Optimizing Energy Allocation for Energy Harvesting Node with Hybrid ARQ

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Abstract —Efficiently using scarce energy is more critical for the nodes which are supplied by energy harvesting. However, it is difficult to optimize the transmit energy of each retransmission when future Channel State Information (CSI) and accurate retransmission number cannot be obtained in Hybrid Automatic Repeat Request (HARQ) system. In this paper, we propose a novel HARQ scheme to allocate the transmit energy of Energy Harvesting Node (EHN) while the battery can be recharged from received signals. In the proposed scheme, the amount of energy used in each transmission is selected to maximize a utility function which is defined as the conditional throughput divided by the energy consumption of this transmission, i.e., instantaneous energy efficiency. To simplify the operational complexity of EHN, a suboptimal closed form solution is also presented. Simulation results demonstrate that the proposed HARQ scheme can improve both energy efficiency and normalized throughput significantly.

Index Terms—HARQ, energy efficiency, energy harvesting, utility function

I. INTRODUCTION

In recent times, energy efficiency has been a major concern to researchers across the globe. Various techniques have been proposed to utilize the energy more efficiently [1]-[3]. The energy efficiency is more critical for Energy Harvesting Node (EHN), i.e., the nodes which are supplied completely (or mainly) by the energy harvested from environment. Energy can be harvested from many environment resources, such as solar, wind, vibration or other physical phenomena [4]-[6]. In addition, energy can also be scavenged from ambient radio signals, namely Wireless Energy Harvesting (WEH). A node capable of WEH is equipped with a specially designed receiver which can simultaneously decode information and harvest energy from the received Radio-Frequency (RF) signal [7]-[10].

Since harvested energy which supplies power to rechargeable battery is limited, many researchers have optimized the energy management policy to increase its performance. In [11], energy management policies for energy harvesting sensor nodes have been proposed to stabilize the data queue for single-user communication and some delay optimality properties have also been derived under a linear approximation. Using a geometric framework, [12] has obtained the optimal solution for minimizing the transmission completion time in an energy harvesting system. [13] has introduced a directional water-filling algorithm to maximize the throughput, and minimizing the transmission completion time of the communication session with energy harvesting. In relay system, [14] has proposed time switching-based relaying (TSR) protocol and power splitting-based relaying (PSR) protocol to enable energy harvesting and information processing at the relay.

In automatic repeat request (ARQ)/hybrid ARQ (HARQ) system, retransmissions change the conventional harvesting energy management policy due to packet/codeword combining. In [15], a cooperative automatic retransmission request (CARQ) protocol has been introduced for wireless sensor network (WSN) and a generalized discrete time Markov chain (DTMC) model has been proposed for analyzing the throughput and energy efficiency of the protocol. For wireless Energy Harvesting Sensor (EHS) nodes, [16] has found outage optimal power control policies with Automatic Repeat Request (ARQ)-based packet transmissions.

By fixing the conditional Word Error Ratio (WER) and adapting transmit power accordingly, [17] has proposed a simple energy efficient HARQ scheme. Motivated by this idea and extended it into EHN, we consider the optimization problem of energy allocation. For an EHN implemented with HARQ, the energy efficiency depends heavily on the energy taken from battery for each transmission. It is desirable that each information bit can be transmitted successfully while the energy consumption is minimum. Hence, we propose a novel scheme where \( E_i \), the energy used in \( i \)-th \( (i \geq 1) \) transmission, is selected to maximize the utility function \( U(E_i) \) which is defined as the conditional throughput of \( i \)-th transmission divided by \( E_i \). The optimal energy, \( E^* \), can be obtained via one dimension search (such as Golden selection). Since the numerical search may not be affordable for some low complexity EHNs, a suboptimal simple closed form solution, \( E^\dagger \), is also presented. Simulation results demonstrate that, with the proposed scheme, the battery energy can be used much more efficiently compared with pure-FEC (no HARQ) or conventional HARQ systems.

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In the rest of this paper, Section 2 describes the overall system model and assumptions. Section 3 gives the definition of normalized throughput and energy efficiency. Section 4 proposes the energy efficient HARQ scheme with optimal and suboptimal solutions, and the simulation results are presented in Section 5. Section 6 concludes the paper.

II. SYSTEM MODEL

We consider a point-to-point communication between an energy harvesting node (EHN) and an Access Point (AP) as shown in Fig. 1. Assume that the system operates in time domain division duplex (TDD) mode which consists of a downlink for transmission from AP to EHN and an uplink for transmission from EHN to AP. In downlink, AP sends signals with power $P_{\text{AP}}$, then EHN receives the data and extracts the energy from received signals simultaneously. The extracted energy is charged to battery which indicates the characteristic of EHN. In uplink, EHN transmits signals to AP by using some of the energy of battery. We also consider that the battery has to output power for the functions of "other parts", e.g., environment monitoring and so on. The arrows in Fig. 1 demonstrate the directions of energy transferring. The frame structure is illustrated in Fig. 2 with more details as follows.

![Diagram of Energy Harvesting Node (EHN)](image)

**Fig. 1. System model of point-to-point communication between EHN and AP**

At $i$-th time slot, AP sends signal with power $P_{\text{AP}}$, and when it reaches EHN, the signal power becomes $g_i P_{\text{AP}}$, where $g_i$ is the channel gain of block fading channel. That means $g_i$ is constant within each time slot and vary independently across the time slots. A fraction of received signal is used for decoding data from AP and the rest is used for energy harvesting. We assume the data decoding is reliable.

![Diagram of Frame Structure of EHN](image)

**Fig. 2. The frame structure of EHN**

Similar to [14], we compute the energy harvested during the $i$-th downlink subslot by

$$E^h_i = \alpha \cdot g_i P_{\text{AP}} T$$

(1)

where $T/2$ is the duration of downlink slot, $0 < \alpha < 1$ is the energy conversion efficiency which depends on the rectification process and the energy harvesting circuitry. The fraction of energy consumed in decoding downlink signal is also included in $\alpha$.

The harvested energy, $E^h_i$, is charged into the battery. We assume that the capacity of battery is sufficiently large hence at the beginning of $i$-th uplink subslot the energy in battery becomes

$$E_{\text{cell}}^i = E_{\text{cell}}^i + E^h_i$$

(2)

where $E_{\text{cell}}^i$ is the energy in battery at the beginning of downlink subslot.

The transmitter in EHN uses a fraction of battery energy, $E_i (0 \leq E_i \leq E_{\text{cell}}^i)$, for uplink data transmission. $E_i$ consists of circuit energy consumption $E_c$ and the energy of the signal transmitted through antenna. The transmit power $P_i$ is given by

$$P_i = \frac{E_i - E_c}{T/2}$$

(3)

where $T/2$ is the duration of uplink subslot. And then, the energy left in battery is

$$E_{\text{cell}}^{i+1} = E_{\text{cell}}^i - E_i$$

(4)

We assume that the Chase combining HARQ (CC-HARQ) is used for uplink data transmission, while Stop-and-Wait ARQ protocol is adopted in medium access control (MAC) layer. We also assume round trip time (RTT) is small enough since EHN is generally applied in short distance WSN and thus waiting window is short. Let $s$ be a vector representing the modulated codeword transmitted by EHN. In the $i$-th slot of the CC HARQ process, the signal received by AP can be expressed as

$$y_i = \sqrt{P_i} g_i s + z_i, \quad i = 1, 2, \ldots$$

(5)

where $z_i$ is the additive white Gaussian noise vector, $P_i$ is the transmit power defined in (3) and $g_i$ is the channel
power gain satisfying $\mathbb{E}[g_i] = 1$. Without loss of generality, we assume that $\mathbb{E}[|h_i|^2] = 1$, $\mathbb{E}[|h_i|^2] = \sigma_n^2$. Hence the instantaneous SNR is

$$\tilde{\gamma}_i = \frac{P \cdot g_i}{\sigma_n^2}$$  \hspace{1cm} (6)

At the $i$th transmission, the received signals $y_1, \ldots, y_i$ are soft combined and then fed to the decoder. The combined SNR is given by [17]

$$\gamma_i = \sum_{k=1}^{i} P_k \cdot \tilde{\gamma}_{i-k} + \frac{g_i P_i}{\sigma_n^2}$$  \hspace{1cm} (7)

where $\gamma_0 = 0$.

Based on decoding result of AP, acknowledgement (ACK)/negative acknowledgement (NACK) will be sent back to the EHN over the error-free downlink feedback channel. If AP feeds back an ACK, EHN will send new codeword in next slot and the slot index $i$ for next slot will be initialized to 1. Otherwise, the erroneous codewords will be retransmitted by EHN until successful decoding. This has assumed sufficiently large maximum transmission number such that residual error rate of HARQ is negligible.

### III. NORMALIZED THROUGHPUT AND ENERGY EFFICIENCY

In this paper, normalized throughput is defined as the average number of correctly received codewords at AP per uplink subslot which is given by

$$R = \frac{1}{\bar{N}}$$  \hspace{1cm} (8)

where $\bar{N}$ is the average transmission number of a codeword:

$$\bar{N} = \mathbb{E} \left[ 1 + \sum_{i=1}^{\infty} q(\gamma_i) \right] = 1 + \sum_{i=1}^{\infty} \tilde{q}_i$$  \hspace{1cm} (9)

where $q(x)$ is the codeword error rate (WER) of decoder when the instantaneous SNR is $x$, $\tilde{q}_i \triangleq \mathbb{E} [q(\gamma_i)]$. For typical FEC codes, there is no exact formula available for $q(\gamma_i)$. The well known simplest approximation is the step approximation. Besides, exponential approximation has been proposed in [18]. For turbo-like codes, more accurate approximation can be found in [19], [20]. The formula proposed in [19] is

$$q(\gamma) \approx Q \left( \frac{\mu - 1}{\sqrt{\sigma}} \gamma \right)$$  \hspace{1cm} (10)

where $Q(\cdot)$ is the Gaussian $Q$ function, $\mu$ and $\sigma$ are parameters completely determined by the encoder/decoder design.

For the pure FEC system (single transmission), the normalized throughput is given by

$$R_{\text{FEC}} = \mathbb{E} [1 - q(\gamma_i)] = 1 - \tilde{q}_i$$  \hspace{1cm} (11)

In this paper, the overall energy efficiency is defined as

$$\eta = \frac{R}{\mathbb{E}[E_i]}$$  \hspace{1cm} (12)

where $\mathbb{E}[E_i]$ is the average energy consumption of the EHN transmitter per slot.

We assume also that $E^h$ is the only energy source of the battery shown in Fig. 1. The unit "other parts" represents other functionalities (in addition to EHN AP communication) implemented in EHN. The examples of such functionalities include environment monitoring, data processing and etc. We assume that the operations of these functionalities rely completely on the power supply from the battery. The average output power is given by

$$P^{out} = \frac{1}{T} \mathbb{E} [E^h_i - E_i]$$  \hspace{1cm} (13)

Larger $P^{out}$ implies more and powerful functionalities can be implemented in EHN.

### IV. PROPOSED ENERGY EFFICIENT HARQ SCHEME

At $i$-th slot, EHN can autonomously decide how much energy ($E_i$) should be used by the EHN transmitter. Assuming perfect channel estimation, then EHN knows $g_1, g_2, \ldots, g_i$ and does not know $g_{i+1}, g_{i+2}, \ldots$. Theoretically, the optimal $E_i$ not only depends on $g_1, g_2, \ldots, g_i$ but also depends on what will happen in future slots. To simplify the problem, we propose to optimize the local energy efficiency of each slot.

Conditioned on the $i$th transmission (i.e. all previous transmissions fail), the conditional WER can be approximated by [21]

$$\pi_i \approx \frac{q(\gamma_i)}{q(\gamma_{i-1})}$$  \hspace{1cm} (14)

which is 1 if $P_i = 0$ and is 0 if $P_i = \infty$.

Thus the conditional throughput is defined as the average number of correctly received codewords at $i$th transmission when all previous transmissions fail,

$$\tilde{\eta}_i = 1 - \pi_i = \frac{q(\gamma_{i+1}) - q(\gamma_i)}{q(\gamma_{i-1})}$$  \hspace{1cm} (15)

According to (12), we know that the value of conditional throughput divided by consumed energy at $i$th transmission demonstrates the instantaneous energy efficiency, so we define a utility function as

$$U(E_i) = \frac{1 - \pi_i}{E_i} = \frac{q(\gamma_{i+1}) - q(\gamma_i)}{q(\gamma_{i-1})}E_i$$  \hspace{1cm} (16)

and the energy used for uplink transmission in slot $i$ is given by

$$E_i^* = \arg\max_{E_i \geq 0} U(E_i)$$  \hspace{1cm} (17)
with \( q(\gamma) \) given in (10), it is difficult to solve the closed form \( E^* \) from (17). Although the numerical value of \( E^* \) can be obtained through one-dimension search (e.g. Golden Section), such numerical search may not be affordable for low complexity EHNs. Hence in the following we will present a simple approximation for \( E^* \).

From (16) we can see that, if \( q(\gamma_i) \) is close to zero, \( U(E_i) \approx 1/E_i \) is a decreasing function of \( E_i \), which is maximized at smaller \( E_i \), which will in turn result in larger \( q(\gamma_i) \); On the other hand, if \( q(\gamma_{i-1}) - q(\gamma_i) \) is close to zero, \( U(E_i) \) is also close to zero. Hence we may approximately assume that, for the optimal \( E_i \), \( q(\gamma_i) \) cannot be very close to 1 or 0.

Consider the \( q(\gamma) \) shown in (10). When the value of \( Q(x) \) is not very close to 1 or 0, we can approximate \( Q(x) \) using Taylor expansion as

\[
Q(x) \approx \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}, \quad |x| < 1
\]

In case \( i=1 \), the utility function is

\[
U(E_1) = \frac{1-q(\gamma_1)}{E_1} \approx \frac{1}{E_1} \left[ \frac{1}{\sqrt{2\pi}} + \frac{\mu -1/\gamma_1}{\sigma} \right]
\]

where \( \gamma_1 = P/E_1 \frac{\alpha}{\beta} = 2g_1(E_1 - E_1)/(T\sigma^2_1) \). Take derivative of the right hand side (RHS) of (19) and let it be zero, we get

\[
E^*_1 \approx E_1^* = \min \left\{ \frac{E_1}{1-q(\gamma_1)}, \frac{T\sigma^2_1}{2(\mu-\sigma)g_1} + E_1 \right\}
\]

where the first term in \( \min \{\cdot, \cdot\} \) corresponds to the maximum of RHS of (19), the second term corresponds to the right boundary of (19).

In case \( i>1 \), by substituting (18) and (10) into the numerator of (16), we have

\[
U(E_i) = \frac{1}{\sqrt{2\pi} \sigma} \frac{E_i}{q(\gamma_{i-1})} \frac{1}{\gamma_i} - \frac{1}{E_i}, \quad i > 1
\]

Define a new equivalent objective function as

\[
J(\beta) = \left[ 1 - \frac{\beta}{1+\beta} \right] \frac{1}{\beta + a}
\]

where \( \beta = P_i/c, \quad c = \gamma_{i-1} \sigma^2_1/g_i, \quad a = 2E_i/(cT) \). It is easy to show that \( \beta = \sqrt{a} \) will maximize \( J(\beta) \). Taken into consideration of the boundary of RHS of (19), we have the suboptimal solution as:

\[
E_i^* \approx E_i^{**} = \left\{ \begin{array}{ll}
\frac{T\sigma^2_1}{2(\mu-\sigma)g_i} + E_i, & -1 \leq x \leq 1, \\
\frac{T\sigma^2_1}{2(\mu+\sigma)g_i} + E_i, & x > 1,
\end{array} \right.
\]

V. SIMULATION RESULTS

In this section, we present simulation results that demonstrate the performance improvement obtained from proposed HARQ scheme. In the simulation, we consider the system model as Fig. 1. The slot duration \( T \) is set to 2, the energy conversion efficiency of EHN is set to \( \alpha = 0.7 \). The channel power gain \( g_i \) is modeled as i.i.d. Nakagami-\( m \) fading whose probability density function (PDF) is Gamma distribution [17]:

\[
f_g(g) = \frac{m^m g^{m-1}}{\Gamma(m)} \exp(-mg), \quad i = 1\ldots, K
\]

where \( \Gamma(\cdot) \) is the Gamma function, \( m \) is the Nakagami fading parameter, and \( \mathbb{E}[g_i] = 1 \) which normalizes the channel power to unit. In our simulation, we set \( m = 2 \). The receiver noise power \( \sigma^2_1 \) is normalized to 1. For the FEC code, we adopt the LDPC (1152,576) code defined in [22]. The decoder adopts layered sum-product algorithm decoding with maximum iteration number as 25. In this case, the parameters in (10) are \( \mu = 0.8051, \sigma^2 = 0.0029 \).

The simulated overall energy efficiency, as defined in (12), is shown in Fig. 3 for both \( E_i = E^*_i \) and \( E_i = E^{**}_i \), where \( E^*_i \) is obtained by numerical search of (17) and \( E^{**}_i \) is given by (20) and (23). For the reason of comparison, the energy efficiency of pure FEC system (NO HARQ) and conventional HARQ are also shown in Fig. 3. In these two schemes, the energy allocation is \( E_i = E_{\text{Alloc}} \), which means that each transmission will use up all energy available in battery. We can see that HARQ can improve the energy efficiency compared with NO HARQ system, and the proposed scheme can further improve the energy efficiency. More specifically, we quantify the obtained gain to illustrate our results. For instance, at \( P=2\text{dB} \), the proposed HARQ scheme with \( E^* \) and \( E^{**} \) improve EE by about 10% and 12% respectively, compared with conventional HARQ.
Fig. 3. Comparison of energy efficiency

Fig. 4. Comparison of normalized throughput

Fig. 5. Average output power of proposed HARQ scheme

Fig. 6. Normalized throughput with output power

VI. CONCLUSIONS

Energy efficiency is important to nodes relying on the energy harvested from environment. In this paper, we propose to use HARQ to improve the energy efficiency and design a novel energy efficient HARQ transmission scheme, in which the transmit power of each HARQ transmission is optimized to maximize the local energy efficiency of current transmission. Simulation results have demonstrated that proposed scheme has better energy efficiency and throughput performance, compared to other conventional schemes.

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