\infty} \phi \cdot \Pr[\mathbf{P} = \phi]. \tag{5}$$

Using t_p-state transition probabilities, we have,

$$\Pr[\mathbf{P} = \phi] = \left[p_{22}(t_p)^{(\phi-1)} p_{21}(t_p)\right], \tag{6}$$

and hence, after simplifying,

$$E\{\mathbf{P}\} = \frac{1}{p_{21}(t_p)}. \tag{7}$$

Definition 2: (*COP cycle*) The length of a cycle in COP based SW is defined as the duration between two probing phases, which gives a single probing ACK.

Thus, if a COP cycle starts after a probing ACK, out of subsequent $\mathbf{K}$ data frame transmissions (which is a RV), all but one are successful, which is followed by $E\{\mathbf{P}\}$ number of probing frames on average. To find $E\{\mathbf{K}\}$, as defined in (2), we now have,

$$\Pr[\mathbf{K} = \kappa] = \begin{cases} 0 & \text{for } \kappa = 1 \\ p_{11}(m)^{(\kappa-2)} p_{12}(m) & \text{for } \kappa \geq 2. \end{cases}$$

which gives, after simplification,

$$E\{\mathbf{K}\} = \frac{1 + p_{12}(m)}{p_{12}(m)}. \tag{8}$$

A COP cycle contains one failed data frame transmission out of average $E\{\mathbf{K}\}$ attempts and $E\{\mathbf{P}\}$ probing frame transmissions. The total time spent in $E\{\mathbf{K}\}$ data frame attempts, including the last data NAK, is $[(E\{\mathbf{K}\} - 1)ms + s + T_p]$. The time spent in $E\{\mathbf{P}\}$ probing frame transmissions, including the last probing ACK, is $E\{\mathbf{P}\}t_p s + 2T_p$. Thus, from (1), the data throughput in COP based SW is:

$$\mathcal{R}_{COP} = \frac{E\{\mathbf{K}\} - 1}{(E\{\mathbf{K}\} - 1)ms + s + T_p + E\{\mathbf{P}\}t_p s + 2T_p}. \tag{9}$$

The energy consumed per COP cycle is that for sending $E\{\mathbf{K}\}$ data frames and $E\{\mathbf{P}\}$ probing frames. Accounting for the waiting period, and as in (4), neglecting the time taken in ACK/NAK and probing frame transmissions, the average energy consumed per successful data frame is approximately given by:

$$\mathcal{E}_{COP} = \frac{E\{\mathbf{K}\}(e_d + e_a) + (E\{\mathbf{K}\} - 1)(m-1)e_w + E\{\mathbf{P}\}\left(e_p + t_p e_w\right)}{E\{\mathbf{K}\} - 1}, \tag{10}$$

A proof of correctness of (6) and the developments thereafter is given in Appendix I.

C. *Channel Aware Probing (CAP) based SW*

In CAP, we propose to adapt the probing periodicity with the fading state. The analysis approach of CAP is similar to that of the COP protocol, but the probing interval t_p is now additionally a function of channel fading parameters. Depending on the availability of fading parameters we propose three variants.

1) CAP1: Here, in probing mode, we propose to wait for AFD (the average time between a negative crossing and the next positive crossing of the threshold power level by the instantaneous received power), which is a function of fading margin F and Doppler frequency f_D. Let $AFD(P_{th})$ be the AFD (in absolute time unit) of the channel corresponding to a power threshold P_{th}. For Rayleigh channel it is given by:

$$AFD(P_{th}) = \frac{e^{\rho^2} - 1}{\rho f_D \sqrt{2\pi}},$$

where $\rho = \sqrt{\frac{P_{th}}{\bar{P}_r}}$, and $\bar{P}_r$ is the average received power – a function of F. Define $\bar{A}_f$ as the AFD in time slot unit. Thus,

$$\bar{A}_f = \left\lceil \frac{AFD(P_{th})}{s} \right\rceil . \tag{11}$$

Data throughput $\mathcal{R}_{CAP1}$ is given by (9), (7), and (8), with t_p replaced by $\bar{A}_f$. Similarly, $\mathcal{E}_{CAP1}$ is given in (10) with t_p replaced by $\bar{A}_f$.

2) CAP2: Unlike in CAP1 protocol, in CAP2 we propose to adapt the probing periodicity with the average fading information as well as the current received signal strength that is fed back via the NAK frames. The intuition is that, with the knowledge of current channel fading state, the recovery interval can be decided more accurately, thereby reducing the time waste before a transmission attempt.

The possible values of received power can be $P_r = 0$ to ∞. The range of P_r of interest via NAK frames in CAP2 is 0 to P_{th}. So, when $P_r \leq P_{th}$, the signal level is quantized and sent via the NAK frame to the transmitter. Note that, while the channel state is still modeled as a two-state Markov process, the quantizer at the receiver-end is used only to facilitate the modified average waiting time calculations at the transmitter when the receiver determines that the channel state is 'bad'.

If L is the number of quantization levels, $\log_2 L$ bits are needed for the received power information feedback. Step size of the quantizer is $\delta = \frac{P_{th}}{L}$, with the i-th level, for $i = 0, 1, 2, \cdots, L-1$, located as:

$$\{Q_i, Q_{i+1}\} = \{i\delta \text{ to } (i+1)\delta\}.$$

Thus, at the i-th quantization level with $Q_i = i\delta$ and $L = \frac{P_{th}}{\delta}$, the output of the quantizer is $(Q_i + \frac{\delta}{2})$.

As the power feedback signifies the fading depth, referring to Fig. 2, if the point A indicates the current receive power level, the recovery is expected to be sooner than $AFD(P_{th})$ interval.

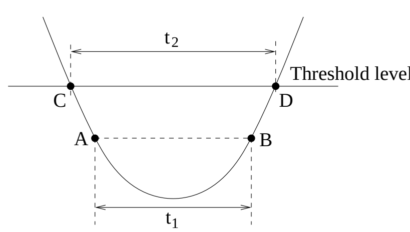


Fig. 2. Pictorial representation of fading process to decide on optimum probing process

Denote, $AFD(P_{th}) \triangleq \bar{t}_2$. If the point A lies in $\{Q_i,\ Q_{i+1}\}$, then the corresponding AFD (of the quantized feedback) is $AFD(Q_i + \frac{\delta}{2}) \triangleq \bar{t}_1$. In CAP2, with the quantized knowledge of the point A, the probing interval W_i is the remaining average time to recover from fading, which is given by,

$$W_i = \bar{t}_1 + \frac{\bar{t}_2 - \bar{t}_1}{2}. \tag{12}$$

For Rayleigh fading channel, the received power $\mathbf{P_r}$ at A (see Fig. 2) is exponentially distributed as:

$$p_{P_r}(r) = \frac{1}{\bar{P}_r} e^{-\frac{r}{\bar{P}_r}}. \tag{13}$$

Hence, considering error-free feedback, the probability p_i that the received power feedback is $Q_i + \frac{\delta}{2}$ is:

$$p_i = \int_{Q_i}^{Q_{i+1}} p_{P_r}(r)dr = e^{-\frac{Q_i}{\bar{P}_r}} - e^{-\frac{Q_{i+1}}{\bar{P}_r}}.$$

The corresponding conditional probability, given that a NAK is received, can be found as: $p_{i|nak} = \frac{p_i}{\sum_{i=0}^{L-1} p_i}$. Subsequently, the average probing period in CAP2 is:

$$E\{\mathbf{W}\} = \sum_{i=0}^{L-1} W_i \; p_{i|nak}.$$

The performance of CAP2 can be obtained similarly as follows. Throughput $\mathcal{R}_{CAP2}$ is given by (9), (7), and (8), with t_p replaced by $\left\lceil \frac{E\{\mathbf{W}\}}{s} \right\rceil$. Similarly, $\mathcal{E}_{CAP2}$ is given in (10) with t_p replaced by $\left\lceil \frac{E\{\mathbf{W}\}}{s} \right\rceil$.

3) CAP3: From Fig. 2 it can be noted that, there could be two possible situations. If the first probe results in a NAK, it is possible that the received signal level is improving, i.e., the channel state is at point B (but may be at a different level than that of A, which corresponds to a degrading state). However, probing at an average interval of $\left\lceil \frac{E\{\mathbf{W}\}}{s} \right\rceil$ slots cannot not capture the slope of signal quality variation.

In CAP3, we propose a heuristic that, for the received signal power in the i-th quantization level the first probing interval be $W_i^{(1)} = \bar{t}_1 + \frac{\bar{t}_2 - \bar{t}_1}{2}$ and the subsequent probings in that fading cycle be $W_i^{(2)} = \frac{\bar{t}_2 - \bar{t}_1}{2}$. Therefore, as in CAP2, the average waiting times can be computed as:

$$E\{\mathbf{W}^{(x)}\} = \sum_{i=0}^{L-1} W_i^{(x)} \; p_{i|nak} \text{ where } x = 1, 2.$$

Denote the average waiting time in number of slots as:

$$w_x \triangleq \left\lceil \frac{E\{\mathbf{W}^{(x)}\}}{s} \right\rceil, \text{ for } x = 1, 2. \tag{14}$$

To compute the average number of contiguous probings $E\{\mathbf{P}\}$ in a fading cycle, given by (5), we have,

$$\Pr[\mathbf{P} = \phi] = \begin{cases} p_{21}(w_1) & \text{for } \phi = 1 \\ p_{22}(w_1) p_{22}(w_2)^{(\phi-2)} p_{21}(w_2) & \text{for } \phi \geq 2. \end{cases}$$

Simplifying,

$$E\{\mathbf{P}\} = \frac{p_{21}(w_2) + p_{22}(w_1)}{p_{21}(w_2)}. \tag{15}$$

So, the expected total waiting time in CAP3 probing mode in a fading cycle $\mathbf{w_P}$ is:

$$E\{\mathbf{w_P}\} = \sum_{\phi=1}^{\infty} \{E\{\mathbf{W}^{(1)}\} + (\phi - 1)E\{\mathbf{W}^{(2)}\}\} \cdot \Pr[\mathbf{P} = \phi] = E\{\mathbf{W}^{(1)}\} + E\{\mathbf{W}^{(2)}\} \frac{p_{22}(w_1)}{p_{21}(w_2)}.$$

We note that a cycle in CAP3 is the same as a COP cycle, with the differences in $E\{\mathbf{P}\}$ and probing periodicity. The total time spent in $E\{\mathbf{K}\}$ data frame attempts, including the last data frame NAK, is $(E\{\mathbf{K}\}-1)\,ms+s+T_p$. The total time spent in $E\{\mathbf{P}\}$ probing frames, including the last probing ACK, is $\left\lceil\frac{E\{\mathbf{w_p}\}}{s}\right\rceil s+2T_p$, where $E\{\mathbf{K}\}$ is given in (8). Thus, from (1), the data throughput is:

$$\mathcal{R}_{CAP3}=\frac{E\{\mathbf{K}\}-1}{\Big[\big(E\{\mathbf{K}\}-1\big)ms+s+T_p\Big]+\left\lceil\frac{E\{\mathbf{w_p}\}}{s}\right\rceil s+2T_p}.$$

Accounting for the waiting period in each transmission attempt, and with the same approximation as in (4) and (10), the average energy consumed per successful frame is given by:

$$\mathcal{E}_{CAP3}=\frac{E\{\mathbf{K}\}(e_d+e_a)+\big(E\{\mathbf{K}\}-1\big)(m-1)e_w+E\{\mathbf{P}\}e_p+\left\lceil\frac{E\{\mathbf{w_p}\}}{s}\right\rceil e_w}{E\{\mathbf{K}\}-1},$$

where $E\{\mathbf{P}\}$ is obtained from (15).

D. CAP3a

In CAP3a, we aim to improve the data throughput further without significantly affecting the energy consumption performance. In CAP3 we tried to improve the data throughput by reducing the waiting time beyond the first probing frame retransmission. In CAP3a, we instead propose to reduce the waiting time for all probing frames by assuming (optimistically) that all fading scenarios correspond to the receiver power level at point B. Accordingly, the probing period in CAP3a is, $W_i=\frac{t_2-t_1}{2}$. With this reduced W_i, the system performance expressions in CAP3a are obtained similarly as in CAP2.

E. Channel aware SW (CASW) protocol

In this approach, the channel state is accounted for deciding the next *data* frame transmission instant. In 'good' state, when a ACK is received, the transmission periodicity is m slots. When a NAK is encountered (i.e., in 'bad' state), unlike in the CAP protocol, we propose that the transmitter keeps sending the data frames with a periodicity π, which is a function of channel fading and received feedback information. For example, in CASW1 with 1-bit NAK, $\pi=\bar{A}_f$, as defined in (11); in CASW3a with NAKs having received signal power information, $\pi=w_2$, as defined in (14). The data transmission periodicity is reverted to m slots as soon as a data ACK is received. This cycle continues with the channel fluctuations.

Definition 3: A *CASW cycle* is the duration between the ends of two consecutive lost data frames.

Thus, a CASW cycle contains $\mathbf{J}$ successful data frames ($\mathbf{J} \geq 0$, a RV), a lost frame, followed by a waiting period π after the data loss event. The expected value of $\mathbf{J}$, defined in (2), is obtained as follows:

$$P[\mathbf{J} = \xi] = \begin{cases} p_{22}(\pi) & \text{for } \xi = 0 \\ p_{21}(\pi)[p_{11}(m)]^{\xi-1} p_{12}(m) & \text{for } \xi \geq 1. \end{cases}$$

After substitution and simplification we have,

$$E\{\mathbf{J}\} = \frac{p_{21}(\pi)}{p_{12}(m)}.$$

The data throughput (defined in (1)) of the CASW protocol is given by:

$$\mathcal{L}_{CASW} = \frac{E\{\mathbf{J}\}}{(E\{\mathbf{J}\}ms + s + T_p) + \pi s},$$

where the first term in the denominator is the time spent in $(E\{\mathbf{J}\} + 1)$ frame transmissions and the second term is due to waiting π slots after the last transmission failure.

The energy consumption per successful frame is approximately given by:

$$\mathcal{E}_{CASW} = \frac{1}{E\{\mathbf{J}\}} \left[(E\{\mathbf{J}\} + 1)(e_d + e_a) + E\{\mathbf{J}\}(m-1)e_w + \pi e_w\right],$$

where the first consumption component in the numerator is due to $(E\{\mathbf{J}\} + 1)$ data frames, the second added term is due to $E\{\mathbf{J}\}$ intermediate waiting phases, and the third term accounts for the additional π slots waiting after the last (failed) data frame transmission.

IV. Numerical and Simulation Results

Performance of the SW protocol variants were studied numerically from the developed expressions in Section III, and the results were compared by implementing the ARQ protocols over the simulated fading channels in MATLAB. In simulation, the in-built Rayleigh channel model was used, where the received signal envelop is complex Gaussian distributed. Corresponding to a widely acceptable model for the Gaussian process, the power spectral density has a band limited non-rational spectrum [29],

$$S(f) = \begin{cases} S(0)\left[1 - \left(\frac{f}{f_D}\right)^2\right]^{-0.5} & \text{for } -f_D < f < f_D, \\ 0 & \text{otherwise.} \end{cases}$$

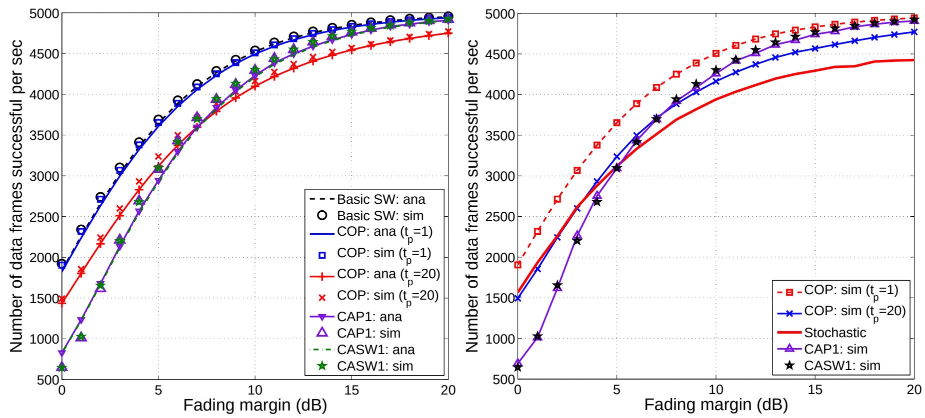
This spectrum has the associated correlation coefficient $\sigma(\tau) = J_0(2\pi f_D|\tau|)$, where τ is the time difference between two samples [29]. From the variation of σ as a function of $f_D|\tau|$ it was noted that [27], for $f_D|\tau| < 0.1$ the fading process is correlated, which corresponds to slow fading. In our performance study under slow fading conditions, we maintained $f_D|\tau| < 0.02$ and $\tau = s$, as in [27].

Typical system parameters were taken as follows: $f_D = 50$ Hz, slot size $s = 0.2$ ms, and $\eta = 0.1$. At the operating frequency of 1 GHz, $f_D = 50$ Hz corresponds to 54 kmph mobile speed and coherence time of 20 ms. Thus, the condition of constant channel state in a slot is easily met. $s = 0.2$ ms corresponds to 512 bits data frame size at 2.5 Mbps channel rate. For short range links, the propagation delay can be ignored. Accordingly, all results are drawn with $m = 1$, which neglects queueing and processing delays at the nodes. The energy consumption entities are obtained as: $e_d = T_f(i_t^2 + i_r^2)R$, $e_a = T_p(i_t^2 + i_r^2)R$, $e_w = 2i_w^2 sR$, and $e_p = 2T_p(i_t^2 + i_r^2)R + (s - 2T_p)2i_w^2 R$, where i_t, i_r, and i_w are the current consumptions in transmission, reception, and waiting (idling) modes, respectively, and R is the resistance of the circuit. These current consumption values were taken from Texas Instrument's CC1000 data sheet: $i_t = 17.4$ mA, $i_r = 19.7$ mA, and $i_w = 426$ μA. We considered normalized resistance, $R = 1$ Ω.

A. *Case 1: Binary feedback*

This case includes COP, CAP1, CASW1 (CASW with $\pi = \bar{A}_f$, defined in (11)), and stochastic learning based SW. In COP, two different probing periodicities are chosen: $t_p = 1$ corresponds to maximized data throughput, and $t_p = 20$ corresponds to a reduced energy consumption. We compare the performances of CAP1 and CASW1 with basic SW, COP, and stochastic learning based approaches. The numerical results match quite well with the simulated data. A slight mismatch at low fading margins could be due to the error introduced in first-order Markov model approximation of the fading channels.

1) Data throughput: Numerical and simulation results on throughput measure of the SW protocol variants are presented in Fig. 3. The results in Fig. 3(a) indicate that, binary feedback based channel aware SW protocols (CAP and CASW) have in fact the slowest performance. However, since energy saving is a more critical performance measure in low power and delay tolerant wireless applications, a little slowed down frame success rate would be possibly acceptable, provided a significant energy saving can be achieved. This is indeed the case with CAP1 and CASW1, as observed from the plots in Fig. 4. The plots in Fig. 3(b) indicate that, beyond a certain low value of fading margin, CAP1 and CASW1 have higher data frame success rates compared to COP with a high probing periodicity as well as compared to the stochastic learning approach. Also, the throughput performance of COP based SW is observed to have a strong impact of probing periodicity t_p. At a low t_p, its throughput is comparable to that of the basic SW. On the other hand, if t_p is set high, the throughput of COP base SW is not only inferior to the basic SW, it is also poorer than CAP1 and CASW1 above a certain fading margin. This is because, in COP a fixed t_p implies increasingly unnecessary waiting as the fading margin is increased under the same channel fading condition. As an example, at $f_D = 50$ Hz, $\bar{A}_f = 20$ slots corresponds to 7 dB fading

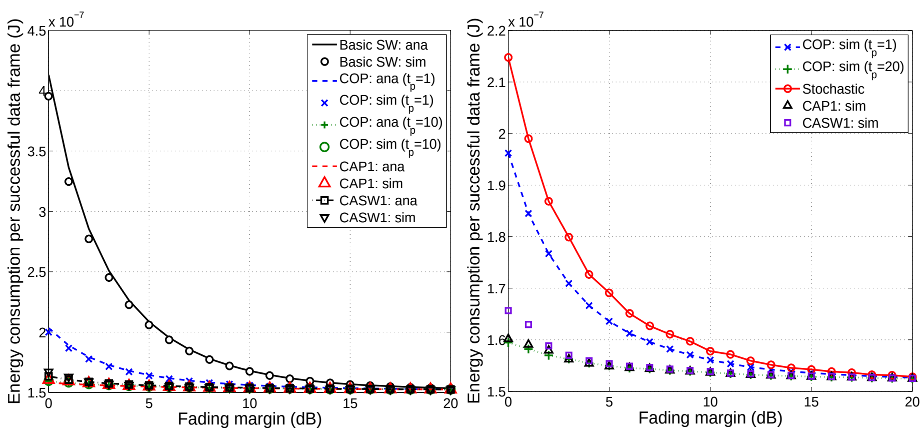


(a) Comparison with basic SW and COP (b) Physical layer aware approaches

Fig. 3. Comparison of throughput performance with binary feedback.

margin. Fig. 3(b) shows that, the throughputs of CAP1 and CASW1 improve beyond that of COP with $t_p = 20$ at about 7 dB fading margin. This observation signify that, waiting beyond $\bar{A}_f$ is not beneficial to the system throughput. A poorer throughput performance of CAP1 and CASW1 below 7 dB fading margin also indicate that, *waiting as long as $\bar{A}_f$ for a retransmission decision is possibly pessimistic*.

2) Energy consumption: As observed from Fig. 4(a), the basic SW has the highest energy consumption, indicating the penalty for purely channel oblivious transmissions. The COP with $t_p = 1$ also has a quite high energy consumption, which is not the case with $t_p = 20$. CAP1 and CASW1 have nearly the same (low) energy consumption. In Fig. 4(b), the physical layer aware SW protocols are exclusively



(a) Comparison with basic SW and COP (b) Physical layer aware approaches

Fig. 4. Comparison of energy consumption performance with binary feedback.

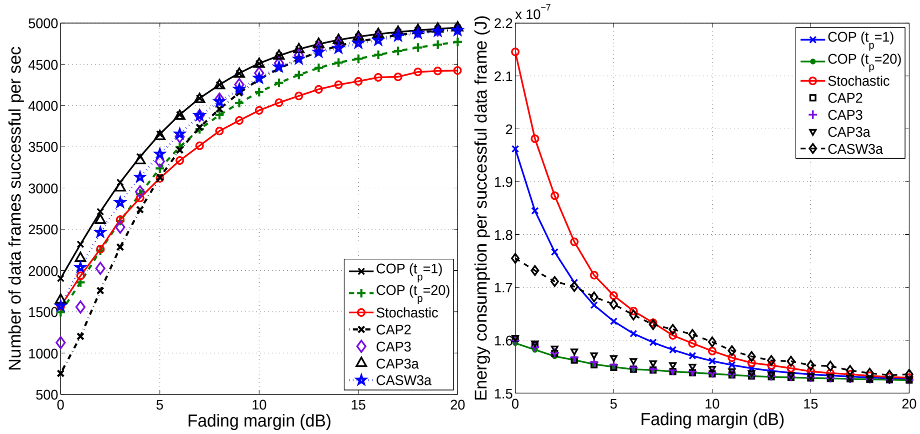
compared, where the performance of stochastic learning approach is also included. It is observed that, beyond very low fading margins, CASW1 has nearly the same energy consumption as that of CAP1. Stochastic learning approach on the other hand has a quite high energy consumption.

From Figs. 3 and 4 we observe that, although COP with a shorter probing periodicity has a higher data frame success rate, CAP1 and CASW1 perform better in terms of lesser energy consumption. Also, COP with a longer probing periodicity performs poorly in terms of data frame success rate without achieving any benefit of reduced energy consumption. Although the stochastic learning approach has a slightly better throughput performance at lower fading margins, but it has a consistently higher energy consumption per successful data frame transmission. It may also be noted that, the region of moderate fading margin is of primary interest, because typically 4 to 10 dB fading margin is provided for transmission in fading channel scenario. Overall, in a correlated fading scenario, by choosing an optimum probing periodicity (in CAP1) or optimum data frame retransmission instant (in CASW1) as a function of the receiver's acceptable power threshold dependent AFD, energy consumption performance can be substantially improved over the COP based SW as well as the stochastic control based SW with a little sacrifice on the throughput performance. *Since CASW1 is a simpler protocol (without any probing), it may be preferred over CAP1 in a scenario with binary feedback.*

B. Case 2: Received signal power feedback

From the binary feedback based CAP and CASW performance results we have noted that, while substantial saving on energy consumption can be achieved, a penalty of decreased data delivery rate is incurred, which is more at lower fading margins. The studies on received signal strength feedback based optimal waiting are to improve the throughput performance without compromising on energy saving. This study include CAP2, CAP3, CAP3a, and CASW3a (CASW with $\pi = w_2$, defined in (14)), in addition to COP (with $t_p = 1$ and $t_p = 20$) and stochastic learning based SW. Similarly as in Case 1, numerical results match with the simulated values. In the presented results below, only the simulation results are shown to aid visualization of distinct trends of the different approaches.

1) Data throughput: The throughput plots in Fig. 5(a) show that, CAP2, CAP3, and CAP3a perform increasingly better with respect to COP with $t_p = 20$, signifying the benefit of more informed decision of reduced waiting before a retransmission decision. The plots also show that the throughput performance of CAP3a is better than stochastic learning based SW, thus eliminating the concern of poorer throughput at lower fading margins. CASW3a also shows an improved performance, but is marginally poorer than CAP3a. This is because, a shorter than $\bar{A}_f$ waiting is associated with a higher chance of reception error, and failure of a retransmitted data frame induces a longer delay in successful delivery of a data frame.



(a) Data throughput (b) Energy consumption

Fig. 5. Data throughput and energy consumption performance with received signal strength feedback.

2) Energy consumption: The energy consumption plots of the competitive SW protocols are shown in Fig. 5(b), where for CAP and CASW received signal strength feedback is used. It is noted that, CAP3a performs nearly as good as COP with $t_p = 20$, which is also consistently better than the stochastic learning approach. CASW3a has a reasonably higher energy consumption, which is due to the fact that, a failed data frame transmission is more costly, even though it is done after a calculated delay. This difference is more prominent at a lower fading margin where the possibility of such failures is high.

Combinedly looking at the throughput and energy consumption performances, when the received power level feedback is available, CAP3a offers an overall superior performance.

C. Effects of mobility

The effects of nodal mobility on throughput and energy saving are shown in Fig. 6. The decreasing trends of success rate and increasing trends of energy consumption with velocity are intuitive. As noted from Fig. 3, although CASW1 offers the lowest energy consumption of all, it is at the cost of decreased data throughput. CAP3a improves the throughput performance to nearly as good as that of COP with $t_p = 1$, but at the cost of a marginally increased energy consumption, which increases with speed.

The throughput and energy consumption trade-off performances of CASW1 and CAP3a at some typical system operation parameters are captured in Table I. Since there is no benchmark for optimum t_p in COP, and stochastic learning based SW fairs poorly in energy consumption as well as throughput, the trade-off performances are compared with the basic SW.[†] We observe that, while CASW1 and CAP3a both offer

[†]A similar comparison can be easily drawn with respect to the COP based SW or stochastic learning based approach.

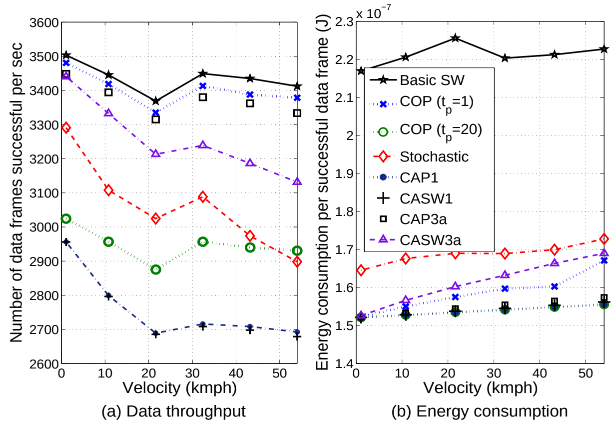


Fig. 6. Effects of nodal mobility on throughput and energy consumption performance. The legends for the data points apply for both plots.

TABLE I

ENERGY SAVING (E-GAIN) AND THROUGHPUT TRADE-OFF (R-LOSS) IN CASW1 AND CAP3A PROTOCOLS OVER BASIC SW PROTOCOL AT DIFFERENT FADING MARGINS (FM). $f_D = 50$ Hz.

FM (dB)	CASW1		CAP3a	
	E-gain	R-loss	E-gain	R-loss
4	29.9%	21.5%	29.4%	2.3%
6	19.9%	13.0%	19.4%	1.4%
8	13.0%	8.0%	12.3%	1.0%
10	8.2%	5.2%	7.7%	0.8%
12	5.0%	3.4%	4.7%	0.6%

nearly identical energy consumption, using the received signal strength information during the 'bad' channel states, CAP3a virtually eliminates the loss in throughput performance of CASW1. The *extra* overhead involved in achieving this performance gain over basic SW and CASW1 is some *additional* bits needed (say, 7 bits, to enable 256 quantization level feedback) in the NAK frames in CAP3a.

V. CONCLUSIONS

We have proposed two variants of energy efficient stop-and-wait (SW) ARQ protocols, namely, CAP and CASW, for short range delay tolerant communication applications with correlated channel errors. In CAP, in the event of a NAK, small probing frames are transmitted after judiciously chosen waiting intervals. The data frame transmission resumes as soon as a probing frame is successfully acknowledged. In CASW, when a 'bad' channel condition is encountered, the transmitter waits for a calculated time, before resuming transmission of a data frame. Performance of the proposed protocols over Rayleigh fading channel have been analyzed by two-state Markov model approximation and compared with the competitive SW protocols. It has been shown that, with binary feedback about the channel condition, CAP as well as CASW with a waiting period of average fading duration offer significantly less energy consumption per successful data frame while trading off in frame success rate performance. When the received signal strength information is available in the NAK frames, CAP with a suitably reduced waiting delay achieves an equally high energy saving with a significantly less frame success rate trade-off. The energy consumption gains associated with the proposed protocols are more in harsh fading conditions, which are prevalent in mobile wireless environments.

APPENDIX I

A proof of concept is presented below to justify the analytical arguments in Section III-B. In COP protocol, t_p is the probing periodicity which determines multi-step transition probability to yield the probability distribution of number of probings $\mathbf{P}$. If t_p is very large such that the fading channel state between two consecutive probing attempts becomes uncorrelated (i.e., when t_p becomes larger than the coherence time), the distribution of $\mathbf{P}$ in (6) can be obtained by considering the channel as memoryless.

For Rayleigh fading channel, the probability density function of received power at A (or B, see Fig. 2) is given by (13). Recall that, the probing mode continues as long as a NAK is received, i.e., the received power level is below P_{th}. From (13), the probability of NAK reception can be written as,

$$p_{nak} = \int_0^{P_{th}} \frac{1}{\bar{P}_r} e^{-\frac{a}{\bar{P}_r}}\, da. \tag{A.1}$$

In a memoryless channel, p_{nak} is nothing but the steady state probability of finding the system in 'bad' state, given by: $p_{nak} = \frac{1-p_{11}}{1+p_{21}-p_{11}}$. Since the received power levels at consecutive NAK are independent of each other for a large t_p, using (A.1), the probability distribution of $\mathbf{P}$ simply becomes:

$$\Pr[\mathbf{P} = p] = p_{nak}^{(p-1)}(1 - p_{nak}). \tag{A.2}$$

To prove that (6) converges to (A.2) for a large t_p, we use the limiting probability concept [30, p. 204] on (6), which implies that, after a large number of state transitions the elements in the matrix $M(t_p)$ converge to two specific (steady state) values, p_{nak} and $1 - p_{nak}$. Thus, $M(t_p)$ for a large t_p becomes:

$$M(t_p) = \begin{bmatrix} (1 - p_{nak}) & p_{nak} \\ (1 - p_{nak}) & p_{nak} \end{bmatrix},$$

and correspondingly, the expression (6) becomes identical to (A.2).

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