Proactive Scheduling for Zero-Energy Device Networks with Fast Uplink Grant

Nikos A. Mitsiou, *Student Member, IEEE*, Sotiris A. Tegos, *Member, IEEE*, Panagiotis D. Diamantoulakis, *Senior Member, IEEE*, Panagiotis G. Sarigiannidis, *Senior Member, IEEE* and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—To address the inefficiency in terms of resource utilization of grant-free (GF) protocols, the fast uplink (FU) grant medium-access protocol has been proposed. In this work, we design a proactive wireless power transfer (WPT) framework for FU grant zero-energy massive machine-type communication. Specifically, zero-energy devices (ZEDs) first harvest energy during the WPT phase and then transmit data based on the FU grant protocol. Moreover, a multi-arm bandit traffic prediction scheme is adopted. Then, considering that due to the FU grant protocol ZEDs may harvest energy for several WPT rounds prior to data transmission, we extract the ZEDs' outage probability during uplink. Based on the derived expressions, a chance-constrained optimization problem is formulated, which minimizes the energy consumption for WPT, while guaranteeing an acceptable outage probability for the ZEDs during data transmission. Simulations validate the theoretical analysis and illustrate that the proposed scheme outperforms GF access.**

***Index Terms*—fast uplink grant, zero-energy devices (ZEDs), proactive allocation, massive machine-type communication (mMTC), traffic prediction, multi-arm bandit (MAB)**

I. INTRODUCTION

Massive machine-type communication (mMTC) and ubiquitous wireless connectivity are among the main enablers of widespread digitization in sectors such as industries, intelligent transport systems, smart cities, etc. [1]. Thus, it is imperative for beyond fifth generation and sixth generation (6G) of wireless networks, except from human type communication (HTC), to also focus on supporting mMTC, by improving networks' performance in terms of energy consumption, scalability, reliability, latency, and spectral efficiency [1], [2]. To provide a scalable mMTC deployment, energy neutrality of future networks is critical. To this end, the zero-energy mMTC (ZE-mMTC) service will aim to deploy countless zero-energy devices (ZEDs) [3], with continuous operation equal to the lifetime of the device, which do not consume power from the device's battery but rather harvest the required energy [1]–[3].

The design of ZE-mMTC networks will be enabled through the combination of ultra-low power receivers, wireless power transfer (WPT) [1], which is an efficient remote approach to simultaneously charge numerous ZEDs, and appropriate medium access protocols. Nonetheless, seamless integration of wireless information transmission (WIT) and WPT is a major challenge for ZE-mMTC networks. Conventional four-way handshake mechanisms in LTE are not suitable for small payload transmissions, while grant-free (GF) protocols, despite reducing signaling overhead, suffer from a large number of collisions in mMTC networks. The behavior of mMTC traffic differs from that of traditional HTC, since HTC traffic tends to be heterogeneous, whereas mMTC traffic is homogeneous with small payloads and correlated [2]. Thus, by utilizing the inherent properties of mMTC traffic, proactive resource allocation and scheduling is doable [2], [4].

To this end, fast uplink (FU) grant has been utilized for resource allocation based on traffic prediction [4]–[8]. FU grant requires an one-way handshake, reducing the access delay, while only devices which are given an uplink grant can transmit data, thus mitigating collisions [2]. Specifically, in [4], a hidden Markov model (HMM) was proposed to model the MTC traffic and a traffic prediction algorithm was designed, which was shown to outperform conventional random access. However, despite its importance, the algorithm in [4] needs feedback from all unscheduled ZEDs which is not practical for mMTC networks. In [5], an FU access scheme was proposed considering the age of information (AOI) of the mMTC devices, while road safety as an actual application of FU grant was discussed. Furthermore, in [6], power allocation for FU access based on multi-arm bandit (MAB) was studied. MAB was used for allocating the transmit power of all users, subject to a recently defined quality of service metric, however the activation probability of the mMTC devices was considered perfectly known at the base station (BS). Finally, FU access with NOMA was studied in [7], while, in [8], a long short-term memory based traffic prediction scheme was developed.

In this work, we investigate the integration of FU grant with WPT for ZE-mMTC networks. Specifically, we design a traffic prediction algorithm based on MAB, which achieves the same performance as the algorithm proposed in [4], but observes only the activity of the scheduled ZEDs. In the FU grant protocol, only a subset of ZEDs are given permission to transmit data. Thus, ZEDs may harvest energy for several WPT rounds. Under Rayleigh conditions, and by taking into account the harvested energy accumulation at the ZEDs, we extract the closed-form expression for the outage probability of the ZEDs during uplink. Then, based on the FU scheduling provided by the MAB and the derived outage expressions, we formulate a chance-constrained optimization problem, which minimizes the BS energy consumption during the WPT phase,

N. A. Mitsiou and G. K. Karagiannidis are with the Wireless Communications and Information Processing (WCIP) Group, Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54636, Thessaloniki, Greece (e-mails: nmitsiou@ece.auth.gr; geokarag@auth.gr).

G. K. Karagiannidis is also with the Cyber Security Systems and Applied AI Research Center, Lebanese American University (LAU), Lebanon.

S. A. Tegos and P. D. Diamantoulakis are with the Department of Applied Informatics, University of Macedonia, 54636 Thessaloniki, Greece (e-mails: sotiris.a.tegos@gmail.com; padiaman@ieee.org).

P. G. Sarigiannidis is with the Department of Informatics and Telecommunications Engineering, University of Western Macedonia, 501 00 Kozani, Greece (e-mail: psarigiannidis@uowm.gr).

The work of N. A. Mitsiou and P. G. Sarigiannidis has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957406. The work of G. K. Karagiannidis was supported by the European Regional Development Fund by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call: "Special Actions: Aquaculture—Industrial Materials—Open Innovation in Culture (project code: T6YBP-00134). The work of S. A. Tegos and P. D. Diamantoulakis was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 7280).

while ensuring an outage probability threshold for the ZEDs during the WIT phase. The MAB scheduling and energy minimization problem are executed prior to each time slot, thus providing a proactive WPT framework for ZE-mMTC.

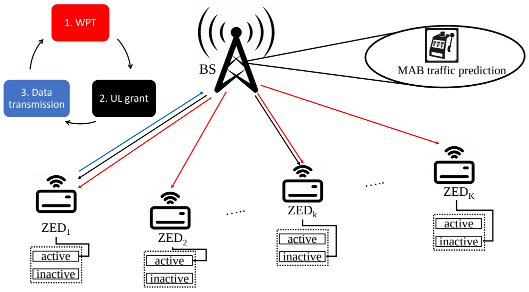

Fig. 1: System model.

II. SYSTEM MODEL

We consider a network consisting of K ZEDs and a BS which is also a power beacon, as shown in Fig. 1. The radio link is divided into orthogonal resources and the BS schedules up to $L \ll K$ devices for transmission, without interference. Each device is stimulated to generate data packets at different time slots controlled by different processes at the application layer, e.g., external events. We denote the activation of the i-th ZED at discrete time slot t by the random variable A_i^t, which is equal to one if the device is active and zero otherwise. The activation pattern of the devices is considered to be dependent to N independent two-state Markov processes [4]. Each Markov process is characterized by On and Off states, where the state at time t, $S_n^t \in \{0,1\}$, is controlled by temporal transition probabilities δ_n^1, δ_n^0 [4], i.e.,

$$\begin{aligned} &\Pr\left(S_n^{t+1}=0|S_n^t=1\right)=\delta_n^0, \\ &\Pr\left(S_n^{t+1}=1|S_n^t=0\right)=\delta_n^1. \end{aligned} \tag{1}$$

Moreover, the Markov states that are in the On state may activate certain ZEDs. Specifically, the probability that the Markov process n activates the i-th device is denoted as q_{nk}. The probability that the i-th ZED is active is given by [4]

$$\begin{aligned} \Pr\left(A_i^t=1|\mathbf{S^t}\right) &= 1-\bigcap_{n=1}^{N}\Pr\left(A_i^t=0|S_n^t\right) \\ &= 1-\prod_{n=1}^{N}(1-q_i^n)^{S_n^t}, \end{aligned} \tag{2}$$

where $\mathbf{S^t}=\{S_1^t,...,S_N^t\}$. Furthermore, the probability that the i-th device is active at time $t+1$ is expressed as

$$\Pr\left(A_i^{t+1}=1|\mathbf{S^t}\right) \quad = 1-\prod_{n=1}^{N} z(n), \tag{3}$$

where $z(n)=\begin{cases} 1-\delta_n^1+\delta_n^1(1-q_i^n), & S_n^t=0 \\ \delta_n^0+(1-\delta_n^0)(1-q_i^n), & S_n^t=1. \end{cases}$

The communication between the BS and the ZEDs is separated into two phases. The first is the WPT phase, in which all ZEDs harvest energy. The second phase is the WIT phase in which ZEDs transmit data using the energy harvested during past WPT rounds. We note that using different frequency bands for energy harvesting and data transmission in ZED networks is feasible, as it stems from the demonstration in [9]. However, due to FU grant, the BS allocates orthogonal resource blocks only to the set of L most possible to be active ZEDs. The scheduled devices participate in the WIT phase only if they have data to transmit, thus if an inactive device is scheduled by the BS for transmission, this uplink resource is wasted. For both downlink and uplink, we assume Rayleigh fading, thus the channel coefficients follow the complex Gaussian distribution, i.e., $h, g \sim \mathcal{CN}(0,1)$.

A. WPT phase

The WPT part consists of u channel uses of duration T_c seconds, during which the BS charges the underlying ZEDs. The energy harvested by the i-th ZED at time t is given by

$$E_i^t=\frac{\eta_i P_0(t)|h_i(t)|^2}{\kappa d_i^\alpha}uT_c, \tag{4}$$

where $P_0(t)$ is the BS transmit power, $\eta_i \in (0,1)$ is the energy conversion efficiency, h_i is the downlink channel coefficient between the BS and the i-th ZED, d_i is the distance between the BS and the i-th ZED, α is the path loss exponent, and κ denotes the path loss at the reference distance d_0. Also, the harvested energy from the noise is negligible. However, a ZED may not be given an uplink grant for several communication rounds, thus its total harvested energy at time t is given by

$$E_i^t=\sum_{j=t-J}^{t}\frac{\eta_i P_0(j)|h_i(j)|^2}{\kappa d_i^\alpha}uT_c, \tag{5}$$

where J is the number of WPT rounds for which a ZED has not transmitted data. It should be highlighted that J is known, since the BS proactively allocates the available orthogonal blocks to all ZEDs and observes their activity. Due to Rayleigh fading, the probability density function (PDF) of the harvested energy during J WPT rounds is a sum of independent exponential random variables with rate parameter $\beta_i=\left(\frac{\eta_i P_0(t)}{\kappa d_i^\alpha}uT_c\right)^{-1}$. Thus, three cases need to be studied.

Case 1: When $\beta_i=\beta$ for all J time slots, the PDF of the harvested energy by the i-th device is given by [10]

$$f_{E_i^t}(x)=\frac{\beta^J x^{J-1}}{(J-1)!}e^{-x\beta}. \tag{6}$$

Case 2: Assuming that β_i is different in each time slot, the PDF of the harvested energy by the i-th device during J time slots can be written as [10]

$$f_{E_i^t}(x)=\sum_{j=t-J}^{t}\frac{\prod_{m=t-J}^{t}\beta_m}{\prod_{m\neq j}(\beta_m-\beta_j)}e^{-\beta_j x}. \tag{7}$$

Case 3: This case generalizes both the first and the second case. Assuming J time slots, from which m have different parameters β_s with $s=\{1,...,m\}$ and k_s have the same parameter β_s, the PDF of the harvested energy by the i-th device can be expressed as [10]

$$\begin{aligned} f_{E_i^t}(x) &= \sum_{s=1}^{m}\beta_s^{k_s}e^{-x\beta_s}\sum_{j=1}^{k_s}\frac{(-1)^{k_s-j}}{(j-1)!}x^{j-1} \\ &\times \sum_{v_1+\ldots+v_m=k_s-j}\prod_{\substack{l=1 \\ l\neq s}}^{m}\binom{k_l+v_l-1}{v_l}\frac{\beta_l^{k_l}}{(\beta_l-\beta_s)^{k_l+v_l}}, \end{aligned} \tag{8}$$

This article has been accepted for publication in IEEE Wireless Communications Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LWC.2023.3265993

where the sum $\sum_{v_1+\ldots+v_m=k_s-j}$ extends over all m-tuples $(v_1, ..., v_m)$ of non-negative integers with $v_1+...+v_m = k_s-j$.

B. WIT phase

During the WIT phase, the active ZEDs which were also given a grant begin data transmission. The percentage of active ZEDs depends on the traffic prediction accuracy. Due to the ZEDs' low computational capabilities, no resource allocation is employed at their side, therefore ZEDs consume all harvested energy. The duration of the second phase is n channel uses, thus the signal received at the BS from the i-th ZED is written as

$$y_i = \sqrt{\frac{P_i}{\kappa_i d_i^\alpha}} g_i x_i + w_i, \tag{9}$$

where x_i is a zero-mean unit-variance Gaussian codebook transmitted by the ZEDs, w_i is the additive white Gaussian noise with zero mean and variance σ^2, g_i is the uplink channel coefficient, and the transmit power is given by

$$P_i = \frac{E_i^t}{nT_c} = \frac{\sum_{j=t-J}^{t} P_0(j)|h_i(j)|^2}{n\kappa d_i^\alpha}\eta_i u. \tag{10}$$

Since a ZED consumes all its harvested energy during data transmission, the instantaneous received signal-to-noise ratio (SNR) at the BS from the i-th ZED is given by

$$\gamma_i = \frac{P_i|g_i|^2}{\kappa d_i^\alpha \sigma^2} = \frac{|g_i|^2 \sum_{j=t-J}^{t} P_0(j)|h_i(j)|^2}{n\kappa^2 d_i^{2\alpha}\sigma^2}\eta_i u. \tag{11}$$

Considering ZEDs short-packet transmissions, $\epsilon(\gamma, k, n)$ denotes the error probability of transmitting a packet of k information bits over n channel uses with SNR equal to γ. For $n \geq 100$, $\epsilon(\gamma, k, n)$ is approximated as [11]

$$\epsilon(\gamma, k, n) = \mathcal{Q}\left(\frac{C(\gamma) - r}{\sqrt{V(\gamma)/n}}\right), \tag{12}$$

where $r = k/n$ is the source fixed transmission rate, $C(\gamma) = \log_2(1+\gamma)$ is the Shannon capacity, and $V(\gamma) = \left(1 - \frac{1}{(1+\gamma)^2}\right)(\log_2 2e)^2$ is the channel dispersion, which measures the stochastic variability of the channel relative to a deterministic channel with an equal capacity [11].

III. PERFORMANCE ANALYSIS

A useful metric to characterize the performance of the considered system is the outage probability of the i-th ZED, which is defined as the probability that the received SNR at the BS from the i-th ZED, provided in (11), is lower than a threshold x. For short packet transmissions, this threshold can be obtained by solving (12) with respect to γ. We note that the analysis provided in this section is also valid for Shannon capacity communication.

Proposition 1: The outage probability of the i-th ZED, for Case 1, assuming that it harvests energy during J WPT rounds, while the BS transmits with constant power P_0 is given by

$$F_{\gamma_i}(x) = 1 - \frac{2(\beta\lambda_i x)^{\frac{J}{2}}}{(J-1)!} K_J\left(2\sqrt{\beta\lambda_i x}\right), \tag{13}$$

where $\lambda_i = nT_c\kappa d_i^\alpha \sigma^2$ and $K_v(\cdot)$ is the v-th order modified Bessel function of the second kind [12].

Proof: The outage probability is calculated through the CDF of the received SNR at the BS from the i-th ZED. Conditioning on the RV E_i^t, γ_i follows the exponential distribution with rate parameter $\frac{\lambda_i}{E_i^t}$, since $|g_i|^2$ follows the exponential distribution with rate parameter λ. Deconditioning on E_i^t, the CDF of γ_i is given by

$$F_{\gamma_i}(x) = \int_0^\infty \left(1 - e^{-\frac{\lambda_i x}{y}}\right) f_{E_i^t}(y) dy. \tag{14}$$

Using the PDF of the first case given in (6) and [12, (3.471.9)], (13) is obtained, which completes the proof. ■

Proposition 2: The outage probability of the i-th ZED, for Case 2, assuming that it harvests energy during J WPT rounds and the BS transmits a different power $P_{0,j}$ at each of the J time slots, can be expressed as

$$F_{\gamma_i}(x) = 1 - 2\sum_{j=t-J}^{t} A_j \sqrt{\frac{\lambda_i}{\beta_j}x} K_1\left(2\sqrt{\beta_j\lambda_i x}\right), \tag{15}$$

where $A_j = \frac{\prod_{m=t-J}^{t} \beta_m}{\prod_{m \neq j}(\beta_m - \beta_j)}$.

Proof: Using (7) and following similar steps as in Proposition 1, (15) is obtained, which completes the proof. ■

Proposition 3: The outage probability of the i-th ZED, for Case 3, assuming that it harvests energy during J WPT rounds and the BS transmits a different power P_{0s} in m time slots, which is the same in k_s time slots, is given by

$$\begin{aligned} F_{\gamma_i}(x) = 1 - 2\sum_{s=1}^{m}\beta_s^{k_s}\sum_{j=1}^{k_s}\frac{(-1)^{k_s-j}}{(j-1)!}\left(\frac{\lambda_i x}{\beta_s}\right)^{\frac{j}{2}} K_j\left(2\sqrt{\beta_s\lambda_i x}\right) \\ \times \sum_{v_1+\ldots+v_m=k_s-j}\prod_{\substack{l=1 \\ l\neq s}}^{m}\binom{k_l+v_l-1}{v_l}\frac{\beta_l^{k_l}}{(\beta_l-\beta_s)^{k_l+v_l}}. \end{aligned} \tag{16}$$

Proof: Using (8) and following similar steps as in Proposition 1, (16) is obtained, which completes the proof. ■

IV. TRAFFIC PREDICTION

Traffic prediction is vital for implementing FU grant to future ZE-mMTC networks. In [4], a high-accuracy traffic prediction scheme based on HMM was proposed. However, the prediction algorithm of [4] relies on complete knowledge of the environment, i.e., δ^0, δ^1, and the activation probabilities q_i^n. In practice, this knowledge may not be available, thus a different prediction algorithm is necessary.

In this direction, the proposed prediction algorithm relies on MAB. Specifically, we assume that each ZED represents an available arm to play, while the player/BS can play L arms. In classical MAB systems, the player can choose only one arm to play. To address that, we adopt a MAB variation which allows the player to choose L arms [6]. The algorithm is shown in Algorithm 1. We note that using the proposed traffic algorithm, the BS needs to observe the activity of only the L scheduled for transmission ZEDs, i.e., if these ZEDs were active or not, which is denoted as $b_{i'}(t)$. This knowledge can be obtained easily by using spectrum sensing techniques. Therefore, no additional resource scheduling for feedback from the ZEDs is needed, which qualifies Algorithm 1 as a low communication overhead traffic prediction candidate for ZE-mMTC networks.

This article has been accepted for publication in IEEE Wireless Communications Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LWC.2023.3265993

Algorithm 1 MAB based traffic prediction

```
1: Initialize $\psi$, $p_i(0)=\frac{1}{K}$, $r_i=0$, $v_i=0$, $L$
2: for $t=0:T$ do
3:     if $t=0$ then
4:         Choose $L$ ZEDs according to $p_i$
5:     else if $t>0$ then
6:         $z_i=\begin{cases} p_i(t)+\sqrt{\frac{\psi\log t}{v_i(t)}}, & v_i(t)>0 \\ +\infty, & \text{otherwise} \end{cases}$
7:         Choose $i'$ ZEDs with the $L$ greater $z_i$
8:     end if
9:     For the $L$ ZEDs, observe rewards $b_{i'}(t)\in\{0,1\}$:
10:        $r_{i'}(t+1)=r_{i'}(t)+b_{i'}(t)$, $v_{i'}(t+1)=v_{i'}(t)+1$
11:        Update $p_{i'}(t+1)=\frac{r_{i'}(t+1)}{v_{i'}(t+1)}$
12: end for
```

The idea of the action selection is that the square-root term in line 6, called the upper-confidence-bound, is a measure of the uncertainty or variance of the estimate of the i-th ZED being active. Thus, the maximized quantity can be considered as an upper bound for the possible true value of the i-th ZED being active with ψ determining the confidence level. We note that smaller values of ψ increase the exploitation of Algorithm 1, while greater values of ψ increase its exploration. Each time a ZED is selected, $u_i(t)$, which denotes the total number of instances that a ZED has been scheduled for data transmission, increases and, thus, the uncertainty term decreases. On the other hand, each time ZED j, other than i, is not selected, t increases but $u_j(t)$ does not, thus the uncertainty estimate increases. Therefore, all ZEDs will eventually be selected to balance their activity estimation uncertainty.

V. ENERGY MINIMIZATION

In this section, we aim to minimize the energy consumption of the BS, i.e., $uP_0(t)T_c$, which is highly prioritized in beyond 5G networks to reduce their environmental impact. Moreover, the ZEDs' requirements in terms of error probability are guaranteed. It is noted that due to the FU protocol, which provides an uplink grant only to L out of K ZEDs, only the outage probability of the L ZEDs should be considered. The problem can be formulated as follows:

$$\begin{aligned} \min_{P_0(t)} \quad & P_0(t) \\ \text{s.t.} \quad & \mathrm{C}_1: \quad \epsilon_i(\gamma_i(t),k,n)\le\epsilon_{\mathrm{th}}, \quad \forall i\in\tilde{\mathcal{N}}, \\ & \mathrm{C}_2: \quad P_0(t)\le P_{\max}, \end{aligned} \tag{17}$$

where $\tilde{\mathcal{N}}$ is the set containing all L ZEDs, which will be given an uplink grant. C_1 makes problem (17) quite challenging to solve. Specifically, the error probability at time slot t, expressed in C_1, is a function of the SNR, $\gamma_i(t)$, which depends on past time slots, since a ZED can harvest energy for more than one WPT phases, thus no closed-form exists for C_1. However, the BS is aware of the harvested energy PDF, at time slot t, for all ZEDs. To deal with the stochastic constraint C_1, robust optimization is a possible approach, however its solutions can be very conservative, since they take into account very rare, worst-case scenarios, causing the BS to always transmit with maximum power. Since practical mMTC applications can tolerate a degree of outage, chance-constrained programming is used. To this end, C_1 can be equivalently written as

$$\gamma_i(t)\ge G_i(\epsilon_{\mathrm{th}},k,n), \tag{18}$$

where the value of $G_i(\epsilon_{\mathrm{th}},k,n)$ can be computed numerically. Since the exact value of $\gamma_i(t)$ is stochastic and unknown, it is required that C_1 holds with great probability. Therefore, C_1 is approximated by the following chance constraint

$$\Pr(\gamma_i(t)\ge G_i(\epsilon_{\mathrm{th}},k,n))=1-F_{\gamma_i}(G_i(\epsilon_{\mathrm{th}},k,n))\ge p_{\mathrm{th}}, \tag{19}$$

where p_{th} is the level of reliability. Specifically, it denotes the probability that the received SNR at the BS is greater than $G_i(\epsilon_{\mathrm{th}},k,n)$, thus the error of the formulated chance-constrained optimization problem can be defined as $1-p_{\mathrm{th}}$. We note that problem (17), combined with (19), is a chance-constrained, non-convex optimization problem with no tractable solution. However, F_{γ_i} is a non-decreasing function with respect to $P_0(t)$. Thus, by utilizing the monotonicity of F_{γ_i}, problem (17) can be solved according to Algorithm 2. We note that different fading models can be used in the proposed system, while Rayleigh fading is the worst-case scenario.

Algorithm 2 Proposed solution of (17)

```
1: Initialize $P_{\max}$, $n$, $k$, $\mathrm{ub}=P_{\max}$, $\mathrm{lb}=0$, $j_{\max}$, $j=0$, $p_{\mathrm{th}}$
2: $\forall i\in\tilde{\mathcal{N}}$ estimate $p_i=1-F_{\gamma_i}(G_i(\epsilon_{\mathrm{th}},k,n))$ with $P_0(t)=0$
3: if $p_i\ge p_{\mathrm{th}}$, $\forall i\in\tilde{\mathcal{N}}$ then
4:     $P_0(t)=0$
5: else
6:     $i^*=\underset{i}{\mathrm{argmin}}\{p_i\}$
7: end if
8: while $j\le j_{\max}$ and $\mathrm{ub}\ne\mathrm{lb}$ do
9:     $P_0(t)=\frac{\mathrm{ub}+\mathrm{lb}}{2}$, $j=j+1$
10:    if $p_i^*\ge p_{\mathrm{th}}$ then
11:        $\mathrm{ub}=P_0(t)$
12:    else
13:        $\mathrm{lb}=P_0(t)$
14:    end if
15: end while
16: if $\mathrm{ub}=\mathrm{lb}=P_{\max}$ and $p_i^*\le p_{\mathrm{th}}$ then
17:    Problem (17) is infeasible
18: end if
```

In lines 3-5 of Algorithm 2, it is verified whether the selected ZEDs have harvested the required energy during previous WPT phases. If not, a bisection method is employed to calculate the BS minimum transmit power at time t. It is noted that problem (17) can be infeasible, since the BS maximum power may not be sufficient to ensure an acceptable outage probability at a ZED. This infeasibility can be dealt by removing the associated ZED from the uplink scheduling and scheduling the $(L+1)$-th most possibly active ZEDs. To this end, the joint problem of traffic prediction and proactive WPT is addressed by Algorithm 3.

Algorithm 3 Proactive WPT

```
1: Use lines 1-7 of Algorithm 1 to find the set of $L$ active ZEDs
2: Employ Algorithm 2 to find the minimum energy
3: if Algorithm 2 is feasible then
4:     Continue with lines 9-13 of Algorithm 1
5: else
6:     while Algorithm 2 is infeasible do
7:         Replace the user with the infeasible outage constraint with the most possible user to be active from the set of $N-L$ users
8:     end while
9: end if
```

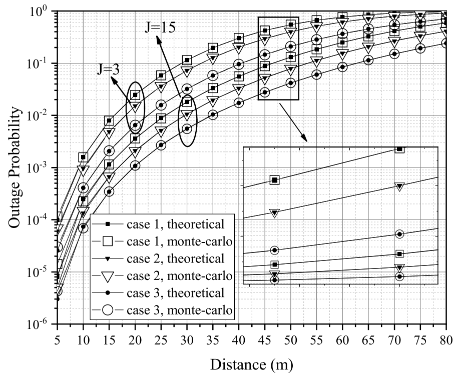

Fig. 2: Outage probability vs distance.

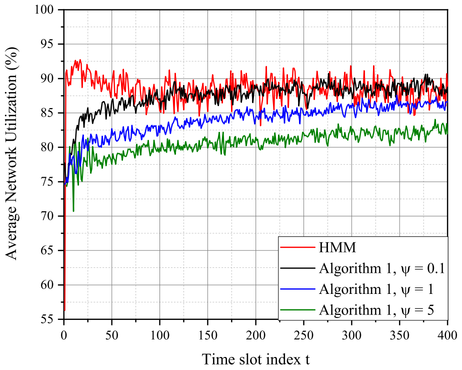

Fig. 3: Average network efficiency.

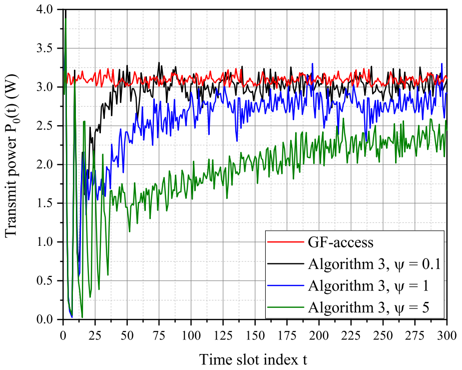

Fig. 4: Average BS transmit power.

VI. NUMERICAL RESULTS

In this section, simulations are presented to evaluate the proposed framework. The results of Fig. 1 are averaged over 10^7 Monte Carlo realizations, while the results of Figs. 2 and 3 are averaged over 500 realizations. We set $n = 2000$, $k = 1000$, $\alpha = 2$, $d_i \in [1, 10]$, $P_{\max} = 5$ W, $\epsilon_{\text{th}} = 10^{-5}$, $k = 96$, $\kappa = 10^3$, $\eta_i = 0.5$, $L = 10, K = 75$, $N = 5$, $q_i^n \in [0,1]$, $\delta^0, \delta^1 \in [0, 0.5]$, $T_c = 1$ μs, and $p_{\text{th}} = 0.99999$, which implies that there is one failed solution per 10^5 realizations of the chance-constrained problem, thus the error is negligible. For these parameters, problem (17) is always feasible.

In Fig. 1, the theoretical analysis of Section III is validated, since the theoretical results coincide with simulations. To demonstrate all cases, the transmit power for each case is chosen differently, thus the comparison between the cases is meaningless. As the distance from the BS increases, the outage probability increases, due to the doubly near-far effect.

In Fig. 3, the average network utilization is plotted versus the evolution of time. The average network utilization describes the percentage of the orthogonal resources which were given to active ZEDs. The HMM prediction benchmark was proposed in [4] and it has perfect knowledge of the network, thus it is considered as the upper bound of traffic accuracy. It is observed that Algorithm 1, for $\psi = 0.1$, despite monitoring only L out of K ZEDs and without perfect knowledge of the network, performs equally to the HMM benchmark. Furthermore, for $\psi = 1$ and $\psi = 5$, Algorithm 1 tends to explore more, i.e., schedules ZEDs for uplink transmission in a more uniform manner, which results to a worse prediction accuracy compared to the HMM benchmark. Nonetheless, it is far superior to GF access, which achieves an network utilization of 7%, thus it is omitted from Fig. 3.

In Fig. 4, the average transmit power of the BS, as derived from Algorithm 3, is plotted against the evolution of time, in time slots. The observed variance is due to the Monte Carlo simulation and because the optimal power allocation, as shown in Algorithm 2, depends on the MAB scheduling of Algorithm 1. It is observed that Algorithm 3 consumes the same power as GF access for $\psi = 0.1$. However, for greater values of ψ, Algorithm 3 consumes less power than GF access. Specifically, for $\psi = 5$, after convergence, the BS consumes approximately 30% less energy than GF access. This is attributed to the fact that for greater values of ψ Algorithm 1 schedules ZEDs for uplink transmission more uniformly. As a consequence, it loses prediction accuracy, as already shown in Fig. 3, however it also schedules ZEDs which have harvested energy for several WPT rounds, thus the required transmit power of the BS decreases. Therefore, Algorithm 3 not only utilizes the available resource blocks more efficiently than GF access, but it can also provide reduced energy consumption.

VII. CONCLUSION

Towards a zero-energy mMTC future, WPT was integrated with FU grant and the outage probability of the ZEDs during uplink was calculated. Moreover, to facilitate FU grant implementation, a MAB traffic prediction algorithm was proposed. Then, prioritizing the energy efficiency of future networks, WPT's consumption was minimized, while guaranteeing an error probability threshold for all ZEDs during the WIT phase. Simulation results validated the theoretic analysis and illustrated that FU grant outperforms grant-free access in terms of resource utilization and energy consumption. Future work could study the impact of WPT-aided FU grant on AOI.

REFERENCES

[1] N. H. Mahmood, S. Böcker, A. Munari, F. Clazzer, I. Moerman, K. Mikhaylov, O. Lopez, O.-S. Park, E. Mercier, H. Bartz *et al.*, "White paper on critical and massive machine type communication towards 6G," *arXiv preprint arXiv:2004.14146*, 2020.

[2] N. H. Mahmood, H. Alves, O. A. Lopez, M. Shehab, D. P. M. Osorio, and M. Latva-Aho, "Six Key Features of Machine Type Communication in 6G," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, Mar. 2020, pp. 1–5.

[3] N. A. Mitsiou, V. K. Papanikolaou, P. D. Diamantoulakis, and G. K. Karagiannidis, "Energy-Aware Optimization of Zero-Energy Device Networks," *IEEE Commun. Lett.*, vol. 26, no. 4, pp. 858–862, Apr. 2022.

[4] M. Shehab, A. K. Hagelskjar, A. E. Kalor, P. Popovski, and H. Alves, "Traffic Prediction Based Fast Uplink Grant for Massive IoT," in *Proc. 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications*. London, United Kingdom: IEEE, Aug. 2020, pp. 1–6.

[5] E. Eldeeb, M. Shehab, A. E. Kalor, P. Popovski, and H. Alves, "Traffic Prediction and Fast Uplink for Hidden Markov IoT Models," *IEEE Internet Things J.*, vol. 9, no. 18, pp. 17 172–17 184, Sep. 2022.

[6] S. Ali, A. Ferdowsi, W. Saad, N. Rajatheva, and J. Haapola, "Sleeping Multi-Armed Bandit Learning for Fast Uplink Grant Allocation in Machine Type Communications," *IEEE Trans Commun.*, vol. 68, no. 8, pp. 5072–5086, Aug. 2020.

[7] M. E. Tanab and W. Hamouda, "Efficient Resource Allocation in Fast-Uplink Grant for Machine-Type Communications with NOMA," *IEEE Internet Things J.*, vol. 9, no. 18, pp. 18 113–18 129, Sep. 2022.

[8] E. Eldeeb, M. Shehab, and H. Alves, "A Learning-Based Fast Uplink Grant for Massive IoT via Support Vector Machines and Long Short-Term Memory," *IEEE Internet Things J.*, vol. 9, no. 5, pp. 3889–3898, Mar. 2022.

[9] M. Cansiz and D. Altinel, "Multiband RF energy harvesting for zero-energy devices," *Electrical Engineering*, pp. 1–10, 2022.

[10] M. Akkouchi, "On the convolution of exponential distributions," *J.Chungcheong math. soc.*, vol. 21, no. 4, pp. 501–501, 2008.

[11] W. Yang, G. Durisi, T. Koch, and Y. Polyanskiy, "Quasi-Static Multiple-Antenna Fading Channels at Finite Blocklength," *IEEE Trans. Inf. Theory.*, vol. 60, no. 7, pp. 4232–4265, Jul. 2014.

[12] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*. Academic press, 2014.