Batteryless Machine-Type Communications
With Average Channel State Information
Energy Beamforming

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ABSTRACT Machine-type communication (MTC) is a key component in 5G and beyond wireless networks, enabling important applications oriented to the industry. In such environments, the limited lifetime of battery-powered solutions becomes a relevant reliability issue. In this paper, we consider a sensor node powered wirelessly by a dedicated multi-antenna power beacon (PB). The harvested energy is directly used by the sensor to power its transceiver and send information to a destination node without storing it in a battery, which would demand non-negligible charging time and potentially compromise the MTC operation. Also, we leverage a packet replication mechanism during information transmission from the sensor to the destination in order to improve the system reliability. We derive the incident power statistics and the outage probability assuming Rician fading channels and only average channel state information at the PB. Then, we define an optimization problem aiming to minimize the energy required by the PB by properly tuning the number of replicated packets and the harvesting time. Results show the existence of an optimal harvesting time as well as an optimal number of replications for a given number of PB antennas, enabling batteryless MTC applications.

INDEX TERMS Machine-type communication, batteryless, power beacon, packet replication, average channel state information.

I. INTRODUCTION

The manufacturing industry is facing a digital transformation driven by the exponential growth of intelligent devices, such as sensors, robots, 3D printing, etc. The future of manufacturing tends towards connecting industry components wirelessly, delivering data more flexibly and adaptively. Such a revolution, known as Industry 4.0, shares concepts with the Internet of Things (IoT), focusing on interconnectivity, automation, machine learning, and real-time data transmission. According to Ericsson [1], 39 billion IoT connections are foreseen for 2026, with around 27.5 billion of them related to the industry.

Machine-type communication (MTC) is one of the key components to integrate communications and manufacturing requirements, evolving industrial applications [2]. Here,
packet replication (PR) is a promising solution as it allows increasing the system reliability without needing a feedback channel. For instance, PR is used in [3] to deal with multipath fading by prioritizing uncorrelated paths to replicate packets. The scheme provides resilience to multipath fading and benefits delay-sensitive applications. In [4], the authors compare automatic repeat request (ARQ) and PR strategies in industrial networks, investigating the trade-offs of energy and bandwidth versus reliability and availability. Notice that the implementation of ARQ implies waiting for an acknowledgment message before retransmitting a packet, while PR relies on pro-actively transmitting multiple replicas of the same packet without waiting for a feedback, at the cost of increasing the required spectral efficiency to meet latency constraints. The PR approach proposed in [4] reduces the packet error rate by approximately six times, at the cost of increasing the energy consumption by around 10% compared to ARQ.

Notice that satisfying MTC service requirements may be power consuming due to the unreliable nature of the wireless medium. Taking the power consumption into consideration, the authors in [5] reduce the communication energy budget by making reliability/latency constraints more flexible. A dynamic allocation algorithm is provided in order to detect when such constraints can be relaxed, aiming for reduced energy consumption. The authors in [6] propose a low-latency distributed scheduling function to minimize the latency while providing high reliability. The process reorganizes the slotted frame into smaller blocks so that each transmitter selects a set of blocks depending on its hop distance from the router, better distributing retransmissions. Then, to save energy, nodes can turn off their radio as soon as their packets are correctly acknowledged. Also, the authors in [7] evaluate the benefits of improving communication reliability by combining PR with modulation diversity using multiple IEEE 802.15.4g transmission modes. Such a combination is shown to increase the system reliability while maintaining the same energy consumption.

Common to [5], [6], and [7] is the effort to save energy from battery-powered MTC devices. Nevertheless, as pointed out by [8], the evolution of industrial manufacturing employing battery-operated sensors today may become a maintenance problem in the future. This is motivated by the need to replace batteries across thousands of devices constantly. In this regard, wireless energy transfer (WET) technology has emerged as a suitable option for charging low-power devices, such as industrial sensors. Specifically, WET enables radio frequency (RF) to direct current (DC) power conversion without physical connections, while enabling small-form factor implementations and natively supporting multi-user charging [9], [10], [11].

WET is a growing research topic in the literature, with recent approaches found, e.g., in [12], [13], [14], and [15]. The authors in [12] study wireless powered communications where multiple access points collaborate using distributed energy beamforming in the downlink, so that energy harvesting (EH) devices can transmit in the uplink. Results show significant gains in terms of coverage and transmission probabilities when multiple access points collaborate for WET. A wireless-powered backscatter communication network is considered in [13], where a transmitter harvests energy from a dedicated RF source. Then, a Dinkelbach-based algorithm is formulated to maximize the energy efficiency by jointly optimizing the time allocation, the reflection coefficient, and the transmit power of the source.

However, perfect instantaneous channel state information (CSI) is usually considered in the design of energy beamforming vectors, thus becoming inefficient, or unfeasible, due to the time and energy consumption during CSI acquisition. Moving to more practical approaches, the work in [14] studies the relationship between the EH rate and the data rate with imperfect instantaneous CSI. By formulating the energy beamforming design as a max-min optimization problem, the proposed scheme achieves more than 90% of the data rate obtained with perfect CSI. Assuming that instantaneous CSI is not available, the authors in [15] study the optimal deployment of power beacons (PBs) to satisfy an energy outage constraint. The proposed solution provides a framework in which neither CSI nor devices’ locations are known, so that PBs’ positions are optimized to maximize the minimum average RF energy.

Another important implication of WET that is often neglected in the literature is the time required to charge a battery/supercapacitor. An EH device uses a rectenna to convert RF into a DC power source, and the recovered DC power is stored in a battery for higher power low duty-cycle operations. That is the basis of harvest-then-transmit schemes, so that WET and wireless information transfer (WIT) phases occur in sequence. However, storing energy in a battery or supercapacitor demands time at least in the order of seconds due to the resistor-capacitor (RC) time constant of the circuit [16], [17], which is unfeasible for some industrial applications. Such charging time is often overlooked by the WET literature, although it plays a crucial role in time-critical applications.

In this work, we focus on a short distance scenario, typical of the WET-enabled solutions emerging in the market. As an example, the PowerSpot® RF Wireless Power Development Kit [18] enables battery-free wireless sensor applications in a charging distance of up to a few meters. In this context, we consider a batteryless industrial sensor node and a nearby dedicated multi-antenna PB, which is employed in order to supply energy to the sensor with high reliability. The recovered DC power at the sensor node powers the transceiver directly by means of the power management unit (PMU) [19], without storing it in a battery. The implication is that WET and WIT phases must occur simultaneously in this case. In the WIT phase, the sensor node transmits information to a destination node that performs automation tasks, so the communication must occur within a maximum time deadline and with a target outage probability constraint. Our approach yields the following contributions:
- We derive the incident power statistics and the outage probability assuming Rician fading channels and average CSI (A-CSI) beamforming at the PB.
- We define an optimization problem to determine the number of replicated packets in the WIT phase and the charging time in the WET phase, to minimize the energy required from the PB. We exploit the convexity and strictly monotonic properties of the problem to solve it iteratively.
- We show the existence of an optimal harvesting time and an optimal number of replications for a given number of antennas at the PB. Remarkably, the optimal values for the practical A-CSI scheme are only slightly larger than those of the ideal full CSI (F-CSI) beamforming.

Notation: Boldface lowercase letters denote column vectors, while boldface uppercase letters denote matrices. \( I \) denotes the identity matrix. \( || \cdot || \), \( | \cdot | \), \( (\cdot)^H \) and \( (\cdot)^T \) stand for the Euclidean norm, absolute value, Hermitian transpose and transpose operations, respectively. \( \mathbb{E}_x[\cdot] \) denotes the statistical expectation over the variable \( x \), and \( j \) is the imaginary unit, \( i.e., j = \sqrt{-1}. \) \( \mathbb{C} \) is the set of complex numbers, \( x \sim \mathcal{CN}(m, R) \) is a circularly-symmetric complex Gaussian random vector with mean vector \( m \) and covariance matrix \( R \), and \( x \sim \mathcal{N}(a, b) \) is a Gaussian random variable with mean \( a \) and variance \( b \). \( F_A(x) \) stands for the cumulative distribution function (CDF) of the random variable \( A \) and \( f_A(x) \) represents its probability density function (PDF). Moreover, \( Q_\nu(\cdot, \cdot) \) is the Generalized order \( \nu \) Marcum \( Q \)-function and \( I_0(\cdot) \) is the Bessel function of the first kind. Additionally, for convenience, the rest of the acronyms and symbols adopted in this work are summarized in Tables 1 and 2, respectively.

II. SYSTEM MODEL

We assume the scenario in Figure 1, consisting of a WET link to power the source using a PB, and a WIT link to transmit data from the source to the destination. Furthermore, WET and WIT phases occur simultaneously during a time \( T_i \), for \( i \in \{\text{A-CSI}, \text{F-CSI}\} \). In the WET link, the PB is equipped with a uniform linear array (ULA) of \( M \) antennas and the source uses a single rectenna to harvest energy, so that the WET channel vector is denoted as \( h \in \mathbb{C}^{M \times 1} \). The PB employs an A-CSI precoder [20], while the recovered DC power at the source is immediately used by the transceiver through the PMU. In the WIT link, the source node employs a PR mechanism, transmitting \( K_i \) replicas of the same packet during the time \( T_i \) to increase the system reliability. Both source and destination are assumed single-antenna. Figure 1 shows the WIT channel for the \( k \)-th replication, denoted by \( z_k \in \mathbb{C} \). Finally, we assume that the communication between source and destination must occur within a maximum time deadline \( T_{\text{max}} \) and with a target outage probability constraint \( O^* \).

A. CHANNEL MODELS

1) WET LINK

The channel between the PB and the source is subject to Rician fading with line of sight (LOS) factor \( \kappa_{\text{wet}} \) and coherence time \( T_c \). The channel vector of the WET link can be written as [21] and [20]

\[
h = \sqrt{\beta_{\text{wet}}} (\tilde{h} + \tilde{h}) \in \mathbb{C}^{M \times 1},
\]

where \( \tilde{h} \) is the deterministic LOS component, and \( \tilde{h} \) is the zero-mean scattering (random) component with covariance \( R = \mathbb{E}[\tilde{h}\tilde{h}^H] \). Then, we have that [20], [21]

\[
\tilde{h} = \sqrt{\frac{\kappa_{\text{wet}}}{1 + \kappa_{\text{wet}}}} e^{j\psi_0} [1, e^{j\phi_1}, \ldots, e^{j\phi_{M-1}}]^T,
\]

\[
\tilde{h} \sim \sqrt{\frac{1}{1 + \kappa_{\text{wet}}}} \mathcal{CN}(0, R),
\]

where \( \psi_t, t \in \{1, \ldots, M - 1\} \), is the mean phase shift of the \( (t + 1) \)-th array element with respect to the first

TABLE 1. List of acronyms adopted in this work.

| Acronym  | Meaning                                      |
|----------|----------------------------------------------|
| ARQ      | Automatic Repeat reRequest                   |
| A-CSI    | Average Channel State Information            |
| BLE      | Bluetooth Low Energy                        |
| CSI      | Channel State Information                    |
| CDF      | Cumulative Distribution Function             |
| DC       | Direct Current                               |
| EH       | Energy Harvesting                            |
| F-CSI    | Full Channel State Information               |
| i.i.d.   | Independent and Identically Distributed      |
| IoT      | Internet-of-Things                          |
| LOS      | Line Of Sight                                |
| MRC      | Maximal Ratio Combining                      |
| MRT      | Maximum Ratio Transmission                   |
| MTC      | Machine-Type Communication                   |
| PA       | Power Amplifier                              |
| PB       | Power Beacon                                 |
| PDF      | Probability Distribution Function            |
| PMU      | Power Management Unit                        |
| PSD      | Power Spectral Density                       |
| PR       | Packet Replication                           |
| RC       | Resistor-Capacitor                           |
| RF       | Radio Frequency                              |
| SNR      | Signal-to-Noise Ratio                        |
| ULA      | Uniform Linear Array                         |
| WET      | Wireless Energy Transfer                     |
| WIT      | Wireless Information Transfer                |

FIGURE 1. System diagram with WET and WIT phases.
TABLE 2. List of symbols adopted in this work.

| Symbol | Meaning |
|--------|---------|
| $M$ | Number of antennas at the PB |
| $K_i$ | Number of replicas of the same packet |
| $T_i$ | Harvesting/Transmission time |
| $R_i$ | Spectral efficiency |
| $i$ | Precoding scheme $i \in \{\text{A-CSI, F-CSI}\}$ |
| $N$ | Number of bits per packet |
| $c$ | Speed of light |
| $B$ | System bandwidth |
| $h$ | Channel vector of the WET link |
| $\hat{h}$ | LOS/Scattering of the WET link |
| $\kappa_{\text{wet}}, \kappa_{\text{wit}}$ | LOS factor of the WET/WIT link |
| $\psi_t$ | Mean phase shift of the $(t+1)$-th array element w.r.t. the first PB antenna |
| $\varphi_0$ | Initial phase shift of the PB antenna array |
| $\theta$ | Azimuth angle to the boresight of the PB antenna array |
| $\beta_{\text{wet}}, \beta_{\text{wit}}$ | Average power gains |
| $f_{\text{wet}}, f_{\text{wit}}$ | Carrier frequencies |
| $d_{\text{wet}}, d_{\text{wit}}$ | Distances |
| $\alpha_{\text{wet}}, \alpha_{\text{wit}}$ | Path-loss exponents |
| $z_k$ | Channel of the $k$-th replication in WIT |
| $\bar{z}_k$ | LOS/Scattering of the WIT link |
| $\bar{z}$ | Mean phase shift of the source’s antenna |
| $T_c$ | WET/WIT channel coherence time |
| $w_i$ | MRT precoder |
| $P_i$ | RF power harvested by the source |
| $P_b$ | Transmit power of the PB |
| $\mathcal{G}(x)$ | Nonlinear rectenna EH function |
| $V$ | EH saturation level |
| $c_0$ | Nonlinear EH rate w.r.t. the input power |
| $c_1$ | Minimum turn-on voltage of the EH circuit |
| $\xi$ | Harvesting efficiency |
| $\eta$ | Drain efficiency of the PA |
| $P_{\text{cir}}$ | Transceiver fixed power consumption |
| $P_{\text{tx}}$ | Transmit power |
| $P_{\text{total}}$ | Total power consumption |
| $P_{\text{max}}$ | Maximal transmit power |
| $\gamma_i$ | Instantaneous SNR |
| $\gamma_0$ | SNR threshold for correct decoding |
| $N_i$ | Noise figure |
| $N_0$ | Noise PSD |
| $|z_\text{MRC}|^2$ | Equivalent channel due to the MRC of $K_i$ |
| $O_i$ | Outage probability |
| $O^*$ | Target outage probability |
| $E_{\text{E}}^*$ | Energy required by the PB |
| $K_{\text{max}}$ | Maximal number of replicas |
| $T_{\text{max}}$ | Maximum time deadline |
| $R_{\text{max}}$ | Maximum spectral efficiency |

antenna, and $\varphi_0$ accounts for an initial phase shift. Assuming half-wavelength equally spaced antenna elements, it follows that $\psi_t = -t \pi \sin \theta$, where $\theta \in [0, 2\pi]$ is the azimuth angle relative to the boresight of the transmitting antenna array. Moreover, the average power gain in the WET link is

$$\beta_{\text{wet}} = \frac{c^2}{(16\pi^2f_{\text{wet}}^2d_{\text{wet}}^2)},$$

where $c$ is the speed of light, $f_{\text{wet}}$ is the carrier frequency in the WET link, $d_{\text{wet}}$ is the PB-source distance, and $\alpha_{\text{wet}}$ is the path-loss exponent.

2) WIT LINK

The source node establishes WIT to the destination through a channel subject to Rician fading with LOS factor $\kappa_{\text{wit}}$. In addition, the same coherence time $T_c$ is assumed, since WET and WIT occur simultaneously. Both nodes are assumed single-antenna. In addition, we assume different channel realizations for each of the $K_i$ replications. Such model is representative of frequency hopping, where replications occur in different channel realizations. Thus, for the $k$-th replication, $k \in [1, K_i]$, we have

$$z_k = \sqrt{\beta_{\text{wit}}(\bar{z} + \tilde{z}_k)} \in \mathbb{C},$$

where $\bar{z}$ is the deterministic (LOS) component, and $\tilde{z}_k$ is the zero-mean scattering (random) component, so that

$$\bar{z} = \sqrt{\kappa_{\text{wit}}1 + \kappa_{\text{wit}}} e^{j\phi},$$

$$\tilde{z}_k \sim \sqrt{\frac{1}{1 + \kappa_{\text{wit}}}} \mathcal{CN}(0, 1),$$

where $\phi$ is the mean phase shift. Moreover, $\beta_{\text{wit}}$ is the average power gain, which is given by

$$\beta_{\text{wit}} = \frac{c^2}{16\pi^2f_{\text{wit}}^2d_{\text{wit}}^2},$$

where $f_{\text{wit}}$ is the carrier frequency in the WIT link, $d_{\text{wit}}$ is the distance, and $\alpha_{\text{wit}}$ is the path-loss exponent.

B. PACKET REPLICATION

In the WIT link, the source node employs PR. Thus, it transmits $K_i$ packets with the same information to the destination in order to increase the reliability against packet losses. The total number of bits per packet is denoted by $N$. Then, the destination employs maximal ratio combining (MRC) in order to combine all replicas of the same packet. Therefore, the normalized rate, or spectral efficiency, for the scheme $i \in \{\text{A-CSI, F-CSI}\}$ is

$$R_i = \frac{K_i N}{B T_i},$$

where $B$ is the system bandwidth. Notice that the replicas are transmitted during the time $T_i$, so that increasing $K_i$ implies a higher spectral efficiency $R_i$ to meet the delay constraints. In addition, the outage probability depends on the quality of

\footnote{For instance, in Bluetooth low energy transceivers channel hopping occurs by default within the 2.4 GHz ISM band, using a 37 channel pseudorandom hopping pattern [22].}
the WIT link and on the energy provided by the WET link, which are detailed in Section IV.

III. INCIDENT POWER STATISTICS

We statistically characterize the incident RF power at the source node during the WET phase. We assume A-CSI precoder following [20]. Such beamforming design does not require instantaneous CSI acquisition, thus, avoiding frequent energy-costly feedback/signaling processes. Note that this is a practical approach for MTC applications since it may be very hard (if possible) to acquire instantaneous CSI for these applications. In addition, as a benchmark, we also consider an F-CSI scheme, where perfect instantaneous CSI of the PB-source link is ideally available at the PB. In a general form, assuming a precoder \( w_i, i \in \{ \text{A-CSI, F-CSI} \} \), the RF power harvested by the source is

\[
P_i = |w_i^H h|^2. \tag{10}
\]

A. AVERAGE CSI (A-CSI) BEAMFORMING

In order to use only average CSI, we observe that

\[
E[h] = \sqrt{\beta_{\text{wet}}} \bar{h}, \tag{11}
\]

thus, the maximum ratio transmission (MRT) precoder with A-CSI is [20]

\[
w_{\text{A-CSI}} = \sqrt{P_{b}} \frac{\bar{h}}{|h|}, \tag{12}
\]

where \( P_{b} \) is the transmit power of the PB. Therefore, substituting (12) into (10) yields

\[
\mathcal{P}_{\text{A-CSI}} = \left| \sqrt{P_{b}} \frac{\bar{h}^H}{|h|} \right|^2
= \beta_{\text{wet}} P_{b} \left| |\bar{h}| + \frac{\bar{h}^H h}{|h|} \right|^2
= \beta_{\text{wet}} P_{b} \delta^2. \tag{13}
\]

Here, \( \bar{h}^H \bar{h} \sim \mathcal{CN}(0, \bar{h}^H \bar{R}_h) \), thus,

\[
\delta = ||\bar{h}| + \frac{\bar{h}^H h}{|h|} |\sim\mathcal{CN} \left( ||\bar{h}|, \frac{\bar{h}^H \bar{R}_h}{|h|} \right). \tag{14}
\]

Moreover, we can decompose \( \delta \) as

\[
\delta = \frac{\sqrt{\bar{h}^H \bar{R}_h}}{\sqrt{2} |h|} (\delta_R + j\delta_I), \tag{15}
\]

where

\[
\delta_R \sim \mathcal{N} \left( \frac{\sqrt{2} ||\bar{h}|^2}{\bar{h}^H \bar{R}_h}, 1 \right), \tag{16}
\]

\[
\delta_I \sim \mathcal{N}(0, 1). \tag{17}
\]

As a consequence, \( \frac{2||\bar{h}|^2}{\bar{h}^H \bar{R}_h} \delta^2 = \delta_R^2 + \delta_I^2 \) follows a non-central chi-squared distribution with \( k = 2 \) degrees of freedom, and non-centrality parameter

\[
\lambda = \frac{2||\bar{h}|^4}{\bar{h}^H \bar{R}_h}. \tag{18}
\]

Given the above, the CDF of \( \mathcal{P}_{\text{A-CSI}} \) is [23]

\[
F_{\mathcal{P}_{\text{A-CSI}}} (x) = 1 - Q_1 \left( a, b \sqrt{x} \right), \tag{19}
\]

where \( Q_v (\cdot, \cdot) \) is the generalized Marcum Q-function of order \( v \), \( a = \sqrt{\frac{2}{\bar{h}^H \bar{R}_h} ||\bar{h}|^2} \) and \( b = \sqrt{\frac{P_{b} \beta_{\text{wet}}}{\bar{h}^H \bar{R}_h}} ||\bar{h}|. In addition, assuming i.i.d. Ricean fading channels, we have \( R = I^{\frac{1}{1+\kappa_{\text{wet}}}} \) [20], [21], so that

\[
\bar{h}^H \bar{R}_h = \frac{M_{\text{wet}}}{(1 + \kappa_{\text{wet}})^2}. \tag{20}
\]

As a consequence,

\[
a = \sqrt{2 \kappa_{\text{wet}}} M, \tag{21}
\]

\[
b = \sqrt{\frac{2(1 + \kappa_{\text{wet}})}{P_{b} \beta_{\text{wet}}}}. \tag{22}
\]

Furthermore, we can obtain the PDF of the incident RF power as the derivative of (19), so that

\[
f_{\mathcal{P}_{\text{A-CSI}}} (x) = \frac{1}{2} e^{-\frac{|a x + b|^2}{2}} b^2 I_0(a \sqrt{x}), \tag{23}
\]

where \( I_0(\cdot) \) is the modified Bessel function of the first kind.

Let us remark that average CSI of the WET link at the PB could be obtained by an initial setup of the source node, and updated periodically by exchanging pilot symbols.

B. FULL CSI (F-CSI) BEAMFORMING

In this case, \( h \) is assumed perfectly known; thus, the MRT precoder is [20]

\[
w_{\text{F-CSI}} = \sqrt{P_{b}} \frac{h}{|h|}, \tag{24}
\]

which substituted in (10) yields

\[
\mathcal{P}_{\text{F-CSI}} = \left| \sqrt{P_{b}} \frac{h^H}{|h|} \right|^2 = \beta_{\text{wet}} P_{b} |h|^2. \tag{25}
\]

Note that \( \mathcal{P}_{\text{F-CSI}} \) is known since we assume F-CSI. However, let us remark that F-CSI beamforming is the ideal solution, but rather unrealistic. That is because perfect knowledge of \( h \) at the PB would require frequent control signaling from the source node to the PB, consuming additional energy and time resources, which are very limited in our scenario. As a consequence, F-CSI is employed in this work only as a performance benchmark for A-CSI, while the latter does not require instantaneous CSI acquisition.

IV. ENERGY AND RELIABILITY ANALYSIS

Notice that the system reliability is affected by the performance of both links. A poor WET channel will decrease the energy availability at the source, impacting the received signal-to-noise ratio (SNR) at the destination during WIT. Meanwhile, a poor WIT channel will directly affect the communication between the source and destination.

\[\text{2The analysis presented here is valid for any channel model, not only for Ricean channels. Our choice for the Ricean fading channels is to provide a flexible characterization of many practical scenarios, since the severity of the fading can be adjusted through } \kappa_{\text{wet}}.\]
A. ENERGY HARVESTING

Herein, we discuss the electronics of the source node, which impacts both EH and power consumption. First, let us discuss the nonlinear model of the rectenna, which describes the saturation of the output DC power given a large RF input power due to the diode breakdown. Such modeling is circuit-specific and obtained via curve fitting based on measured data. Here, we follow the non-linear function in [19] in order to model the total energy harvested by the rectenna, as

\[ G(x) = \frac{W(1 - e^{-c_0x})}{1 + e^{-c_0(c_1 - x)}}, \quad (26) \]

with \( W \) denoting the saturation level, \( i.e., \) the maximal DC power produced by the EH circuit when the RF input is excessively large, \( c_0 \) reflects the nonlinear harvesting rate with respect to the input power, while \( c_1 \) determines the minimum turn-on voltage of the EH circuit. Then, for a given incident RF power \( P_i \) at the source, the non-linear function in (26) defines a harvesting efficiency

\[ \xi_i = \frac{G(P_i)}{P_i}. \quad (27) \]

B. TRANSCIEVER MODEL

Regarding the WIT circuitry, the power consumption of low-power transceivers is usually modeled as a linear function encompassing the drain efficiency \( \eta \) of the power amplifier (PA), and an additional fixed power consumption \( P_{\text{circ}} \) associated with other circuit elements of the transceiver [24]. Therefore, to produce a transmit power \( P_i^{\text{tx}} \), the transceiver consumes

\[ P_i^{\text{total}} = \frac{P_i^{\text{tx}}}{\eta} + P_{\text{circ}}. \quad (28) \]

Assuming that all energy harvested by the rectenna is employed by the transceiver, we have that \( P_i^{\text{total}} = G(P_i) \), where \( P_i \) is the RF input power at the rectenna when the PB employs the precoder \( i \in \{\text{A-CSI, F-CSI}\} \). Thus, the transmit power is

\[ P_i^{\text{tx}} = \min \left\{ \max \left\{ 0, \frac{\eta G(P_i) - P_{\text{circ}}}{\eta} \right\}, P_i^{\text{max}} \right\}, \quad (29) \]

in which the max operation comes from the fact that \( P_i \geq G^{-1}(P_{\text{circ}}) \) must be harvested in order to output \( P_i^{\text{tx}} \geq 0 \), while the min operation constraints the transmission power to a maximum \( P_i^{\text{max}} \).

C. OUTAGE PROBABILITY

An outage occurs when the instantaneous SNR at the destination \( \gamma_i \), for \( i \in \{\text{A-CSI, F-CSI}\} \), falls below the SNR threshold \( \gamma_0 \) after \( K \) replications. Assuming the Shannon limit and spectral efficiency of \( R_i \) bits/s/Hz, we set \( \gamma_0 = 2^{R_i} - 1 \) [25].

Meanwhile

\[ \gamma_i = \frac{P_i^{\text{tx}} \beta_{\text{wit}} |z|_2^2}{N_i N_0 B}, \quad (30) \]

where \( N_i \) is the noise figure, \( N_0 \) is the noise power spectral density (PSD), and \( |z|_2^2 = \sum_{k=1}^{K_i} |z_k|^2 \) due to the MRC of the \( K_i \) replicas, whose CDF can be written as [23]

\[ F_{|z|_2^2}(x) = 1 - Q_{K_i} \left( \sqrt{2K_i \kappa_{\text{wit}}}, \sqrt{2(1 + \kappa_{\text{wit}})} x \right). \quad (31) \]

Thus, the outage probability can be written as

\[ O_i = \Pr (\gamma_i < \gamma_0) = \Pr \left( |z|_2^2 < \frac{\gamma_0 N_i N_0 B}{P_i^{\text{tx}} \beta_{\text{wit}}} \right). \quad (32) \]

Notice that the Shannon limit approximates very well the average error probability in the finite blocklength regime for the scenario of this paper. As shown in [26], the approximation error in Rician fading can be very small depending on the size of the codeword and LOS factor of the channel. In the scenario considered in this work, the approximation error using the outage probability is smaller than 1.6%.

1) AVERAGE CSI

When only average CSI is available, \( P_{\text{A-CSI}} \) is a random variable and we can exploit the statistical characterization given in Section III to write the overall outage probability. Then, it can be obtained as the average of the incident RF power over the CDF of \( |z|_2^2 \), so that

\[ O_{\text{A-CSI}} = \mathbb{E}_{P_{\text{A-CSI}}} \left[ F_{|z|_2^2} \left( \frac{\gamma_0 N_i N_0 B}{P_i^{\text{tx}} \beta_{\text{wit}}} \right) \right] \]

\[ = \int_{L_1}^{L_2} F_{|z|_2^2} \left( \frac{\gamma_0 N_i N_0 B}{\eta (G(x) - P_{\text{circ}}) \beta_{\text{wit}}} \right) f_P_{\text{A-CSI}}(x) \, dx \]

\[ + F_{|z|_2^2} \left( \frac{\gamma_0 N_i N_0 B}{P_i^{\text{max}} \beta_{\text{wit}}} \right) \int_{L_2}^{\infty} f_P_{\text{A-CSI}}(x) \, dx, \quad (33) \]

where \( L_1 \) and \( L_2 \) are established based on (29), so that to output \( 0 \leq P_i^{\text{tx}} \leq P_i^{\text{max}} \) the source node must harvest \( P_{\text{circ}} \leq G(P_{\text{A-CSI}}) \leq (P_i^{\text{max}} \eta^{-1} + P_{\text{circ}}) \). Therefore, the first integral considers \( P_{\text{A-CSI}} \) ranging from \( L_1 \) to \( L_2 = G^{-1}(P_{\text{circ}}) \) to \( L_2 = G^{-1}(P_i^{\text{max}} \eta^{-1} + P_{\text{circ}}) \), with the transmission power given by \( P_{\text{A-CSI}} = \frac{\gamma_0 N_i N_0 B}{P_i^{\text{max}} \beta_{\text{wit}}} \). The second integral ranges from \( L_2 \) to \( \infty \), which stands for the case of the transmission power saturated at \( P_{\text{A-CSI}} = P_i^{\text{max}} \).

2) FULL CSI

Here, \( P_{\text{F-CSI}} \) is known,\(^4\) thus, the outage probability for the F-CSI scheme can be obtained as (31)

\[ O_{\text{F-CSI}} = F_{|z|_2^2} \left( \frac{\gamma_0 N_i N_0 B}{P_i^{\text{tx}} \beta_{\text{wit}}} \right) \]

\[ = 1 - Q_{K_i} \left( \sqrt{2K_i \kappa_{\text{wit}}}, \sqrt{2(1 + \kappa_{\text{wit}})} \frac{2\gamma_0 N_i N_0 B(1 + \kappa_{\text{wit}})}{\eta (G(P_{\text{F-CSI}}) - P_{\text{circ}}) \beta_{\text{wit}}} \right). \quad (34) \]

\(^3\)We have omitted the index \( i \) in \( \gamma_0 \) in order to lighten the notation, but \( i \in \{\text{A-CSI, F-CSI}\} \) can be easily inferred from the context.

\(^4\)Let us remark that the transmit power used by the source node when the F-CSI precoder is employed at the PB is also limited to \( P_i^{\text{max}} \).
D. PROBLEM FORMULATION

Our goal is to configure \( K_i \) and \( T_i \), for \( i \in \{A-CSI, F-CSI\} \), in order to minimize the energy required by the PB, so as to meet a target reliability constraint \( O^* \). This optimization problem can be formulated as

\[
\begin{align*}
\text{minimize} & \quad E_i = P_h T_i \\
\text{s.t.} & \quad O_i \leq O^*, \quad T_i \leq T_{\text{max}}, \quad R_i \leq R_{\text{max}}.
\end{align*}
\] (35a)

Observe that since \( P_h \) is fixed, the energy-minimization problem is also a latency-minimization problem, i.e., \( T_i \) should be as small as possible in order to meet (35b). However, due to the mathematical complexity of the outage probabilities, it is not possible to obtain a closed-form expression to solve the optimization problem. Nevertheless, notice that the outage probability of the A-CSI beamforming in (33) is impacted by \( T_{A-CSI} \) and \( K_{A-CSI} \) only in the CDF of \( |z_2|^2 \), defined in (31) in terms of the generalized Marcum \( Q \)-function. For the F-CSI beamforming, the outage probability in (34) is also written using the generalized Marcum \( Q \)-function.

The impact of \( T_i \) is observed only in the second argument of \( Q_{K_i}(\cdot, \cdot) \), which depends on \( y_0 \) (a function of the transmission rate \( R_i = \frac{N K_i}{T_i} \)). By its turn, \( K_i \) defines the order of \( Q_{K_i}(\cdot, \cdot) \) and impacts both its arguments. Notice that \( K_i \) is restricted to integer values and it also impacts the transmission rate. Thus, increasing \( K_i \) will be beneficial in order to meet the target \( O^* \), but it will demand higher energy from the PB so that the source node can transmit at higher rates. As a consequence, practical values for \( K_i \) need to be limited to a given \( K_{\text{max}} \).

Furthermore, as pointed out by [27], the Marcum \( Q \)-function is convex and strictly monotonic with respect to both arguments when the order (\( K_i \) in our case) is fixed. The convexity and strictly monotonic properties of \( Q_{K_i}(\cdot, \cdot) \) allow us to transform the inequality constraint in (35b) into an equality in order to save resources. As a consequence, for a given \( k \in [1, K_{\text{max}}] \), we can redefine the bivariate optimization problem in (35a) into

\[
\begin{align*}
\text{minimize} & \quad E_i = P_h T_i \\
\text{s.t.} & \quad O_i = O^*, \quad T_i \leq T_{\text{max}}, \quad R_i \leq R_{\text{max}}.
\end{align*}
\] (36a)

Such a problem is equivalent to finding \( T_i \) that yields \( O_i = O^* \), which can be solved through numerical methods that narrow the range of values in an interval, as the golden-section search algorithm with parabolic interpolation. The advantage of the golden-section search technique combined with parabolic interpolation, compared to approaches based on the Newton’s method, for example, is faster convergence without the need for differentiation [28]. Let us remark that the optimization in (36a) is solved during the setup of the source node. Then, as the scenario considered here has no mobility, the optimization needs only to be updated if the topology changes, yielding negligible complexity to the system operation.

Algorithm 1 summarizes our proposed approach, in which we define a maximal number of replicas \( K_{\text{max}} \) and a maximum time deadline \( T_{\text{max}} \), typical of MTC applications. Then, for each \( k \in [1, K_{\text{max}}] \) we first find \( T_i \) that yields \( O_i = O^* \). However, notice that solutions with small \( k \) may not meet the reliability constraint \( O^* \) within the time deadline \( T_{\text{max}} \). Thus, if \( T_i > T_{\text{max}} \) the condition in line 4 ensures that these solutions are not taken into account. On the other hand, if \( T_i < T_{\text{max}} \) the algorithm runs until \( T_i \) decreases when \( k \) increases, i.e., the situation that increasing the number of replicas is beneficial in order to meet \( O^* \), but not compromised by the higher energy demand from the PB. Another important condition in line 4 is with respect to the spectral efficiency of the source node. High \( k \) or small \( T_i \) may yield impractical values for \( R_i \), which is thus limited to \( R_{\text{max}} \) in our solution.

V. NUMERICAL RESULTS

In this section, we present numerical results to illustrate our analysis. The default parameters for simulations are listed in Table 3, unless stated otherwise. For the WET link, we follow a scenario typical of the PowerSpot® RF Wireless Power Development Kit [18], which enables 915 MHz energy transfer up to a maximal charging distance of 6 m. In addition, the non-linear EH function at the sensor node follows [19]. In the WIT link, the energy consumption is representative of a Bluetooth low energy (BLE) transceiver as in [29], while the MTC constraints are representative of a mobile automation scenario with \( O^* = 10^{-6} \) and \( T_{\text{max}} = 10 \) ms [30].

First, Figure 2 illustrates at the top the non-linear energy harvesting function \( G(P_i) \) versus the incident power \( P_i \), given by (26), while at the bottom it shows the harvesting efficiency \( \xi_i \) as a function of \( P_i \), as in (27). As we can observe, \( G(P_i) \) saturates at \( \mathcal{W} = 10.73 \) mW when \( P_i \geq 14 \) dBm, while it exhibits a maximal harvesting efficiency of \( \xi_i = 73\% \) when \( P_i = 9 \) dBm. Therefore, in order to maximize the
energy efficiency one should operate below the saturation level, so that energy is not wasted, and as close as possible to the point of maximal $\xi_i$. In our scenario, $P_i$ depends on the transmission scheme (A-CSI or F-CSI), but it can be roughly approximated using $P_{fb}$, the average power gain of the WET link, and the beamforming gain due to the $M$ antennas, so that $P_{fb} = 45$ dBm yields $P_i \approx 9$ dBm when $M = 4$ antennas, i.e., exactly at the point of maximal energy efficiency of Figure 2. Therefore, our strategy focuses on maximizing the energy efficiency by optimizing $T_i$ for a fixed $P_{fb}$.

Figure 3 plots the optimal time $T_i^*$ as a function of the number of replicated packets $K$. Notice that the minimal energy $E_i^*$ used by the PB can be directly inferred from Figure 3, since $E_i^* = P_{fb}T_i^*$. As we observe, there is an optimal pair $(K_i^*, T_i^*)$ that minimizes $E_i^*$. Comparing A-CSI with the F-CSI benchmark, we observe that $T_{i,max}^*$ is larger than $T_{FCSI}^*$, but still lower than $T_{max}$, enabling industrial MTC applications [2]. Also, for both schemes we observe that PR is important to reduce the energy required by the PB, since $K_i^*$ and $T_i^*$ must increase in order to meet the strict reliability constraints. The optimal $K_i^*$ and $T_i^*$ can be decreased if a larger number of antennas is employed at the PB, which improves the energy beamforming performance. Furthermore, we observe that $(K_i^*, T_i^*)$ is larger than $(K_{FCSI}^*, T_{FCSI}^*)$, with the gap increasing when $O^*$ decreases. Nevertheless, this is expected since we are considering an ideal F-CSI beamforming that serves only as a performance benchmark. Interestingly, the practical A-CSI beamforming still enables MTC applications.

Figure 4 shows the optimal $T_i^*$ that minimizes the energy required by the PB for different outage probability constraints, which is complemented by Figure 5 showing the optimal $K_i^*$ that minimizes the energy required by the PB for different $O^*$. We observe that with lower $O^*$, both $K_i^*$ and $T_i^*$ must increase in order to meet the strict reliability constraints. The optimal $K_i^*$ and $T_i^*$ can be decreased if a larger number of antennas is employed at the PB, which improves the energy beamforming performance. Furthermore, we observe that $(K_{A-CSI}^*, T_{A-CSI}^*)$ is larger than $(K_{FCSI}^*, T_{FCSI}^*)$, with the gap increasing when $O^*$ decreases. Nevertheless, this is expected since we are considering an ideal F-CSI beamforming that serves only as a performance benchmark. Interestingly, the practical A-CSI beamforming still enables MTC applications.

Next, Figure 6 illustrates the minimal energy $E_i^*$ required by the PB as a function of the LOS factor $\kappa_w$ in the

### TABLE 3. Simulation parameters.

| Description                        | Value                      |
|-----------------------------------|----------------------------|
| EH saturation level               | $W = 10.73$ mW             |
| EH unitless constants             | $c_0 = 0.2308$             |
|                                  | $c_1 = 5.365$              |
| Drain efficiency of the PA        | $\eta = 33\%$             |
| Fixed power consumption           | $P_{circ} = 1.33$ mW       |
| Maximal transmission power        | $P_{tx}^{max} = 3.3$ dBm   |
| Transmit power of the PB          | $P_i = 45$ dBm             |
| Number of antennas at the PB      | $M \in \{4, 8\}$ antennas |
| Distances                         | $d_{wet} = 3$ m            |
|                                  | $d_{writ} = 100$ m         |
| LOS parameters                    | $\kappa_{wet} = 4$ dB      |
|                                  | $\kappa_{writ} = 2$ dB     |
| Path-loss exponents               | $\alpha_{wet} = \alpha_{writ} = 3$ |
| Carrier frequencies               | $f_{wet} = 915$ MHz        |
|                                  | $f_{writ} = 2.45$ MHz      |
| Channel coherence time            | $T_{i,c} = 10$ ms          |
| Target outage probability         | $O^* = 10^{-6}$            |
| Maximum time deadline             | $T_{max} = 10$ ms          |
| Maximum number of replicas        | $K_{max} = 10$             |
| Maximum spectral efficiency       | $R_{max} = 8$ bps/Hz       |
| Noise figure                      | $N_f = 10$ dBm             |
| Noise PSD                         | $N_0 = -204$ dB/Hz         |
| Packet length                     | $N = 56$ bits              |
| Bandwidth                         | $B = 100$ kHz              |
WET link. Here we consider A-CSI and F-CSI schemes with \( M = 8 \) antennas and \( O^* = 10^{-6} \). As we observe, the gap between both schemes decreases considerably when \( \kappa_{\text{wet}} \) increases. For example, \( E_{\text{A-CSI}}^* \) is 100% higher than \( E_{\text{F-CSI}}^* \) when \( \kappa_{\text{wet}} = 2 \) dB, while this gap drops to 60% when \( \kappa_{\text{wet}} = 4 \) dB and 10% when \( \kappa_{\text{wet}} = 8 \) dB. Such observation highlights that A-CSI is a viable beamforming option, especially if the PB can be positioned in a favorable condition, with strong LOS with respect to the source node.

Finally, Figure 7 plots \( E_i^* \) as a function of the distance between source and destination nodes, \( d_{\text{wit}} \). We consider A-CSI and F-CSI schemes with \( M = 8 \) antennas, \( O^* = 10^{-6} \) and \( \kappa_{\text{wet}} \in [4, 6] \) dB. Corroborating with Figure 6, F-CSI exhibits the same performance for both considered \( \kappa_{\text{wet}} \). Comparing A-CSI and F-CSI beamforming, we notice very similar performance when \( d_{\text{wit}} \) is small. For instance, \( E_{\text{A-CSI}}^* \) is 40% higher than \( E_{\text{F-CSI}}^* \) when \( d_{\text{wit}} = 80 \) m with \( \kappa_{\text{wet}} = 4 \) dB, which is a typical transmission range of the considered BLE transceiver. Nevertheless, Figure 7 also shows that the increase in the energy consumption of A-CSI with \( d_{\text{wit}} \) can be mitigated by positioning the PB in a favorable condition. For instance, \( E_{\text{A-CSI}}^* \) is 10% higher than \( E_{\text{F-CSI}}^* \) at \( d_{\text{wit}} = 80 \) m with \( \kappa_{\text{wet}} = 6 \) dB, reinforcing the importance of a strong LOS with respect to the source node.

VI. CONCLUSION
This paper considered a batteryless MTC scenario with a dedicated multi-antenna PB to power the source node using A-CSI beamforming. The energy recovered at the source is used by the transceiver without storing it on a battery, since the charging time is typically in the order of a few seconds. That is a relevant issue often overlooked in the WET literature, and very relevant in MTC. Then, we derived the incident power statistics and the outage probability, assuming that the source employs PR in the WIT link to the destination. We formulated an iterative optimization algorithm in order to minimize the power consumed by the PB subject to stringent reliability constraints in the WIT link. The numerical results
showed the existence of an optimal harvesting time, as well as an optimal number of packet replications given the number of PB antennas. More importantly, the proposed scheme combining average CSI and packet replication was able to meet both the reliability and latency constraints of typical industrial MTC applications.

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