Wireless Powered Communications with Finite Battery and Finite Blocklength

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Abstract

We analyze a wireless communication system with finite block length and finite battery energy, under quasi-static Nakagami-m fading. Wireless energy transfer is carried out in the downlink while information transfer occurs in the uplink. Transmission strategies for scenarios with/without energy accumulation between transmission rounds are characterized in terms of error probability and energy consumption. A power control protocol for the energy accumulation scenario is proposed and results show the enormous impact on improving the system performance, in terms of error probability and energy consumption. The numerical results corroborate the existence and uniqueness of an optimum target error probability, while showing that a relatively small battery could be a limiting factor for some setups, specially when using the energy accumulation strategy.

Index Terms

Finite blocklength communications, wireless energy transfer, finite battery, power control.

I. INTRODUCTION

The Internet of Things (IoT) is a recent communication paradigm which promises to bring wireless connectivity to “...anything that may benefit from being connected...” [1], ranging from tiny static sensors to vehicles and drones. Consequently, coming wireless communication systems will have to support a much larger number of connected devices, including autonomous machines

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and devices, with applications having stringent requirements on latency and reliability as \[2\]: factory automation, with maximum latency around 0.25-10 ms and maximum error probability of $10^{-9}$; smart grids (3-20 ms, $10^{-6}$), professional audio (2 ms, $10^{-6}$), etc. Powering and keeping operational uninterruptedly such a potential massive number of IoT nodes is a major challenge \[3\]. Wireless Energy Transfer (WET) has been proposed as an attractive solution for this requirement because radio-frequency (RF) signals can carry both energy and information, which enables energy constrained nodes to harvest energy and receive information \[4\], \[5\], allowing to prolong their lifetime almost indefinitely.

The exploitation of WET becomes very attractive specially for IoT scenarios where replacing or recharging batteries require high cost and/or can be inconvenient or hazardous (e.g., in toxic environments), or highly undesirable (e.g., for sensors embedded in building structures or inside the human body) \[6\]. With further advances in antenna technology and energy harvesting (EH) circuit designs, WET is believed to become very efficient such that it will be implemented widely in the near future. Indeed, WET techniques are now evolving from theoretical concepts into practical devices for low-power electronic applications \[7\]. Wireless-powered communication networks (WPCNs), where the wireless terminals are powered only by WET and transmit their information using the harvested energy, have been widely investigated in the last years. The feasibility of WET for low-power cellular applications has been studied using experimental results, which have been summarized in \[8\]. A classic multi-user WPCN was investigated in \[9\], where authors develop a “harvest-then-transmit” protocol which allows users to first collect energy from the signals broadcasted by a single-antenna hybrid access-point (AP) in the downlink and then to use their harvested energy to send independent information to the hybrid AP in the uplink. Diverse strategies have been considered in the recent scientific literature in order to improve the performance of WPCNs, such as relay-assisted \[10\]–\[19\], Hybrid Automatic Repeat-reQuest (HARQ) \[20\], and power control \[21\]–\[23\], mechanisms.

All the above studies are under the ideal assumption of communicating with large enough blocks in order to invoke Shannon theoretic arguments to address error performance. However, as pointed out in \[24\], important characteristics of WET systems are: i) power consumption of the nodes on the order of $\mu$W; ii) strict requirements on the reliability of the energy supply and of the data transfer; iii) information is conveyed in short packets. This third requirement is due to intrinsically small data payloads, low-latency requirements, and/or lack of energy resources to support longer transmissions \[25\]. This agrees well with several aforementioned
IoT scenarios with stringent latency requirements. Although performance metrics like Shannon capacity, and its extension to nonergodic channels, have been proven useful to design current wireless systems, they are not necessarily appropriate in a short-packet scenario [26], where a more suitable metric is the maximum achievable rate at a given block length and error probability. This metric has been characterized in [27], [28] for both Additive White Gaussian Noise (AWGN) and fading channels. Indeed, recent works in finite-blocklength information theory have shed light on a number of cases where asymptotic results yield inaccurate engineering insights on the design of communication systems once a constraint on the codeword length is imposed, e.g., in fast fading scenarios and low-rate transmissions [29]–[33]. WPCNs at finite blocklength regime have received attention in the scientific community recently. In [34] we analyze and optimize a single-hop wireless system with energy transfer in the downlink and information transfer in the uplink, under quasi-static Nakagami-m fading in ultra-reliable communication (URC) scenarios, representative of wireless systems with strict error and latency requirements. The results demonstrate that there are optimum numbers of channel uses for both energy and information transfer for a given message length. The impact of a decode-and-forward relay-assisted communication setup is evaluated in [35] in terms of throughput and delay, also in URC scenarios. On the other hand, subblock energy-constrained codes are investigated in [36], and a sufficient condition on the subblock length to avoid energy outage at the receiver is provided. In [25], a node charged by a power beacon attempts to communicate with a receiver over a noisy channel. Authors investigate the impact of the number of channel uses for WET and for wireless information transfer (WIT) on the system performance. Also, tight approximations for the outage probability/throughput are given in [37] for an amplify-and-forward relaying scenario, while retransmission protocols, in both energy and information transmission phases, are implemented in [24] to reduce the outage probability compared to open-loop communications.

Moreover, power allocation strategies have been recently investigated in the literature to enhance the performance of short packets communication systems. In [38], the authors investigate the optimal power allocation algorithms for low-density parity-check (LDPC) codes with specific degree distributions using multi-edge-type density evolution error boundaries, while the error probability in delay-limited block-fading channels is analyzed. A single point-to-point wireless link operating under queuing constraints, in the form of limitations on the buffer violation probabilities, is considered in [39]. The performance of different transmission strategies (e.g., variable-rate, variable-power, and fixed-rate transmissions) is also studied at finite blocklength
regime. Furthermore, the maximum achievable channel coding rate at a given blocklength and error probability, when the codewords are subject to a long-term (e.g., averaged-over-all-codeword) power constraint is investigated in [40], in which power control strategies for both AWGN and fading channels are developed. However, to the best of our knowledge, there are only few papers, e.g., [21]–[23], where power allocation strategies are proposed for WPCNs but based on the assumption of infinite blocklength. Particularly interesting is the work in [23], where authors propose a low-complexity solution, called fixed threshold transmission (FTT) scheme, and show that its performance is very close to the optimal. This strategy assumes a threshold transmit power value to determine whether transmission takes place or not. If the channel state of the current transmission attempt is of poor quality, then saving energy for future transmission attempts may be a wiser choice.

This paper aims at WPCN scenarios with short packets, but with several differences with respect to the related literature. The system is composed of a point-to-point communication link under Nakagami-m quasi-static fading, with WET in the downlink and WIT in the uplink, as in many of the related works. However, we analyze the error probability and average energy consumption under a finite battery constraint for scenarios with and without energy accumulation between transmission rounds. In addition, we propose a power control protocol for the scenario with energy accumulation between transmission rounds in order to enhance the system performance in terms of error probability by taking advantage of the channel state information (CSI) at the transmitter side, while at the same time the average energy consumption improves. The proposed strategy could be seen as a variant of the finite-blocklength scenarios of the FTT scheme investigated in [23]. Notice that the infinite blocklength assumption in [23] leads to a non-optimal threshold transmit power in our scenario, as the true required threshold is much higher when communicating with short packets.

The main contributions of this work can be listed as follows.

- Accurate closed-form approximations for the error probability in scenarios where all the energy harvested at each WET phase is used to transmit in the next WIT phase. Here, channels for WET and WIT phases are assumed reciprocal, which is different from the result in [34] where those channels are independent and holds only for infinite battery.
- A power control algorithm for scenarios with energy accumulation between transmission rounds, which takes into account the message blocklength and consequently it can be seen as a more practical implementation of the FTT scheme proposed in [23]. Notice that allowing
energy accumulation between transmission rounds is beyond the scope of our previous work in [34];

- An analysis of the average energy consumption in addition to the error probability, which is not addressed in [23] and [34], for scenarios with and without energy accumulation between transmission rounds. Saving energy for future transmissions allows to improve the system performance in terms of error probability while reducing the energy consumption. A relatively small battery could be a limiting factor for some setups, and specially when using the energy accumulation strategy which also depends heavily on the chosen target error probability.

Next, Section II presents the system model and assumptions. Section III discusses a scenario without energy accumulation between transmission rounds, while the case with energy accumulation is analyzed in Section IV by proposing a power control protocol. Section V presents the numerical results. Finally, Section VI concludes the paper.

**Notation:** \( X \sim \Gamma(m, 1/m) \) is a normalized gamma distributed random variable with shape factor \( m \), Probability Density Function (PDF) \( f_X(x) = \frac{m^m}{\Gamma(m)} x^{m-1} e^{-mx} \) and Cumulative Distribution Function (CDF) \( F_X(x) = 1 - \frac{\Gamma(m, mx)}{\Gamma(m)} \). Let \( \mathbb{E}[\cdot] \) denote expectation, \( |\cdot| \) is the absolute value operator, and \( 1(\cdot) \) is an indicator function which is equal to 1 if its argument is true and 0 otherwise. Also, \( \mathbb{P}[A] \) is the probability of event \( A \), while \( \min(x, y) \) and \( \max(x, y) \) are the minimum and maximum values between \( x \) and \( y \), respectively.

**II. System Model and Assumptions**

Consider the point-to-point wireless communication system shown in Fig. I in which \( S \) represents the information source, \( D \) is the destination, and both are single antenna, half-duplex, devices. \( D \) is assumed to be externally powered, while \( S \) may be seen as a sensor node with very limited energy supply and finite battery. First, \( D \) charges \( S \) during \( v \) channel uses in the WET phase, and doing that, acts as an interrogator, requesting information from \( S \). Then, \( S \) transmits \( k \) information bits over \( n \) channel uses in the WIT phase. We define a “transmission round” as a pair of consecutive WET and WIT phases, in that order. Notice that \( S \) can transmit its data using all the energy available in its battery at the start of each WIT phase (without energy accumulation between transmission rounds) or just make use of a part of that energy, saving the rest for future transmissions (with energy accumulation between transmission rounds). We
Fig. 1. System model with WET in the downlink and WIT in the uplink.

consider a time-constrained setup, which implies that $D$ has to decode the received signal for each arriving information block.

In addition, channel reciprocity holds as shown in Fig. 1 because we consider the same frequency bands for both WET and WIT phases. Nakagami-$m$ quasi-static channels are assumed, where the fading process is constant over a transmission round ($v + n$ channel uses) and independent and identically distributed from round to round. We consider normalized channel gains, then $g = h^2 \sim \Gamma(m, 1/m)$, while the duration of a channel use is denoted by $T_c$.

In the scenario without energy accumulation between transmission rounds, perfect CSI is assumed only at $D$ when decoding after the WIT phase. For the scenario with energy saving, CSI is also assumed at the transmitter side. Although CSI acquisition in an energy-limited setup is not trivial, our analysis based on perfect CSI gives an upper-bound on the performance of real scenarios, where additional delay and imperfections in channel estimation are present. In addition, notice that CSI at the transmitter side can be acquired via feedback from $D$ or even if $D$ sends pilots taking advantage of channel reciprocity.

III. Harvest then Transmit (HTT)

In this section we analyze the scenario without energy accumulation between transmission rounds.

A. WET Phase

In this phase, $D$ charges $S$ during $v$ channel uses. The energy harvested at $S$ during the $i$th transmission round is

$$E_i = \frac{\eta P_d h_i^2 \kappa d^\alpha}{\kappa d^\alpha} v T_c = \frac{\eta P_d g_i}{\kappa d^\alpha} v T_c,$$

where $P_d$ is the transmit power of $D$, $0 < \eta < 1$ is the energy conversion efficiency, $d$ is the distance between $S$ and $D$, $\alpha$ is the path loss exponent and $\kappa$ accounts for other factors as...
the carrier frequency, heights and gains of the antennas [41]. In addition, we assume that \( P_d \) is sufficiently large such that the energy harvested from noise is negligible. Harvested energy is first stored in a rechargeable battery of capacity \( B_{\text{max}} \), and becomes available in the current round. Then, the charge of the battery at the beginning of the \( i \)th WIT phase is updated as follows

\[
B_i = \min(B_{\text{max}}, E_i) = \min(g_i, \lambda) \frac{\eta P_d}{\kappa d^\alpha} v T_c,
\]

(2)

where \( \lambda = \frac{B_{\text{max}} \kappa d^\alpha}{\eta P_d v T_c} \).

B. WIT Phase

After the WET phase, \( S \) uses all the energy in its battery to transmit a message of \( k \) bits to \( D \) over \( n \) channel uses. The signal received at \( D \) during the \( i \)th round can be written as

\[
y_{d,i} = \sqrt{\frac{P_{s,i}}{\kappa d^\alpha}} h_i x_{s,i} + w_{d,i},
\]

(3)

where \( x_s \) belongs to the zero-mean, unit-variance Gaussian codebook transmitted by \( S \), \( \mathbb{E}[[x_s]^2] = 1 \), \( w_d \) is the Gaussian noise vector at \( D \) with variance \( \sigma_d^2 \) and

\[
P_{s,i} = \frac{B_i}{n T_c} = \frac{\eta v P_d}{n \kappa d^\alpha} \min(g_i, \lambda)
\]

(4)

is the transmit power. Thus, the instantaneous Signal-to-Noise Ratio (SNR) at \( D \) is

\[
\gamma_i = \frac{P_{s,i} g_i}{\kappa d^\alpha \sigma_d^2} = \frac{\eta v P_d g_i}{n \kappa^2 d^\alpha \sigma_d^2} \min(g_i, \lambda) = \beta g_i \min(g_i, \lambda),
\]

(5)

where \( \beta = \frac{\eta v P_d}{n \kappa^2 d^\alpha \sigma_d^2} \).

C. Error Probability and Average Power Consumption

The information theoretic analysis for infinite blocklength says that no error occurs as long as \( \gamma > 2^r - 1 \) [41]. However, if we communicate over a noisy channel and we are restricted to use a finite number of channel uses, then no protocol is able to achieve perfectly reliable communication [42]. Let \( \epsilon_i \) be the error probability for the information block transmitted in the \( i \)th round which, considering blocklength \( n \geq 100 \), is well approximated by [43, Eq.(5)]

\[
\epsilon_i \approx Q\left( \frac{C(\gamma_i) - r}{\sqrt{V(\gamma_i)/n}} \right),
\]

(6)

where \( r = k/n \) is the source fixed transmission rate, \( C(\gamma_i) = \log_2(1 + \gamma_i) \) is the Shannon capacity, \( V(\gamma_i) = \left( 1 - \frac{1}{(1+\gamma_i)^2} \right) (\log_2 e)^2 \) is the channel dispersion, which measures the stochastic
variability of the channel relative to a deterministic channel with the same capacity [27], and
\[ Q(x) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt. \]
For quasi-static fading channels the error probability is [28, eq.(59)]
\[ \varepsilon = \mathbb{E}[\varepsilon_i] \approx \int_{0}^{\infty} Q\left( \frac{C(\gamma_i) - r}{\sqrt{V(\gamma_i)/n}} \right) f_{G}(g) dg. \]
For quasi-static fading channels the error probability is [28, eq.(59)]
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where (a) comes from using (5). Notice that it seems intractable to find a closed-form solution for (7). Then, first we resort to an approximation of
\[ Q\left( p(\mu g^t) \right) \approx \Omega(\mu g^t) = \begin{cases} 1, & g \leq \zeta^2 \\ \frac{1}{2} - \frac{\phi}{\sqrt{2\pi}} (\mu g^t - \theta), & \zeta^2 < g < \varphi^2 \\ 0, & g \geq \varphi^2 \end{cases} \]
where \( \zeta = \sqrt{\frac{\beta}{\mu}}, \varphi = \sqrt{\frac{\vartheta}{\mu}}, \theta = 2^r - 1, \phi = \sqrt{\frac{\beta}{2\pi}(2^{2^r}-1)^{-\frac{1}{2}}}, \theta = \frac{1}{\phi} \sqrt{\frac{\beta}{2}} \) and \( \vartheta = \theta + \frac{1}{\phi} \sqrt{\frac{\beta}{2}} \), which leads to the following result.

**Theorem 1.** For the system described in Section III, the error probability in (7) can be approximated as in (9) and (10) for finite and infinite battery devices, respectively.

\[ \varepsilon \approx 1 + \frac{\Gamma(m,m\lambda)}{\Gamma(m)} - \frac{\omega_1}{\Gamma(m)} \left[ \Gamma(m, mz_{11}) + \Gamma(m, mz_{21}) \right] - \frac{\omega_1}{\Gamma(m)} \left[ \Gamma(m, mz_{12}) + \Gamma(m, mz_{22}) \right] + \frac{\omega_2}{\Gamma(m)} \left[ \Gamma(m+2,mz_{12}) - \Gamma(m+2,mz_{11}) \right] + \frac{\lambda}{m} \Gamma(m+1, mz_{22}) - \frac{\lambda}{m} \Gamma(m+1, mz_{21}), \]

\[ \varepsilon_{\lambda=\infty} \approx 1 - \frac{\omega_1}{\Gamma(m)} \Gamma(m, m\sqrt{\frac{\vartheta}{\beta}}) - \frac{\omega_1}{\Gamma(m)} \Gamma(m, m\sqrt{\frac{\vartheta}{\beta}}) + \frac{\omega_2}{m^2\Gamma(m)} \left[ \Gamma(m+2, m\sqrt{\frac{\vartheta}{\beta}}) \right. \]

\[ \left. - \Gamma(m+2, m\sqrt{\frac{\vartheta}{\beta}}) \right]. \]

**Proof.** See Appendix A.

**Remark 1.** Differently from [34, eq.(10)], where battery is assumed infinite and the WET and WIT channels are considered independents, results in Theorem 1 hold for both, finite and infinite battery, and considering reciprocal channels.
Theorem 2. The average transmit power of node $S$ when using the Harvest then Transmit protocol is given by

$$\bar{P} = \eta v P_d \frac{1}{n K_d^\alpha} \left[ 1 - \frac{\Gamma(m + 1, m \lambda)}{\Gamma(m + 1)} + \lambda \frac{\Gamma(m, m \lambda)}{\Gamma(m)} \right],$$

for finite and infinite battery devices, respectively.

Proof. See Appendix B.

Notice that the average energy consumption can be easily computed as $n T_e \bar{P}$ or $n T_e \bar{P}_{\lambda=\infty}$ for finite and infinite battery devices, respectively.

IV. ALLOWING ENERGY ACCUMULATION

Herein we analyze a scenario with energy accumulation between transmission rounds, where the charge of the battery is now given by

$$B_i = \min(B_{\max}, B_{i-1} + E_i - P_{s,i-1} n T_e),$$

with $E_i$ obeying (11). We develop a power control protocol, with channel knowledge at $S$, in order to improve the performance of the scenario discussed in Section III.

A. Power Control Strategy

Authors in [23] propose the FTT power control protocol, based on the assumption that transmitting with certain power such that $\gamma > 2^\gamma - 1$ is sufficient for error-free communication. However, this assumption is not true in a finite blocklength setup. Thus, we develop a Finite Blocklength variant of the FTT protocol (FB-FTT), which can be summarized as follows.

1) Let $\epsilon_{th}$ be the maximum error probability at $D$.
2) Then, $S$ chooses a transmit power $\hat{P}_s$, so that $\epsilon_i = \epsilon_{th}$ according to (6).
3) If there is not enough energy in the battery for $S$ to transmit with sufficient power, then $S$ stays silent and saves energy for the next transmission round. That WIT block is considered lost, and $S$ attempts to transmit a new WIT block at the next round.

Notice that the idea behind the FB-FTT strategy is to transmit with a power that allows to achieve a given SNR $\hat{\gamma}$ at $D$, which causes an error probability $\epsilon_{th}$, as long as there is a transmission
from $S$. Then, knowing $\hat{\gamma}$ and the noise power at $D$, and based on (5), the required transmit power is

$$\hat{P}_{s,i} = \frac{\hat{\gamma} \kappa d^3 \sigma_d^2}{g_i}. \quad (14)$$

Therefore, (13) can be rewritten as

$$B_i = \min \left( B_{\max}, E_i + B_{i-1} - \hat{P}_{s,i-1} n T c \mathbf{1}(B_{i-1} > \hat{P}_{s,i-1} n T c) \right). \quad (15)$$

Also, finding in closed form the required $\hat{\gamma}$ to reach an $\epsilon_{th}$ is algebraically impossible since we would have to solve for $\gamma$ the following equation coming from (6)

$$r = \log_2(1 + \gamma) - \sqrt{1 - \frac{1}{(1 + \gamma)^2} \frac{\log_2 e \ Q^{-1}(\epsilon_{th})}{\sqrt{n}}}. \quad (16)$$

However, since the required $\hat{\gamma}$ is fixed for each system setup $(n, k, \epsilon_{th})$, $S$ does not need to compute $\hat{\gamma}$ much often\(^1\), and an iterative method is proposed here to solve (16). Next we define $M^{(t)}$ as

$$M^{(t)} = \sqrt{1 - \frac{1}{(1 + \gamma^{(t)})^2}}, \quad (17)$$

where $t$ is the iteration index. Substituting (17) into (16) and isolating $\gamma$ yields

$$\hat{\gamma}^{(t)} = 2^{r - \frac{1}{\sqrt{n}} M^{(t-1)} \log_2 e \ Q^{-1}(\epsilon_{th})} - 1. \quad (18)$$

The iterative method to find $\hat{\gamma}$ is fully described in Algorithm II where $\hat{\gamma}_\Delta$ is the acceptable maximum difference between the value of $\hat{\gamma}$ found by the proposed algorithm and its real required value. The choice for $M^{(0)} = 1$ comes from the fact that this is a good approximation for high SNR, as can be seen from (17). In Section V we show that the proposed method converges very fast for practical setups.

**Remark 2.** When achieving $\epsilon_i = \epsilon_{th}$ is impossible, an alternative strategy could be transmitting with the maximum available power that the harvested energy allows. We refer to this second strategy as Finite Blocklength Fixed Threshold Uninterrupted Transmission (FB-FTUT) and it is only included in Section V in order to assess the performance of the FB-FTT protocol.

\(^1\)Notice that the value of the required $\hat{\gamma}$ could be even programmed in $S$ from the very beginning for static scenarios.
Algorithm 1 Finding the required $\gamma$ for a given $(n, k, \epsilon_{th})$

1: $t = 1$, $M^{(0)} = 1$
2: Calculate $\hat{\gamma}^{(t)}$ using (18)
3: Calculate $M^{(t)}$ using (17)
4: if $|\hat{\gamma}^{(t)} - \hat{\gamma}^{(t-1)}| > \gamma_{\Delta}$ then
5: $t \rightarrow t + 1$
6: Return to line 2
7: end if
8: End

B. Overall Error Probability and Mean Power Consumption

The overall error probability for this scenario is given by

$$\varepsilon = (1 - \epsilon_{\text{out}}) \epsilon_{\text{th}} + \epsilon_{\text{out}},$$

(19)

where $\epsilon_{\text{out}} = \mathbb{P}[B_i < \hat{P}_{s,i} n T_e]$ is the probability that the energy available in the battery is insufficient to achieve the required $\gamma$ at $D$ for a given target error $\epsilon_{\text{th}}$.

Notice that $\epsilon_{\text{out}}$ depends on the value of $\epsilon_{\text{th}}$. The higher the value of $\epsilon_{\text{th}}$, smaller $\hat{\gamma}$ and transmit power $\hat{P}_s$ are required, and the smaller the value of $\epsilon_{\text{out}}$, and vice versa. Unfortunately, it seems intractable to find a closed-form expression for $\epsilon_{\text{out}}$ due to the complexity of (15), and we resort to simulations in Section V in order to compute it. In addition, we can notice that $\varepsilon \geq \epsilon_{\text{th}}$ always, thus a relatively high value of $\epsilon_{\text{th}}$ can seriously limit the system performance for some setups. An interesting fact related with this is given in the following lemma.

Lemma 1. There is an optimum value of $\epsilon_{\text{th}}$, $\epsilon_{\text{th}}^*$, that minimizes the overall error probability.

Proof. Let $\epsilon_{\text{out}} = s(\epsilon_{\text{th}})$ and $\varepsilon = q(\epsilon_{\text{th}})$, with $\epsilon_{\text{th}}, s(\epsilon_{\text{th}}), q(\epsilon_{\text{th}}) \in [0, 1]$. We know that $\epsilon_{\text{out}}$ is a decreasing function, $s$, of $\epsilon_{\text{th}}$ with $s(0) = 1$ and $s(1) = 0$, while $q(0) = q(1) = 1$ according to (19). Notice that when $\epsilon_{\text{th}} = 1$, the source $S$ does not transmit and all it does is saving energy. In that case, the overall error probability is the worst possible. When $\epsilon_{\text{th}}$ starts decreasing, $S$ is required to transmit with more and more power in order to fulfill the requirement. However, when $\epsilon_{\text{th}} = 0$ the required power is practically impossible and all that $S$ can do is saving energy, like when $\epsilon_{\text{th}} = 1$, and again the error performance is the worst possible. Then, in some point
between $\epsilon_{th} = 0$ and $\epsilon_{th} = 1$ an inflexion occurs. The singularity of this point is shown by simulations in Section V.

In addition, the energy consumption of $S$, characterized in terms of its average transmit power, is as follows

**Theorem 3.** The average transmit power of $S$ when using the proposed power control scheme, and when $m > 1$, is

$$
\bar{P} = (1 - \epsilon_{out})\gamma \kappa d^\alpha \sigma_d^2 m \left[ \frac{1}{m-1} - \frac{\Gamma(m-1, m\lambda)}{\Gamma(m)} \right],
$$

$$
\bar{P}_{\lambda=\infty} = (1 - \epsilon_{out})\gamma \kappa d^\alpha \sigma_d^2 \frac{m}{m-1},
$$

for finite and infinite battery devices, respectively.

**Proof.** See Appendix C

V. NUMERICAL RESULTS

In this section, we present numerical results to investigate the performance of the proposed scheme as a function of the system parameters. Unless stated otherwise, results are obtained by setting $m = 3$, $\alpha = 3$, $k = 192$ bits and $d = 15m$. We also assume that $\kappa = 30$ dB average signal power attenuation at a reference distance of 1 meter. Following the state-of-the-art in circuit design, we consider $\eta = 0.5$ [8], while we set $P_d = 30$dBm and $T_c = 10\mu s$, thus $\sigma_d^2 = -115$dBm is a valid assumption. Moreover, $\gamma_\Delta = 10^{-3}$ which imposes a high accuracy in the required value of $\gamma$ found by Algorithm 1.

A. On the Accuracy of (9), (10)

To measure the accuracy of the approximations made in (9) and (10) we evaluate the following error metric

$$
\xi = \frac{|\epsilon(9) - \epsilon(\rho)|}{\epsilon(9)},
$$

where $\epsilon(9)$ is the error probability in (7) and $\epsilon(\rho)$, $\rho \in \{9, 10\}$, are the approximate error probabilities in (9) and (10), for finite and infinite battery capacities, respectively. In order to obtain $\epsilon(9)$ we resort to numerical evaluation. Accordingly to Fig. 2a there is not a significant difference in the error approximation using (9) and (10) for a relative small transmit power $P_d = 30$dBm, while this error starts to increase when the gap between the harvested energy and
the battery size grows, e.g., $P_d = 60$ dBm and $B_{\text{max}} = 10^{-9}$ J. The error probability for those cases is shown in Fig. 2b. Notice that for $P_d = 30$ dBm, $\varepsilon \sim 10^{-1}$, while for $P_d = 60$ dBm the error when using relatively large batteries, e.g., $B_{\text{max}} \geq 10^{-7}$ J, is inferior to $10^{-4}$ due to the higher energy availability at $S$. The error probability improves when the number of WET channel uses ($v$) increases. In addition, a relatively small battery, e.g., $B_{\text{max}} = 10^{-9}$ J, limits the error probability because the energy availability at each transmission round is severely limited and also, the chances of saving energy for future attempts decrease. Thus both, the error approximation (Fig. 2a) and the error probability (Fig. 2b), are affected by a small battery.

B. On the Convergence of Algorithm 1

For scenarios with energy accumulation between transmission rounds, the required transmit power at $S$ is calculated at each round based on $\hat{\gamma}$, which can be found by running Algorithm 1. Fig. 3 shows the required number of iterations to solve Algorithm 1 as a function of the target
error probability, $\epsilon_{th}$, for setups with $n \in \{100, 200, 500\}$ channel uses. We can notice the very fast convergence of the iterative method in solving (16), even for a rigorous accuracy of $\hat{\gamma}_\Delta = 10^{-3}$. As shown in the figure, small values of $\epsilon_{th}$ require more iterations, specially for relatively large values of $n$. When $n$ increases, the rate diminishes and the required $\hat{\gamma}$ becomes smaller, thus more iterations are necessary to solve the problem with the given accuracy. If we decrease $\hat{\gamma}_\Delta$ the convergence would be slower. On the other hand, if we adopt a less demanding value of $\hat{\gamma}_\Delta$ such as $10^{-2}$, three iterations would be sufficient. As mentioned in Section IV, the value of $\hat{\gamma}$ has to be updated only when some element in $(n, k, \epsilon_{th})$ changes. Thus, it could be possible that Algorithm 1 does not run in $S$, but in another entity which broadcasts its value.

C. On the Performance of the Proposed Scheme

Fig. 4 presents the the overall error probability (Fig. 4a) and average transmit power (Fig. 4b), as a function of $\epsilon_{th}$ for $v = 800$, $n \in \{100, 200\}$ channel uses and infinite battery capacity, while comparing the three protocols previously discussed: HTT (Section III), FB-FTT and FB-FTUT (Section IV). In Fig 4a it is shown the existence and uniqueness of the optimum value of $\epsilon_{th}$ for the FB-FTT protocol, which supports the result given in Lemma 1. The FB-FTT scheme has the best performance for practical scenarios, e.g., $\epsilon_{th} < 10^{-1}$, although the difference when comparing to FB-FTUT becomes smaller for relatively large values of $n$. For $n = 200$ channel uses, the system has the best performance, thus $\epsilon_{th}^*$ is the smallest. In that case, the power control curves almost reach the allowable limit of $\epsilon = 10^{-6}$ for $\epsilon_{th} = 10^{-6}$. Notice that when $n$
increases, the required SNR and therefore the transmit power become smaller, and even when $S$ spends more time transmitting, the energy consumption decreases as shown in Fig 4b. This holds until certain $n$, $n^*$, and beyond that the weight of the transmitting time is more relevant than the small transmit power. Decreasing $\epsilon_{th}$ allows saving more energy while the average transmit power decreases as shown in Fig. 4b, however the error performance is bounded by this value. Notice also that the average transmit power, and consequently the average energy consumption, is practically the same for both FB-FTT and FB-FTUT strategies, thus FB-FTT is more energy efficient since it allows reaching a better error performance. Finally, we can note the remarkable performance gap between HTT and the power control protocols, which reinforces the appropriateness of the idea behind saving energy between transmission rounds.

In Fig. 5 we evaluate the impact of battery capacity, $B_{max} \in \{10^{-9}, 10^{-8}, 10^{-7}, \infty\}$J, while
comparing the performance of HTT and FB-FTT protocols in terms of $\varepsilon$ (Fig. 5a) and $\hat{P}$ (Fig. 5b) as a function of $P_d$, for $\epsilon_{th} = 10^{-6}$ and $v = 800$, $n = 200$ channel uses. As shown in Fig. 5a, the impact of a finite battery capacity on the error performance is insignificant for the HTT protocol since there is no energy accumulation between transmission rounds. Only when a high amount of energy is being transferred, e.g., $P_d > 45$ dBm, the gap starts to be appreciable. This is equivalent to system scenarios with a large number of WET channel uses ($v$), a larger influence of the line of sight ($m$), or with small operating distances, etc. However, for the FB-FTT scheme the situation is more delicate since the larger the battery capacity, the greater the chances to save more energy for future transmissions, thus the better the error performance (Fig. 5a) and the larger the average energy consumption (Fig. 5b). Notice the small system performance gap
between setups with $B_{\text{max}} = 10^{-7} \text{J}$ and $B_{\text{max}} = \infty$. It is evident that for $P_d > 30 \text{dBm}$ we have $\epsilon^*_{\text{th}} < 10^{-6}$, since the system setup favors a better performance. In that case the gap between $B_{\text{max}} = 10^{-7} \text{J}$ and $B_{\text{max}} = \infty$ could become more significant. Also, the overall error probability improves for $P_d < 30 \text{dBm}$ and/or $m < 3$ if we choose a smaller target error probability. The average transmit power for HTT protocol remains almost constant around $\hat{P} = -33 \text{dBm}$ for $B_{\text{max}} = 10^{-9} \text{J}$ and $P_d > 35 \text{dBm}$ since $\mathbb{E}[E_i] \gg B_{\text{max}}$, e.g., $\mathbb{E}[E_i]|_{P_d=35 \text{dBm}} \approx 8 \cdot 10^{-3} \text{J}$, thus $B_i = B_{\text{max}}$ and according to (4) $P_{s,i} \approx \frac{10^{-9.1}}{200 \cdot 10^{-9.8}} = 0.5 \cdot 10^{-6} \rightarrow -33 \text{dBm}$, both holding almost all the time. The FB-FTT protocol reaches an even small energy consumption since it does not spend all the available energy in each round, specially when channel conditions are favorable.

In Fig. 6 we fix the system delay in delivering each message by setting $n + v = 1000$ channel uses, e.g., $1000T_c = 10 \text{ms}$, which could be fundamental in systems with very stringent delay constraints, such as Ultra-Reliable Communication over Short Term (URC-S) scenarios for future wireless systems [26]. Results are given as a function of $n$, for $\epsilon_{\text{th}} \in \{10^{-3}, 10^{-6}, 10^{-9}\}$ and $B_{\text{max}} = 10^{-7} \text{J}$. In URC-S scenarios, a high reliability is also required, which could be achieved via the proposed FB-FTT scheme as shown here. Notice that the HTT performance is very poor, e.g., $\varepsilon > 10^{-1}$ all the time, while with the appropriate chosen value of $\epsilon_{\text{th}}$, the FB-FTT protocol can achieve an error probability around $\varepsilon = 10^{-6}$ for $n \sim 250$ channel uses. Also, when $n \geq 350$ channel uses, a target error probability greater than $10^{-6}$ is required in order to achieve the optimum system performance. Then, $n^* \sim 250$ channel uses and $\epsilon^*_{\text{th}} \sim 10^{-6}$.

---

**Fig. 6.** $\varepsilon$ as a function of $n$ for $\epsilon_{\text{th}} \in \{10^{-3}, 10^{-6}, 10^{-9}\}$, $B_{\text{max}} = 10^{-7} \text{J}$ and fixed delay $n + v = 1000$ channel uses.
VI. Conclusion

In this paper, we evaluated a point-to-point communication system at finite blocklength regime with WET in the downlink, WIT in the uplink and a finite battery capacity. We attained closed-form expressions for error probability and average transmit power in scenarios where energy accumulation between transmission rounds are allowed or not, and Nakagami-\(m\) reciprocal channels are assumed. For scenarios allowing energy accumulation we propose a power control protocol with CSI at the transmitter side, which can be seen as a variant for finite blocklength of the FTT scheme \([23]\). The numerical results show that

- the closed-form approximations for the case without energy accumulation between transmission rounds (HTT protocol), under the assumption of finite and infinite battery devices, are pretty accurate when batteries are not extremely small;
- saving energy for future transmissions (FB-FTT scheme) allows to improve the system performance in terms of error probability while reducing the energy consumption;
- the proposed iterative method (Algorithm 1), which allows to find the required SNR for a target error probability, converges very fast;
- the optimum system performance depends on the chosen target error probability value, which in turns depends on the remaining system parameters;
- there is an optimum value of target error probability that minimizes the achievable error probability. However, the higher the target error probability, the lower the energy consumption;
- a relatively small battery could be a limiting factor for some setups and specially for scenarios allowing energy accumulation between transmission rounds.

As a future work we intend to analyze the impact of imperfect CSI, while considering the additional delay and the energy consumption required for CSI acquisition. In addition, it could be interesting to incorporate power allocation strategies in WPCN with HARQ or/and cooperative mechanisms with finite blocklength.

APPENDIX A

PROOF OF THEOREM 1

Let \(I_1\) and \(I_2\) be the first and second integral in \((7)\), respectively. Then, and accordingly to \((8)\), \(\mu_1 = \beta\), \(t = 2\) for \(I_1\) and \(\mu_2 = \beta \lambda\), \(t = 1\) for \(I_2\). Also, \(\zeta_j = \sqrt{\frac{\rho}{\mu_j}}\) and \(\varphi_j = \sqrt{\frac{\vartheta}{\mu_j}}\), where \(j \in \{1, 2\}\).
Substituting (8) into (7), $I_1$ can be approximated as follows

$$I_1 \approx \int_0^{z_{11}} f_G(g)dg + \omega_1 \int_{z_{11}}^{z_{12}} f_G(g)dg - \omega_2 \int_{z_{11}}^{z_{12}} g f_G(g)dg$$

$$\approx F_G(z_{11}) + \omega_1 F_G(z_{12}) - \omega_1 F_G(z_{11}) - \omega_2 \int_{z_{11}}^{z_{12}} \frac{m_m}{\Gamma(m)} g^{m+1}e^{-mg}dg$$

$$\approx 1 - \frac{\omega_1}{\Gamma(m)} \Gamma(m, mz_{11}) - \frac{\omega_1}{\Gamma(m)} \Gamma(m, mz_{12}) + \frac{\omega_2}{m^2 \Gamma(m)} \left[ \Gamma(m+2, mz_{12}) - \Gamma(m+2, mz_{11}) \right],$$

where $\omega_1 = \left( \frac{1}{2} + \frac{\phi_0}{\sqrt{2\pi}} \right)$, $\omega_2 = \frac{\phi_1}{\sqrt{2\pi}}$, $z_{11} = \min(\zeta_1, \lambda)$ and $z_{12} = \min(\varphi_1, \lambda)$. Also, (a) comes from using the CDF definition of a random variable, while substituting the PDF expression for variable $G$ in the last term. In (b), the CDF expression of $G$ is used, while the last term comes from algebraic transformations of the incomplete gamma function definition [45] eq.(8.2.1)]

Similarly to $I_1$, $I_2$ can be approximated as follows

$$I_2 \approx \int_{\lambda}^{z_{21}} f_G(g)dg + \omega_1 \int_{\lambda}^{z_{22}} f_G(g)dg - \omega_2 \lambda \int_{\lambda}^{z_{22}} g f_G(g)dg$$

$$\approx F_G(z_{21}) - F_G(\lambda) + \omega_1 F_G(z_{22}) - \omega_1 F_G(z_{21}) - \omega_2 \lambda \int_{\lambda}^{z_{22}} \frac{m_m}{\Gamma(m)} g^{m+1}e^{-mg}dg$$

$$\approx \frac{\omega_1 - 1}{\Gamma(m)} \Gamma(m, mz_{21}) + \frac{\Gamma(m, m\lambda)}{\Gamma(m)} - \frac{\omega_1}{\Gamma(m)} \Gamma(m, mz_{22}) +$$

$$+ \frac{\omega_2 \lambda}{m\Gamma(m)} \left[ \Gamma(m+1, mz_{22}) - \Gamma(m+1, mz_{21}) \right],$$

where $z_{21} = \max(\zeta_2, \lambda)$ and $z_{22} = \max(\varphi_2^2, \lambda)$.

Then, substituting (23) and (24) into $\varepsilon \approx I_1 + I_2$ (7) we attain (9). Now, notice that in the case of infinite battery assumption, $\lambda \to \infty$, $\varepsilon \approx I_1$ holds. Also, $z_{11} = \zeta_1 = \sqrt{\frac{2}{\beta}}$ and $z_{12} = \varphi_1 = \sqrt{\frac{2}{\beta}}$, which allows to attain (10).

**APPENDIX B**

**PROOF OF THEOREM 2**

By using (4) and the PDF and CDF expressions of the channel gain $g$ we attain

$$\bar{P} = \mathbb{E}[P_{s,i}] = \int_0^\infty P_{s,i} f_G(g)dg = \frac{\eta v P_d}{nkd^\alpha} \left[ \int_0^\lambda g f_G(g)dg + \lambda \int_\lambda^\infty f_G(g)dg \right]$$

$$= \frac{\eta v P_d}{nkd^\alpha} \left[ \frac{m_m}{\Gamma(m)} \int_0^\lambda g^{m}e^{-mg}dg + \lambda \left( 1 - F_G(\lambda) \right) \right]$$

$$= \frac{\eta v P_d}{nkd^\alpha} \left[ - \frac{\Gamma(m+1, mg)}{\Gamma(m+1)} \bigg|_0^\lambda + \frac{\Gamma(m, m\lambda)}{\Gamma(m)} \right],$$

$$\approx 1 - \frac{\omega_1}{\Gamma(m)} \Gamma(m, mz_{11}) - \frac{\omega_1}{\Gamma(m)} \Gamma(m, mz_{12}) + \frac{\omega_2}{m^2 \Gamma(m)} \left[ \Gamma(m+2, mz_{12}) - \Gamma(m+2, mz_{11}) \right],$$

(23)
where the first term in (a) comes from algebraic transformations of the incomplete gamma function definition \[45, \text{eq.}(8.2.1)\]. Showing that (25) is equivalent to (12) is straightforward. Now, if \( B_{\text{max}} = \infty \) then

\[
\bar{P}_{\lambda=\infty} = \mathbb{E}[\hat{P}_{s,i}] = \frac{\eta v P_d}{nk d_{\alpha}} \mathbb{E}[g] = \frac{\eta v P_d}{nk d_{\alpha}},
\]

which is equal to (12).

\[
(26)
\]

\section*{Appendix C}

\textbf{Proof of Theorem 3}

The average power consumption of \( S \) can be computed as

\[
\bar{P} = (1 - \epsilon_{\text{out}}) \mathbb{E}[\hat{P}_{s,i}] = (1 - \epsilon_{\text{out}}) \int_0^\lambda \hat{P}_{s,i} f_G(g) \, dg
\]

\[
\overset{(a)}{=} (1 - \epsilon_{\text{out}}) \gamma k d_{a} \sigma_d^2 \int_0^\lambda \frac{m^m}{\Gamma(m)} g^{m-2} e^{-mg} \, dg
\]

\[
\overset{(b)}{=} -(1 - \epsilon_{\text{out}}) \gamma k d_{a} \sigma_d^2 m \frac{\Gamma(m-1, mg)}{\Gamma(m)} \bigg|_0^\lambda,
\]

\[
(27)
\]

where (a) comes from using (14), and (b) from algebraic transformations of the incomplete gamma function definition \[45, \text{eq.}(8.2.1)\] with \( m > 1 \). We attain (20) straightforward from (27). Now, substituting \( \lambda = \infty \) into (27) yields

\[
\bar{P}_{\lambda=\infty} = -(1 - \epsilon_{\text{out}}) \gamma k d_{a} \sigma_d^2 m \frac{\Gamma(m-1, mg)}{\Gamma(m)} \bigg|_0^\infty
\]

\[
= (1 - \epsilon_{\text{out}}) \gamma k d_{a} \sigma_d^2 m \frac{\Gamma(m-1, 0)}{\Gamma(m)},
\]

\[
(28)
\]

which is equal to (21).

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