Energy Harvesting Meets Data-Oriented Communication: Delay-Outage Ratio Analysis

Mehmet C. Ilter, *Senior Member, IEEE*, Paschalis C. Sofotasios, *Senior Member, IEEE*, Mikko Valkama, *Fellow, IEEE*, and Jyri Hämäläinen, *Senior Member, IEEE*

***Abstract*— The data-oriented approach was initially proposed towards novel transmission strategies for individual data-transmission sessions by considering instantaneous operating conditions. Aligned with this, the present contribution focuses on the analysis of the delay outage ratio (DOR), a data-oriented performance metric, when far-field wireless power transfer is utilized with network elements capable of energy harvesting from ambient RF signals prior to the transmission periods. To that end, simple and accurate analytic expressions are derived considering the involved battery charging intervals as well as the length of the data segment, available bandwidth and delay constraints. These expressions are corroborated by numerical simulations and they are subsequently used in developing useful theoretical and practical insights of interest. Besides highlighting the importance of the new data-oriented DOR metric, the offered results are shown to be useful in the design of realistic energy harvesting-based data transmission systems in future networks.**

***Index Terms*— Data-oriented approach, delay-outage ratio, far-field power transfer, battery charging interval, RF energy harvesting, short-packet communications.**

I. Introduction

TRADITIONAL broadband wireless networks were initially designed for large packet sizes without imposing delay constraints. However, current wireless systems introduce different design parameters, such as amount of information bits to be transmitted and available bandwidth, in order to maintain certain quality-of-service (QoS) constraints for short-time packet transmission. In this respect, [1] proposed a more refined analysis of the maximum achievable rate as a function of the block length and target decoding error probability.

As the extent of short packet transmission, the data-oriented transmission [2] constitutes a new transmission strategy which focuses on individual data-transmission sessions rather than on long-term average channel statistics, i.e. the classical channel-oriented approach. This is significantly more effective because it considers both the quality of service (QoS) requirement and the instantaneous, short-term behavior of the wireless environment. Furthermore, unlike the channel-oriented approach, the data-oriented approach focuses on the individual data transmission periods, which is a useful asset or feature particularly in mission-critical applications.

Within the data-oriented approach, the delay outage ratio (DOR) performance metric was introduced in [2], where the impact of latency on various wireless network configurations was the main contribution. In the same context, the DOR metric for the short packet transmission over fading channels was first analyzed in [3]. Then, inspired by it, the authors in [4] determined how the DOR expression can be utilized in searching the optimum constellation points in coded communication scenarios. Likewise, the DOR metric was recently considered in the coverage analysis of reflective intelligent surfaces (RIS)-aided communication systems [5] and over visible light communication scenarios [6]. Similarly, the data-oriented approach was adopted in downlink RSMA based scenarios in [7], where two different precoder designs were investigated based on the proposed DOR metric.

In addition to the data-oriented approach, another interesting recent development is the RF-based energy harvesting (RFEH) that has been attracting considerable attention in energy-constrained wireless networks. The key advantage of RFEH is that it enables sustainable power supply. Therefore, wireless power transfer (WPT) may ultimately revolutionize large share of consumer electronics by providing ambient energy resources. In this respect, wireless powered communication networks (WPCN) were initially proposed for reducing the operational workload of battery replacement/charging over RF-based energy harvesting systems [8]. To that end, the underlying principle is that network elements in WPCN first harvest energy from the signals transmitted by RF energy sources and then utilize the harvested energy for the upcoming communication tasks.

Although various types of related network architectures and protocols have been proposed, the statistical characterization of the associated recharge time has been only partly investigated. Specifically, [9] derived expressions for the involved capacitor voltage, charging time in constant power charging, and charging time distribution as a function of the residual voltage. Then, [10] analyzed the recharge time for a capacity-limited battery over generalized fading channels, while suitable statistical models for the battery charging time in the presence of multiple RF source nodes were reported in [11]. Also, besides investigating the statistical behavior over different fading conditions and the number of energy resources, the effects of different modulation techniques,

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Mehmet C. Ilter and Mikko Valkama are with the Department of Electrical Engineering, Tampere University, 33720 Tampere, Finland (e-mail: mehmet.ilter@tuni.fi; mikko.valkama@tuni.fi).

Paschalis C. Sofotasios is with the C2PS and 6G Center, Department of Computer and Communication Engineering, Khalifa University, Abu Dhabi, United Arab Emirates, and also with the Department of Electrical Engineering, Tampere University, 33720 Tampere, Finland (e-mail: p.sofotasios@ieee.org).

Jyri Hämäläinen is with the Department of Information and Communications Engineering, Aalto University, 02150 Espoo, Finland (e-mail: jyri.hamalainen@aalto.fi).

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such as amplitude shift keying (ASK), quadrature amplitude modulation (QAM), phase-shift keying (PSK), and frequency shift keying (FSK) on charging time, were quantified in [12]. Moreover, [13] proposed a novel routing algorithm considering multi-channel fading and the battery charging time.

In the near-future, energy harvesting-based communications are expected to become significantly more prevalent. Hence, incorporating battery charging intervals into existing DOR analyses is a prerequisite criterion in enabling a data-oriented approach for wireless information transmission based on ambient RF energy. To this end, the required information delivery time should be merged with the corresponding battery charging time for individual packet transmission. To address this necessity, this contribution presents a novel unified analysis considering the battery charging time and individual packet transmission in the DOR analysis of wireless transmission scenarios, where an energy harvester first obtains the required power from a power beacon and then transmits its messages to an information receiver. The derived analytical DOR expressions are validated through Monte Carlo simulations and most importantly, the necessity for the novel data-oriented DOR metric to evaluate energy harvesting-based transmission is underlined. In addition, the derived analytic expressions for the achievable DOR are particularly tractable, which enables the derivation of insightful special cases of interest that will be useful on the realistic design of such systems for target DOR related quality of service (QoS) requirements.

II. RF Energy Harvesting System Model

Fig. 1 illustrates the considered system model where the total transmission time is divided into two cycles, namely the battery charging time, T_c, and the information transmission time, T_d, respectively. In this context, an energy harvester (EH) device first scavenges its transmission energy from a power beacon (PB) for an upcoming data transmission period. Following this, the EH transmits its data to an information receiver (IR) and once the data transmission ends it resets the energy harvesting cycle. Furthermore, it is assumed that the PB-EH and EH-IR links undergo realistic multipath fading conditions.

A. Battery Charging Time, T_c

Based on the considered system model, the harvested power from the PB is formulated as $P_h = P_r\eta$, where η denotes the conversion efficiency of the involved RF waveform to DC output and P_r represents the instantaneous received power [13]. Assuming that the EH battery capacity (C_b) and the discharge depth (D_d) are known, the battery charging time (T_c) is calculated from $T_c = C_b D_d / I_b$. Herein, I_b is the recharging current such that $I_b = P_h/V_b$, with V_b denoting a constant operating voltage of the battery in the EH [14]. Based on this and upon considering the received power and T_c, it is observed that the battery charging time becomes inversely proportional to the received power such that $T_c = \alpha/P_r$, where the conversion coefficient is defined as $\alpha = C_b D_d V_b/\eta$ [14].

Notably, the charging time is defined as the time required to charge a supercapacitor from a residual value to a maximum allowable voltage [9]. Therefore, the battery charging time depends on the residual energy of the node, whereas the RF charging time can be represented as a function of residual voltage across the supercapacitor before charging and it can be modeled as a random variable [9]. To this effect and considering Rician fading conditions between the PB and EH along with the relation between the received signal power and the battery charging time as in [Eq. (10), [14]], the probability density function (PDF) of T_c can be expressed as follows:

$$f_{T_c}(\tau) = \frac{\alpha\,(1+K)\exp(-K)}{\Omega\tau^2 \exp\left(\frac{(1+K)\alpha}{\Omega\tau}\right)} \mathcal{I}_0\left(2\sqrt{\frac{K\,(K+1)\,\alpha}{\Omega\tau}}\right) \quad (1)$$

which is valid for $\tau > 0$. In addition, $\mathcal{I}_0(\cdot)$ denotes the modified Bessel function of the 1st kind with zeroth order [15], whilst K is the Rician $K-$factor which represents the power ratio between the dominant component, encountered in the line-of-sight (LoS) scenario, and the multipath components. Furthermore, α in (1) stands for the conversion coefficient, whereas Ω denotes the average received power.

B. Information Delivery Time, T_d

The instantaneous delivery time of an H bits long packet under optimal rate adaptation scheme is given by

$$T_d = \frac{H}{B\log_2(1+\gamma)} \quad (2)$$

where B is the available bandwidth for data transmission and γ denotes the instantaneous received signal-to-noise ratio (SNR) at the IR. Also, when EH-IR link experiences Rayleigh fading conditipns, the PDF of T_d can be expressed as [16]

$$f_{T_d}(\tau) = \frac{H_{\text{norm}}}{\overline{\gamma}\tau^2} \exp\left(\frac{1}{\overline{\gamma}} + \frac{H_{\text{norm}}}{\tau} - \frac{\exp\left(\frac{H_{\text{norm}}}{\tau}\right)}{\overline{\gamma}}\right) \quad (3)$$

where $\overline{\gamma}$ is the corresponding average SNR and $H_{\text{norm}} = H/B$.

III. Delay Outage Ratio Analysis

It is recalled that the DOR in [2] is defined as the probability that the required information delivery time for a specific transmission exceeds the predefined threshold. However, this is redefined in the considered setup, assuming that the total delivery time consists of two parts such that $T = T_d + T_c$. Hence, in order to introduce the battery charging time to the DOR analysis, the DOR expression is defined as

$$\text{DOR} = \Pr\left[T_d + T_c > T_{th}\right] \quad (4)$$

and the successful delivery ratio is expressed as DOR' $= \Pr\left[T_d \leq T_{th} - T_c\right]$, implying that $T_{th} \geq T_c$. For the case of $T_c = \tau$, and utilizing the cumulative distribution function (CDF) in [eq. (6), [16]], it follows that

$$\text{DOR'} = \text{F}_{T_d}(T_{th} - \tau) = \exp\left(\frac{1}{\overline{\gamma}}\right)\exp\left(-\frac{\exp\left(\frac{H_{\text{norm}}}{T_{th}-\tau}\right)}{\overline{\gamma}}\right) \quad (5)$$

where DOR' $= 1 -$ DOR. Considering (5), the DOR performance can be straightforwardly determined from the CDF

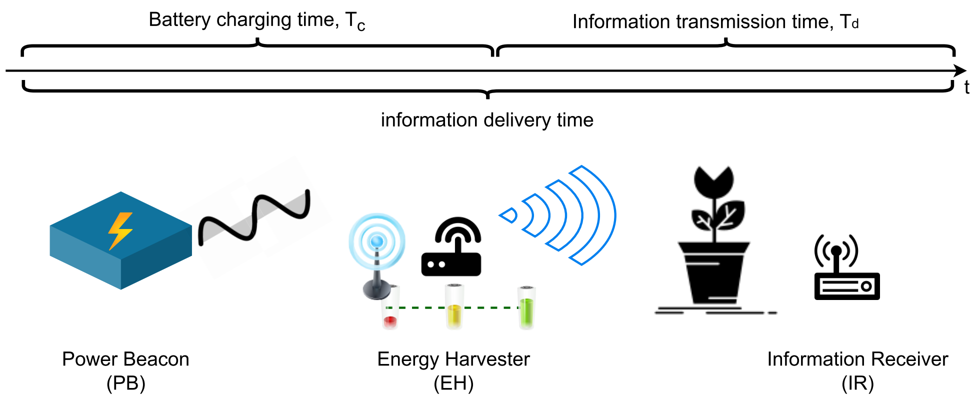

Fig. 1. Basic block diagram illustration of the considered RF energy harvesting system model: An EH first performs energy harvesting to charge its battery thanks to a PB in the area and then transmits its packets to an information receiver.

of the SNR, so the main objective becomes to find the CDF of corresponding received SNR. Importantly, this is by no means a simple extension of the outage probability analysis, since there is a notable inherent technical difference because quantifying high reliability and low latency requires accurate knowledge of the tail of the respective SNR's CDF. This is, in fact, what is required to determine the corresponding DOR.

A. An Accurate Closed-Form Approximation for DOR

It is evident from the formulation in (5) that the value of H in the context of short-packet transmission is typically a few hundred bits, at most, whilst the value of B is commonly at least in the scale of MHz. To this effect and recalling the ratio between H and B, it follows that the inner exponential term in (5) can be approximated by a linear expression, $\exp(x) \approx 1+x$, for $0 < x < 1$. Importantly, this simplifies the algebraic representation of (5), which can now be expressed as

$$\text{DOR'} \simeq \exp\left(\frac{1}{\bar{\gamma}}\right)\exp\left(-\frac{(1+H_{\text{norm}})^{\frac{1}{T_{th}-\tau}}}{\bar{\gamma}}\right). \tag{6}$$

Based on (6) and recalling (1), the corresponding DOR' in the presence of Rician fading conditions can be determined by

$$\begin{aligned}\text{DOR'} \simeq{} & \exp\left(\frac{1}{\bar{\gamma}}-K\right)\frac{\alpha(1+K)}{\Omega} \\ & \int_0^{T_{th}} \exp\left(-\frac{(1+H_{\text{norm}})^{\frac{1}{T_{th}-\tau}}}{\bar{\gamma}}\right) \\ & \underbrace{\times \frac{1}{\tau^2}\exp\left(-\frac{(1+K)\alpha}{\Omega\tau}\right)\mathcal{I}_0\left(2\sqrt{\frac{K(K+1)\alpha}{\Omega\tau}}\right)}_{A_1(\tau)} \mathrm{d}\tau.\end{aligned} \tag{7}$$

Notably, the first exponential term in the integrand of (7) can be expanded according to the binomial expression, yielding

$$(1+x)^a = \sum \binom{a}{k} x^k, |x| < 1 \tag{8}$$

where the generalized binomial expansion can be applied to calculate the binomial coefficient also for non-integer values of a, namely $\binom{a}{k} = \Gamma(a+1)/(\Gamma(a-k+1)\,k!)$ [17], with $\Gamma(\cdot)$ denoting the gamma function [15]. Hence, (7) becomes:

$$\begin{aligned}\text{DOR'} \simeq{} & \exp\left(\frac{1}{\bar{\gamma}}-K\right)\frac{\alpha(1+K)}{\Omega} \\ & \times \prod_{k=0}^{\infty}\int_0^{T_{th}} \exp\left(-\frac{1}{\bar{\gamma}}\binom{\frac{1}{T_{th}-\tau}}{k}H_{\text{norm}}^k\right)A_1(\tau)\,\mathrm{d}\tau.\end{aligned} \tag{9}$$

Based on this and upon expanding the binomial term as $[(T_{th}-\tau)(T_{th}-\tau-1)\ldots(T_{th}-\tau-k+1)\,k!]^{-1}$, as well as noticing that in practice $T_{th} \ll 1$ and $\tau \ll 1$, it follows that $T_{th}-\tau \simeq T_{th}$ and $T_{th} > 0$. As a result, (9) turns into

$$\begin{aligned}\text{DOR'} \simeq{} & \exp\left(\frac{1}{\bar{\gamma}}-K\right)\frac{\alpha(1+K)}{\Omega} \\ & \times \prod_{k=0}^{\infty}\exp\left(-\frac{1}{\bar{\gamma}}\binom{\frac{1}{T_{th}}}{k}H_{\text{norm}}^k\right)\int_0^{T_{th}} A_1(\tau)\,\mathrm{d}\tau.\end{aligned} \tag{10}$$

By also expanding the above binomial term and utilizing the Pochhammer symbol identities, eq. (10) can be re-written as

$$\begin{aligned}\text{DOR'} \simeq{} & \exp\left(\frac{1}{\bar{\gamma}}-K\right)\frac{\alpha(1+K)}{\Omega} \\ & \times \exp\left(-\frac{1}{\bar{\gamma}}\sum_{k=0}^{\infty}\frac{\left(-\frac{1}{T_{th}}\right)_k}{(-1)^k}\frac{H_{\text{norm}}^k}{k!}\right)\int_0^{T_{th}} A_1(\tau)\,\mathrm{d}\tau.\end{aligned} \tag{11}$$

Of note, the above series representation in can be expressed in closed-form in terms of the generalized hypergeometric function, whilst the involved integral in (11) can be evaluated with the aid of the series representation of $\mathcal{I}_0(x)$, [Eq.(8.402), [15]] and [15, eq. (3.353.3)]. To this effect and recalling that ${}_1F_0(a,-,x) = {}_2F_1(a,1;1;x) = (1-x)^{-a}$, it follows that

$$\begin{aligned}\text{DOR} \simeq 1 - \Bigg[& \frac{\alpha(1+K)}{\Omega\exp(K)}\exp\left(\frac{1-(1+H_{\text{norm}})^{\frac{1}{T_{th}}}}{\bar{\gamma}}\right) \\ & \times \sum_{k=0}^{\infty}\frac{T_{th}^{-1-k}}{k!k!}\left(\frac{K(K+1)\alpha}{\Omega}\right)^k E_{-k}\left(\frac{(1+K)\alpha}{\Omega T_{th}}\right)\Bigg]\end{aligned} \tag{12}$$

where $E_n(x)$ denotes the exponential integral function [15]. The series representation in (12) is convergent and can achieve acceptable truncation error by using a reasonable number of terms. Also, it can be used as a benchmark for deriving a simple and particularly accurate closed-form expression for the achievable DOR in the considered setup. To that end, utilizing the identities between the exponential integral functions and the hypergeometric functions, it can be equivalently expressed by (13), as shown at the bottom of the page, where ${}_1F_1(\cdot;\cdot;\cdot)$ denotes the Kummer's confluent hypergeometic function [15]. By expanding the ${}_1F_1(\cdot;\cdot;\cdot)$ function and upon carrying out some algebraic manipulations, equation (13) can be accurately expressed by (14), as shown at the bottom of the page, which the aid of the Pochhammer symbol identities yields

$$\mathrm{DOR} \simeq 1 + \left\{1 - (1-K)\exp[K] - \exp\left[-\frac{\alpha(1-K^2)}{\Omega T_{th}}\right]\right\} \times \frac{\exp\left(\frac{1-\overline{\gamma}K-(1+H_{\mathrm{norm}})^{\frac{1}{T_{th}}}}{\overline{\gamma}}\right)}{1-K} \quad (15)$$

which is a novel, simple and accurate closed-form expression.

B. Special Cases

By recalling that Rayleigh fading constitutes a special case of Rician fading, it follows that the DOR in the case of Rayleigh fading is readily deduced by setting $K = 0$ in (15), yielding

$$\mathrm{DOR} \simeq 1 - \exp\left(-\frac{\alpha}{\Omega T_{th}}\right)\exp\left(\frac{1-(1+H_{\mathrm{norm}})^{\frac{1}{T_{th}}}}{\overline{\gamma}}\right). \quad (16)$$

Furthermore, the particularly simple algebraic form of (15) and (16) enable the derivation of simple analytic expressions with respect to the involved parameters. This of paramount importance in future designs of such systems for target DOR based quality of service requirements.

IV. Numerical Results

In this section, the offered analytic results are employed in quantifying the achievable DOR performance of energy harvesting-based data transmissions and are verified by respective Monte Carlo simulations. To this end, the PB is assumed to emit unit power WPT waveforms to the EH over a Rician fading channel with average fading power, Ω, whilst Rayleigh fading conditions are considered for the EH-IR link with an average SNR, $\overline{\gamma}$. Regarding the battery in the EH, the charging time-related parameters are depicted in Table I. These are indicative practical values, while additional numerical results can be generated for any other parameterization scenario.

TABLE I
ASSUMED CHARGING TIME RELATED PARAMETERS [13], [14]

Battery charging voltage (V_b)	1.2 V	Conversion efficiency (η)	0.5
Battery capacity (C_b)	10 mAh	Discharge Depth (D_d)	0.4

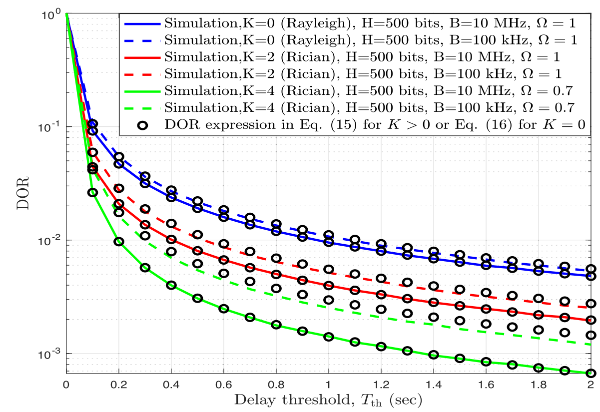

Fig. 2. The DOR performance at the IR over varying delay thresholds and Rician K-factor values where $\overline{\gamma} = 5$ dB.

Fig. 2 presents the DOR performance of the considered model with respect to increasing T_{th} values, assuming different bandwidths, $B = \{10\ \mathrm{MHz}, 100\ \mathrm{kHz}\}$ along with different average fading power values, $\Omega = \{1, 0.7\}$ for $\overline{\gamma} = 5$ dB. As expected, a higher delay threshold jeopardizes the corresponding DOR performance. Also, in line with the T_c expression, the received signal power is directly linked with the battery charging time and its negative effects can be observed for lower K and Ω values. This is expected since LOS conditions are particularly favorable for EH compared to NLOS. Also, an excellent agreement is observed between the analytical and the simulated results, particularly for lower H/B values due to the linear approximation applied into the exponential term in Section III. Fig. 3 demonstrates the effects of the available channel bandwidth and Rician K-factor on the DOR performance, with the considered values for B ranging from 1 MHz to 10 MHz. To filter out the charging time period from the DOR metric, it is assumed that $\Omega = 100$. Then, the DOR curves imply that wider bandwidth and higher $\overline{\gamma}$ values result in better DOR performance, while the use of shorter bit packets enhances the DOR performance due to lower transmission time. Besides, the simulation results are aligned with the DOR expression outlined in (16) although the deviation tends to increase for higher H_{norm} values. This underscores the significance of effective bandwidth management and SNR optimization in achieving superior DOR performance when battery charging time does not constitute a limiting factor.

Finally, Fig. 4 illustrates the effects of battery charging time in the achievable DOR performance when Rayleigh fading is considered in both links. To this end, the DOR performance is

$$\mathrm{DOR} \simeq 1 - \exp\left(\frac{1-(1+H_{\mathrm{norm}})^{\frac{1}{T_{th}}}}{\overline{\gamma}}\right)\left\{1 - \frac{\alpha(1+K)}{T_{th}\Omega\exp(K)}\sum_{k=0}^{\infty}\frac{\alpha^k K^k (1+K)^k}{k!(1+k)!\Omega^k T_{th}^k}\,{}_1F_1\left(1+j;2+j;-\frac{(1+K)\alpha}{\Omega T_{th}}\right)\right\}. \quad (13)$$

$$\mathrm{DOR} \simeq 1 - \exp\left(\frac{1-(1+H_{\mathrm{norm}})^{\frac{1}{T_{th}}}}{\overline{\gamma}}\right)\left\{1 - \frac{\alpha(1+K)}{T_{th}\Omega\exp(K)}\sum_{k=0}^{\infty}\sum_{l=0}^{\infty}\frac{(1)_{k+l}}{(2)_{k+l}k!l!}\left(\frac{\alpha K(1+K)}{\Omega T_{th}}\right)^k\left(-\frac{\alpha(1+K)}{\Omega T_{th}}\right)^l\right\}. \quad (14)$$

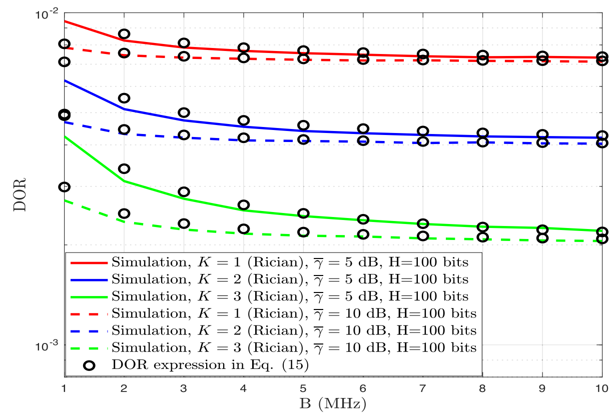

Fig. 3. The DOR performance at the IR over varying available bandwidth and Rician K-factor values where $T_{\text{th}} = 10$ msec.

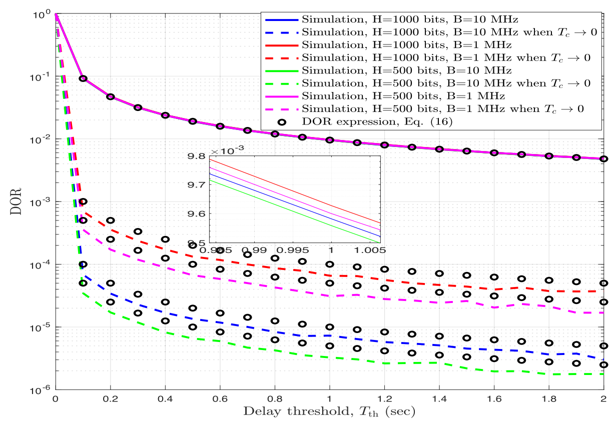

Fig. 4. The DOR performance comparison at the IR when actual T_c and a limiting case of $T_c \to 0$ are considered for $\overline{\gamma} = 10$ dB, respectively.

TABLE II
ABSOLUTE ERRORS OF (16) OVER DIFFERENT EVALUATION PARAMETERS

$\overline{\gamma}$ (dB)	Ω	T_{th} (msec)	H (bits)	B	DOR	$\epsilon_{\text{abs}}^{\text{DOR}}$
10	1	10	300	1 kHz	1	0
10	1	10	300	10 kHz	0.9846	0.0466
10	1	10	300	100 kHz	0.6821	0.0519
10	1	10	300	1 MHz	0.6252	0.0069
10	1	10	300	10 MHz	0.6180	7.6946e-04
10	1	10	300	100 MHz	0.6171	1.5977e-06
30	1	100	2000	100 MHz	0.0915	4.5466e-05

plotted for two different cases, where the first one considers actual T_c values and the second one assumes $T_c \to 0$. The corresponding results underline the necessity for a new DOR expression when an energy harvesting mechanism exists in such systems. Interestingly, the variations observed in the second case disappear when actual T_c is considered and all considered scenarios yield similar performance. To further investigate and highlight the validity of (16) over a broad range of scenarios over different simulation parameters, the absolute errors between DOR values obtained from (16) and simulated ones, $\epsilon_{\text{abs}}^{\text{DOR}} = |\text{DOR} - \text{DOR}^{\text{sim}}|$, are listed in Table II.

V. CONCLUSION

Energy harvesting-based communication schemes are expected to exhibit much wider usage and deployments in the coming years. In this respect, while aligning with the global ecological, energy efficiency and sustainability requirements, incorporating energy harvesting mechanisms into recently established data-centric performance metric becomes essential.

Addressing this important topic, this letter introduced an innovative unified analysis that considers both battery charging times and individual packet transmissions within the delay-outage analysis framework. To this end, novel delay-outage ratio expressions were analytically derived and validated by extensive Monte Carlo simulations. The offered results were subsequently employed in quantifying the achievable DOR performance in the considered scenarios. This also led to the development of meaningful theoretical and practical insights, paving the way for improved transmission strategies in wireless information transmission based on ambient RF energy.

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