Energy Group-Based Dynamic Framed ALOHA for Wireless Networks with Energy Harvesting

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***Abstract*—A novel random access protocol for data collection from a set of energy harvesting (EH) capable wireless nodes is proposed. The scheme is a variant of the dynamic framed ALOHA (DFA) protocol, tailored to EH networks. The proposed scheme, referred to as energy group-DFA (EG-DFA), is based on the observation that, when DFA is operated with EH-capable nodes, the optimal number of slots in a frame (i.e., the frame size) must balance two conflicting performance requirements. First, increasing the data collection rate (*throughput*) is well known to require a frame size equal to the backlog, namely the number of transmitting nodes. Second, since each node can store and harvest a finite energy, the number of (re)transmissions attempts that each node can perform during the channel contention process is limited. Thus, decreasing the number of uncollected data packets due to energy shortages (referred to as *delivery error rate*, DER) calls for a larger frame so as to avoid energy-wasting collisions. Moreover, the optimal frame size depends on both the residual energy at the nodes and the harvesting rate.**

Leveraging these insights, EG-DFA creates groups of nodes according to their energy availability and runs optimized and separated instances of DFA for each group. Simulation results show the advantages of EG-DFA in terms of throughput for a given DER, especially in the low-DER regime.

I. INTRODUCTION

In many applications, such as monitoring through wireless sensor networks, new data packets are generated periodically at wireless nodes (or users) and an access point, or fusion center (FC), is tasked with data collection [1] as shown in Fig. 1. If the FC does not know the identity of the nodes with new data available, referred to as *active users*, a standard strategy to collect information in each data generation period, also known as inventory round (IR), is the dynamic framed ALOHA (DFA) protocol [2]. As shown in Fig. 2, in DFA, each IR consists of a number of time-slotted frames. In the first frame, all active users randomly select one slot for packet transmission. All the users that successfully transmit in the first frame become inactive, while all the others are allowed to retransmit with the same mechanism in the next frame. In this paper we consider a collision channel model, in which a packet is successfully transmitted to the FC in a slot, only if the slot at hand is selected for transmission by a single user, otherwise a collision between two or more packets occur and no packets are correctly retrieved by the FC.

The number of slots L allocated to each frame of the IR is a critical choice in DFA's design. In fact, the *throughput* measures the number of successfully received data packets versus the overall number of allocated slots. At the beginning of each frame, there are B active users (i.e., users with new

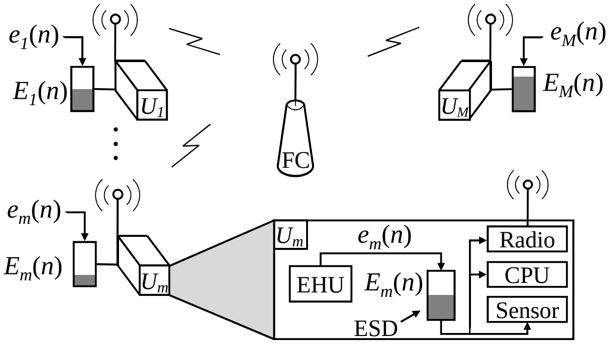

Figure 1. A single Fusion Center (FC) gathers data from M nodes distributed in its surrounding. Each node is equipped with an energy harvesting unit (EHU) and an energy storage device (ESD).

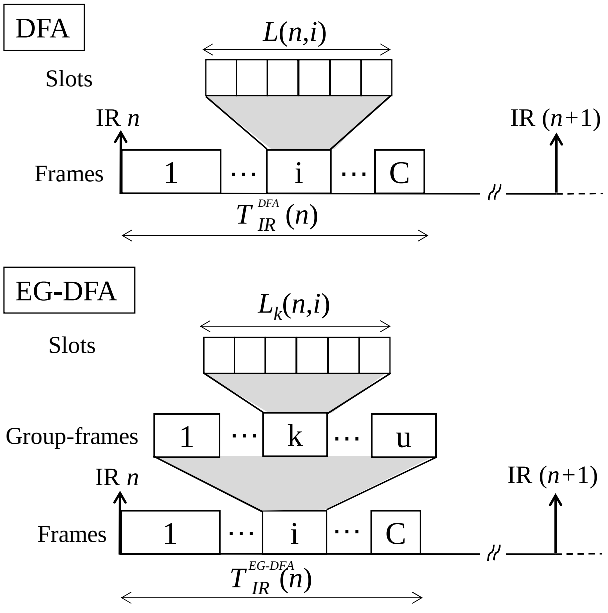

Figure 2. Organization of slots into frames in the dynamic framed aloha (DFA) protocol, and into group-frames and frames in the energy group-DFA (EG-DFA) protocol. The same structure is repeated every T_{int} [s] for each IR. Frames in DFA and group-frames in EG-DFA are designed according to Sec. III-A and Sec. III-B, respectively. Group-DFA (G-DFA) uses a structure similar to EG-DFA (see Sec. III-A).

data that have not yet been correctly received by the FC) denoted as *backlog*. Since the B active users randomly select one slot out of the L available in each frame for packet transmission, the choice of L larger than B entails a lower probability of collision but also a generally smaller throughput. The frame size L is typically selected by the FC, based on an estimate $\hat{B}$ of the current backlog B, as $L = \rho\hat{B}$, where ρ is a convenient design parameter [2].

A. *Design of DFA for Battery-Powered Nodes*

Traditional DFA's design assumes that nodes are *battery-powered*, so that they always have enough energy for transmission within their battery lifetime [2]. Accordingly, all active nodes in any IR are eventually correctly received by the FC via DFA, and in such a scenario the design goal is the maximization of the throughput. It is well-known that in a collision channel model, if the FC exactly knows the backlog B, the choice of a frame size $L = B$ (i.e., $\rho = 1$) maximizes the throughput [2][3]; however, when the FC is not fully aware of the value of B, the optimal L depends on the probability distribution of B [3] (when it is known by the FC).

A simple way to improve DFA's performance is via grouping [4], here referred to as *Group-DFA* (G-DFA). G-DFA divides users in groups, and each groups' data packets are collected by the FC through separated instances of DFA. G-DFA improves DFA's throughput, as decreasing the number of users competing for the same frame increases the chance of a successful transmission.

B. *Design of DFA for Energy-Harvesting Nodes*

Battery-powered nodes require maintenance for battery substitution. This is inappropriate for applications where nodes are not easily accessible after deployment, such as infrastructure monitoring. Energy-harvesting (EH) technologies provide an alternative solution to batteries. In fact, EH-nodes are self-sustained devices that collect the energy needed to operate from the surrounding environment (e.g., by leveraging solar or mechanical energy [5]). The key novelty in EH-nodes is that they have a virtually unlimited lifetime but, cannot guarantee energy availability at any given time due to the inherent randomness of the energy harvesting process [6]. Hence, novel design and analysis approaches are called for by networks operated with EH-nodes, see, e.g. [7][8].

DFA's performance with EH-nodes is generally not optimal for $\rho = 1$ even when the backlog is perfectly known by the FC (i.e., $\hat{B} = B$) [9] since energy wastage due to collisions can lead nodes to run out of energy before transmitting successfully their packets to the FC. It thus becomes imperative to consider, alongside the throughput, the *delivery error rate* (DER) as a figure of merit that quantifies the fraction of active users whose data packets are not successfully collected by the FC in each given IR. Throughput and DER set a fundamental trade-off in the choice of ρ, that is unique for EH networks. Specifically, the main lesson learned from [9] is that in the presence of energy-limited nodes, like EH-powered ones, it is generally advantageous to choose the design parameter ρ larger than unity (i.e., $\rho > 1$) to reduce collisions and thus the DER, even if this choice is suboptimal for the throughput.

C. *Main Contribution*

Based on the insights above, here we propose *energy group*-DFA (EG-DFA) as a novel variant of the DFA protocol tailored to EH networks. The key idea of EG-DFA is to divide users in groups according to their energy availability, and let each group access the channel via a separate instance of DFA, whereby different values of ρ can be selected for each group. EG-DFA combines the grouping gain of G-DFA with the ability to tune ρ to the group's energy availability. In fact, as discussed above, obtaining small DERs in groups with small energies requires large ρ values to decrease energy-wastage due to collisions, whereas ρ close to one is expected to be optimal for groups with large energies.

In the rest of the paper, we first detail the system model and the proposed solution in Sec. II and Sec. III respectively. We then present performance metrics in Sec. IV and numerical results in Sec. V to demonstrate the performance gains of EG-DFA. A low-complexity backlog estimation algorithm tailored to the EG-DFA protocol is then proposed in Appendix A.

II. SYSTEM MODEL

We consider M wireless nodes (users) $U_1, ...U_M$ communicating through a common channel to a FC (see Fig. 1). Users are periodically interrogated by the FC with period T_{int} [s]. At the beginning of each nth interrogation period, the FC starts an IR to collect data from users. We assume that the duration $T_{IR}(n)$ of the nth IR, which is generally a random variable that depends on the backlog size and the number of packet collisions, is much shorter than the time between two successive IR, i.e., $T_{IR}(n) \ll T_{int}$, for all n. Even in this scenario maximizing the throughput is of crucial importance as the FC's goal is to collect data packets as fast as possible to reduce delays. For instance, this is relevant in applications in which the FC has to take control actions based on the information retrieved through the collected packets. As discussed below, in the DFA protocol each IR is divided into frames, and frames into slots as shown in Fig. 1. The duration of a packet transmission fits a single slot. To denote time, we will mostly employ a double index (n,i), which denotes the beginning of the ith frame, $i = 1, 2, ...$, in the nth IR, $n = 1, 2, ...$ (slots are not indexed).

Nodes are equipped with an energy storage device (ESD) that is recharged by an energy harvesting unit (EHU). ESDs can be, e.g., batteries or supercapacitors. Each time a user needs to (re)transmit a packet, it consumes an amount of energy per frame ε [$Joule$], which accounts for all the sources of energy consumption in the bidirectional communication with the FC, including the energy required for packet transmission and for the reception of FC's query and acknowledgment (ACK). To simplify, let us normalize the energy per frame ε to one (i.e., $\varepsilon = 1$). Then, let $E_m(n,i) \in \{0, 1, ..., C\}$ be the energy stored in the ESD of the mth user at the beginning of the ith frame during the nth IR, where C is the ESD capacity.

The energy $E_m(1,1)$ initially stored in the mth user's ESD is a random variable independent and identically distributed (i.i.d.) among users.

The EHU of the mth user harvests energy $e_m(n)$ during the time T_{int} between the beginning of the nth and $(n+1)$th IRs. The harvested energy $e_m(n)$ is a random variable, i.i.d. across users and IRs, independent on the IR duration $T_{IR}(n)$, and with probability mass function (pmf) $p_e(k) = \Pr[e_m(n) = k]$. Note that, as the ESD is finite the energy harvested when the ESD is fully charged is wasted. We assume that each user operates in each nth IR using only the energy stored in its ESD at time $(n,1)$, while the energy harvested during the current IR can only be used in the next IRs. The energy in the mth user's ESD is a random variable that evolves across IRs as $E_m(n+1,1) = \min\{C,\ E_m(n,1) - \sum_i T_m(n,i) + e_m(n)\}$, where the indicator $T_m(n,i)$ equals one if user m transmits in the ith frame of the nth IR, and zero otherwise. We have $\sum_i T_m(n,i) \le E_m(n,1)$. Moreover, the energy in the mth user's ESD evolves across successive frames of any nth IR as $E_m(n,i) = E_m(n,1) - \sum_{k=1}^{i-1} T_m(n,k)$.

At the beginning of the nth IR at time $(n,1)$, the mth user is assumed to have a new data packet to transmit with probability α, and no packet with probability $(1-\alpha)$, independently from the other users and on previously generated packets and IRs (i.e., there is no data buffer). The mth user with a new packet is *active* at time $(n,1)$, if it has enough energy to transmit, i.e., if $E_m(n,1) \ge 1$. At the ith frame at time (n,i), with $i > 1$, the mth user is active if: *i)* it was active at time $(n,1)$; *ii)* its energy is $E_m(n,i) \ge 1$; *iii)* its packet still has to be received correctly by the FC (i.e., all previous attempts, if any, were unsuccessful).

III. ENERGY-GROUP BASED DFA

In this section we first review the DFA and G-DFA protocols and then introduce EG-DFA protocol. Let $M_k(n,i)$ be the number of nodes with energy $E_m(n,i) = k$ at time (n,i), and $B_k(n,i) \le M_k(n,i)$ be the number of *active* nodes, within the $M_k(n,i)$ with energy k. Let

$$B(n,i) = \sum_{k=1}^{C} B_k(n,i) \le \sum_{k=0}^{C} M_k(n,i) = M, \tag{1}$$

be the overall *backlog*, i.e., the total number of active users, at time (n,i). To simplify protocols' description, we assume that the FC exactly knows the backlogs $B_k(n,i)$ at any time. Backlog estimation algorithms for DFA and G-DFA protocols have been investigated in previous works (see e.g., [9], [10]). For the sake of completeness, we propose in Appendix A a simple backlog estimation algorithm specifically designed for the EG-DFA protocol.

A. DFA and G-DFA

In DFA, the number of slots in each frame at time (n,i) is selected as

$$L(n,i) = \lceil \rho B(n,i) \rceil, \tag{2}$$

where $\lceil\rceil$ is the nearest upper integer operator, and the design parameter ρ is selected such that $\rho \in [1, \rho_{\max}]$. Parameter ρ is chosen greater than one since for $\rho < 1$ both throughput and DER are simultaneously penalized, while choosing $\rho \le \rho_{\max}$ is to consider frame sizes of practical values. Each of the $B(n,i)$ active users randomly and uniformly selects one slot for transmissions in the current frame. After the end of the ith frame, the FC updates the backlog size for the next $(i+1)$th frame as $B(n,i+1) = B(n,i) - D(n,i) - S(n,i)$, where $D(n,i)$ denotes the number of packets successfully decoded and $S(n,i)$ indicates the number of users that collided in frame i and that have no energy left in the ESD for transmitting in frame $(i+1)$. The FC keeps announcing frames until no more users are available for transmission so that the ith is the last frame if $B(n,i+1) = 0$. Clearly, since the ESD is finite there cannot be more than C frames in an IR.

G-DFA is characterized by grouping, namely at the beginning of the nth IR, each active user randomly and uniformly selects one out of G groups to belong to. Each group of users then accesses the channel by resorting to G separate instances of DFA (through time-division over the same channel), one for each group. Specifically, in each frame of the IR, G subframes, referred to as *group-frames*, are allocated (see Fig. 2). Each group-frame contains slots intended only for users belonging to the specific group. Note that, only one group-frame per group is allowed within a frame and that all the G instances of DFA are operated with the same ρ.

B. Energy-Group DFA

Similarly to G-DFA, the EG-DFA protocol divides the users into groups. However, in EG-DFA each active user selects its own group in each frame (say at time (n,i)) *based on the energy currently available in its ESD*. Specifically, the kth group at time (n,i) contains all the active users with energy k at time (n,i). Accordingly, those active users that are initially in the kth group at time $(n,1)$ and that collide for j consecutive times ($j < k$) will belong to group $k-j$ in frame j. Note that, even if (colliding) active users change group index across frames, they always compete with the same set of users that were in the same group at time $(n,1)$. We thus have C parallel instances of the DFA protocol (one for each energy level in the ESD), similarly to G-DFA (where $C = G$), but here the kth instance of DFA resolves only users with equal initial energy level k. Furthermore, the instance of DFA for each energy level k is operated with a different parameter ρ_k, so that the trade-off between throughput and DER can be addressed according to the energy availability at nodes.

To elaborate, in the ith frame the FC announces $(C-i+1)$ group-frames since no active users can have energy greater than $(C-i+1)$ at time (n,i). Recall in fact that the energy harvested during an IR will be available only in the next IR. Let $B_k(n,i)$ be the backlog for group k at time (n,i), then the number of slots in the kth group-frame, for $(1 \le k \le C-i+1)$, is

$$L_k(n,i) = \lceil \rho_k B_k(n,i) \rfloor, \tag{3}$$

with ρ_k chosen as $\rho_1 \geq ... \geq \rho_C$, since a larger ρ_k is generally preferable for low-energy group (see Sec. I) as it decreases energy wastage due to collisions. Consequently, active users that collided in the current frame will transmit in the next frame with a generally larger ρ_k.

The backlogs $B_k(n,i)$ are updated at the end of each ith frame as

$$B_k(n,i+1) =, \\ \begin{cases} B_{k+1}(n,i) - D_{k+1}(n,i) & \text{for } 1 \leq k \leq C-i \\ 0 & \text{for } C-i < k \leq C \end{cases} \tag{4}$$

where $D_k(n,i) \leq B_k(n,i)$ is the number of users in group k at time (n,i) that successfully transmitted in frame i. Eq. (4) holds as active users with energy $(k+1)$ at time (n,i) (i.e., $B_{k+1}(n,i)$), which collide in frame i, will be the only $B_k(n,i+1)$ active users in the $(i+1)$th frame with energy k (for $k \geq 1$). The procedure repeats until the overall backlog (1) becomes empty, i.e., $B(n,i+1) = 0$.

IV. PERFORMANCE METRICS

Before introducing the throughput and the DER, let $L_{IR}(n) = \sum_i \sum_{k=1}^{C} L_k(n,i)$ and $D_{IR}(n) = \sum_i \sum_{k=1}^{C} D_k(n,i)$ be the total number of slots allocated and packets successfully received by the FC during the nth IR respectively. The *throughput* [packets/slots] is the ratio

$$\eta = \frac{\liminf\limits_{n\to\infty} \frac{1}{n}\sum_{l=1}^{n} E[D_{IR}(l)]}{\limsup\limits_{n\to\infty} \frac{1}{n}\sum_{l=1}^{n} E[L_{IR}(l)]} \tag{5}$$

between the long-term average numbers of successfully transmitted packets and allocated slots. Expectations in (5) are taken with respect to users' random slot selection process for transmission and the EH process. The DER instead, measures the fraction of users that is not retrieved by the FC as

$$\nu = 1 - \frac{\liminf\limits_{n\to\infty} \frac{1}{n}\sum_{l=1}^{n} E[D_{IR}(l)]}{\alpha M}, \tag{6}$$

where αM is the average number of users with a new packet to transmit at the beginning of an IR if there were no energy limitations (recall that α is the probability that a node has a new measure to transmit in an IR). The DER counts as lost both the packets of active nodes that end up in energy shortage during the IR, and the potential packets of nodes that have no energy since the IR's beginning. This is relevant for EH systems as protocols are expected to be able to collect a large number of packets in the given IR while saving energy for next IRs.

Clearly, there is a critical trade-off between throughput and DER. The throughput accounts for the speed of the collection process, while the DER indicates how many packets of the (average) potential overall batch of αM transmitting nodes are not retrieved due to energy shortages. A reasonable design criterion is thus to maximize the throughput while constraining the DER ν to be smaller than a threshold value $\bar{\nu}$ (i.e., $\nu \leq \bar{\nu}$) as

$$\eta^* = \max_{\rho_1,\dots,\rho_C} \eta \text{ s.t. } \nu \leq \bar{\nu}, \tag{7}$$

with the goal of optimizing parameters $\rho_1, ..., \rho_C$. In this regard, [9] shows that by judiciously selecting parameter ρ in DFA, small DER values can be achieved with limited throughput loss.

V. NUMERICAL RESULTS AND DISCUSSION

Here, we present extensive numerical results to get insights into EG-DFA's design and performance by numerically solving the constrained optimization problem (7) through a grid search.

Fig. 3 illustrates the throughput η^* versus the DER constraint $\bar{\nu}$ for the DFA, G-DFA and EG-DFA protocols. For reference, DFA and G-DFA's performances are shown by assuming that the FC perfectly knows the backlog at all times, while EG-DFA's performance are shown with both known and estimated backlog (see algorithm in Appendix A). We also consider solutions of (7) for the EG-DFA protocol by setting $\rho_k = \rho$ for each group $k \in [1, C]$, thus only exploiting users' grouping gain**.** System parameters are: $M = 100$ nodes; ESD's capacity $C = 8$; number of G-DFA's groups $G = C = 8$; $\alpha = 0.5$; EH's pmf $p_e(\cdot)$ exponential with mean $E[e_m(n)] = 2$.

From Fig. 3, it can be seen that EG-DFA with known backlog outperforms DFA, in terms of throughput, for any DER constraints $\bar{\nu}$, and also G-DFA for moderate-to-low DER values (here $\bar{\nu} \leq 4 \cdot 10^{-1}$). For higher DER constraints ($\bar{\nu} > 4 \cdot 10^{-1}$) G-DFA outperforms EG-DFA. This is because, one can decrease the design parameters ρ_k towards one, as collisions and thus energy wastage are less penalized when increasing the DER threshold $\bar{\nu}$. This implies that, when the EH rate is limited, most of the users have a small stored energy and only few groups in EG-DFA will have non-zero backlogs, thus drastically reducing grouping gain. Conversely, in G-DFA, groups are occupied uniformly (and randomly) regardless of the users' energy, and hence grouping gain is still fully exploited. Notice that, even if backlog estimation reduces EG-DFA's performance, it still allows to outperform both DFA and G-DFA with known backlog for a wide range of DER constraint $\bar{\nu}$. Our results also suggest (not shown) that the optimal ρ_k^* values increases as DER decreases and they increase more as the energy availability (i.e., group index k) gets smaller, consistently with the intuition in Sec. III-B, while they approach unity for each k for large DER values, as in this regime throughput is the relevant metric.

The effects of the ESD capacity C are shown in Fig. 4 for DER constraints $\bar{\nu} \leq \{2 \cdot 10^{-1}, 5 \cdot 10^{-3}\}$. System parameters are: $M = 100$; $G = C$; $\alpha = 0.5$; $E[e_m(n)] = 3$. For small ESD's capacity C, the energy harvested when the ESD is full cannot be stored, and thus users can easily get in energy shortage even when the harvesting rate is large (i.e., $E[e_m(n)] \gg 1$). This causes a meaningful performance loss and it imposes constraints on the achievable values of DER. For instance, if $C < 6$ a DER smaller than $\bar{\nu} \leq 5 \cdot 10^{-3}$ is not achievable by any technique. Moreover, small C values reduce the capability of grouping users and thus enabling small grouping gains only.

In Fig. 5 we show the effects of varying the average harvesting rate $E[e_m(n)]$ on the throughput for DER constraints $\bar{\nu} \leq \{5 \cdot 10^{-2}, 5 \cdot 10^{-3}\}$. Parameters are as above with $C = G = 8$. When the harvesting rate is small (e.g., $E[e_m(n)] \leq 3$), EG-DFA outperforms both G-DFA and DFA for both DER constraints. However, the gap between EG-DFA and G-DFA gets smaller as the harvesting rate increases. In fact, most users have full ESDs, and this causes only high-energy availability groups to have non-zero backlog, thus reducing EG-DFA's grouping gain. G-DFA's grouping gain is instead preserved as groups are uniformly occupied as described above.

As a final remark, note that for large C values EG-DFA can be operated by bundling close energy groups together without increasing the protocol complexity (i.e., number of groups).

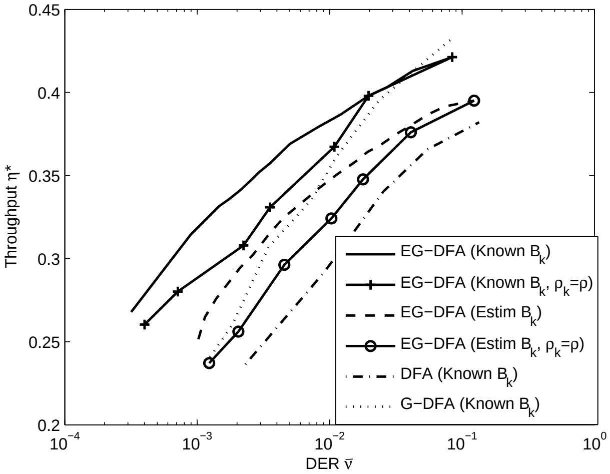

Figure 3. Throughput η^* versus DER $\bar{\nu}$ for the DFA and G-DFA protocols with known backlog, and for EG-DFA with both known and estimated backlog ($M = 100$, $\alpha = 0.5$, $C = G = 8$, $E[e_m(n)] = 2$

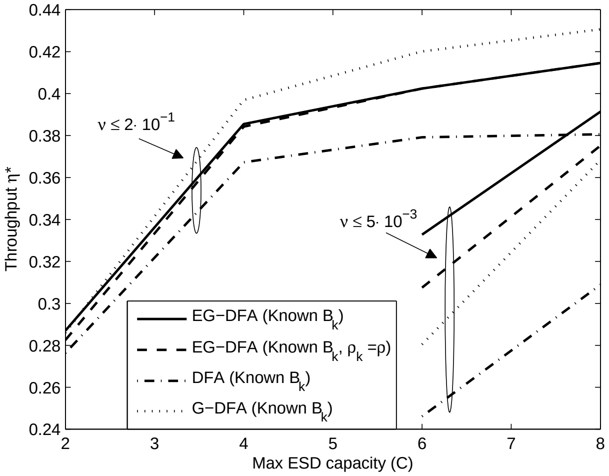

Figure 4. Throughput η^* versus ESD capacity C for the EG-DFA, G-DFA and DFA protocols, assuming perfect knowledge of the backlog. The DER is constrained to be $\nu \leq \{5 \cdot 10^{-3}, 2 \cdot 10^{-1}\}$ respectively ($M = 100$, $\alpha = 0.5$, $G = C$, $E[e_m(n)] = 3$).

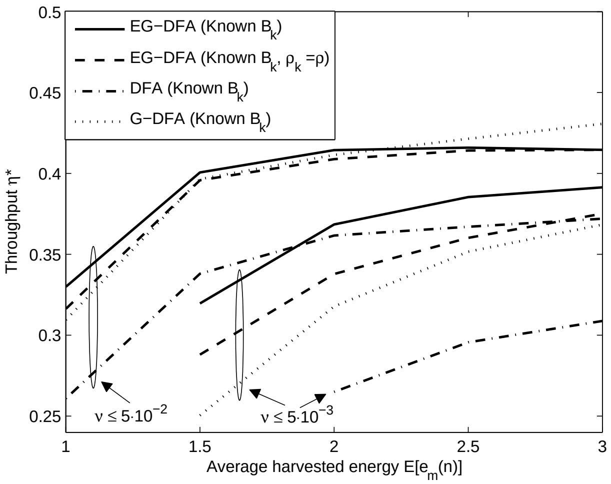

Figure 5. Throughput η^* versus average harvested (normalized) energy per IR $E[e_m(n)/\varepsilon]$ for the EG-DFA, G-DFA and DFA protocols, assuming perfect knowledge of the backlog. The DER is constrained to be $\nu \leq \{5 \cdot 10^{-3}, 5 \cdot 10^{-2}\}$ respectively ($M = 100$, $\alpha = 0.5$, $G = C = 8$).

VI. CONCLUSIONS

The design of protocols for wireless networks with Energy-Harvesting (EH) calls for novel approaches that address the unique requirements imposed by the variability of the energy available at the nodes. In this paper, we have proposed a variant of dynamic framed ALOHA (DFA) that is tailored to the problem of periodic data collection from a set of EH nodes. The proposed scheme, termed energy group-DFA (EG-DFA), improves the performance of DFA by leveraging the observation that the optimal size of the frame in DFA, when implemented over EH nodes, depends critically on the energy levels at the nodes and on the harvesting rate. Performance is evaluated in terms of the trade-off between throughput and delivery error rate (DER), where the latter measures the capability of collecting data from the nodes before they run out of energy. EG-DFA is shown via simulations to outperform known strategies in terms of throughput in the low DER regime. Impacts of the size of the energy storage device and of the harvesting rate are investigated as well. Extensions to this work can include the development of analytical tools for the design of the EG-DFA's optimal frame sizes and to derive performance in closed form.

APPENDIX A: BACKLOG ESTIMATION ALGORITHM FOR EG-DFA

Since optimal backlog estimation algorithms are computational expensive even for DFA [10], here we propose a low-complexity two-phases scheme [9] tailored to the EG-DFA protocol. The first phase is operated by the FC within each nth IR, and it is based on the observations of the channel outcomes (e.g., collided slots) [2]. In the second phase the FC accounts for the EH process.

Phase 1. Let $\hat{M}_k(n,1)$ be the estimated number of users in the kth group at time $(n,1)$. The estimate at time $(1,1)$ is $\hat{M}_k(1,1) = M \Pr[E_m(1,1) = k]$ (i.e., the expected number of users with energy k). The kth group's backlog estimation at time $(n,1)$ is $\hat{B}_k(n,1)=\alpha\hat{M}_k(n,1)$. When the first frame ends, the FC counts the number of successfully received packets $D_k(n,1)$ and collided slots $Z_k(n,1)$ in each kth group-frame. According to (4), the users that transmitted in the $Z_k(n,1)$ collided slots will form the backlog $B_{k-1}(n,2)$ for the $(k-1)$th group in the next frame. However, the FC cannot discern how many users were involved in the collision, and thus an estimation of $B_{k-1}(n,2)$ can be obtained as $\hat{B}_{k-1}(n,2)=Z_k(n,1)\beta(\rho_k)$, where $\beta(\rho_k)$ is the average number of users per observed-collided slot when the frame is dimensioned as $L=\lceil\rho B\rfloor$. This estimator, first proposed in [2] for $\rho=1$ with $\beta(1)\simeq 2.39$, was then extended in [9], where $\beta(\rho)$ was computed, under a large backlog approximation for any ρ, as $\beta(\rho)\simeq(1-e^{-1/\rho})/(\rho-\rho e^{-1/\rho}-e^{-1/\rho})$. By iterating this procedure, the backlog estimate at time (n,i) for the kth group (with $k\geq 1$) is $\hat{B}_k(n,i)=\alpha\hat{M}_k(n,i)$, for $i=1$ and $\hat{B}_k(n,i)=Z_{k+1}(n,i-1)\beta(\rho_{k+1})$ for $i>1$.

Phase 2. Let $M'_k(n)$ be the number of users in the kth group after the nth IR ends and before accounting for the EH process. $M'_k(n)$ is given by the sum of the number of: *i*) users $\sum_{i=1}^{C-k}D_{k+1}(n,i)$ that transmitted successfully within the $(k+1)$th group in the ith frame (known by the FC); *ii*) idle users $M_k(n,1)-B_k(n,1)$ that were initially in the kth group at time $(n,1)$ and that did not have a new measure to transmit, this is estimated (packet generation is random) as $\hat{M}_k(n,1)-\hat{B}_k(n,1)=\hat{M}_k(n,1)\left(1-\alpha\right)$. Accordingly, $M'_k(n)$ is estimated as $\hat{M}'_k(n)=\sum_{i=1}^{C-k}D_{k+1}(n,i)+\hat{M}_k(n,1)\left(1-\alpha\right)$, which might need to be conveniently normalized so that $\sum_{k=1}^{C}\hat{M}'_k(n)=M$. The number of users $M_k(n+1,1)$ at the $(n+1)$th IR's beginning can be obtained from $\hat{M}'_k(n)$ by using the expectation over the EH pmf $p_e(\cdot)$ as $\hat{M}_k(n+1,1)=\sum_{j=0}^{k}\hat{M}'_j(n)p_e(k-j)$ if $0\leq k<C$, while $\hat{M}_k(n+1,1)=M-\sum_{k=0}^{C-1}\hat{M}_k(n+1,1)$ if $k=C$.

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