FRESH: FReshness-aware Energy-efficient ScHeduler for Cellular IoT Systems

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***Abstract*—In cellular Internet of things (IoT) systems, massive low-power terminals update information status to cellular base stations to support diverse IoT applications. In this circumstance, information freshness and energy efficiency become two fundamental concerns. Except data transmissions, information updates consume additional energy for radio activation. To improve the energy efficiency, it is reasonable to aggregate the dynamically generated data. However, the reduced updates will severely deteriorate the information freshness, especially for time-critical IoT applications. To address this issue, we propose an upload scheduling scheme in this paper. Considering dynamic packet arrivals and channel conditions, the upload scheduling problem is formulated from a long-term perspective. To solve this problem, a practical online upload scheduler, named as FReshness-aware Energy efficient ScHeduler (*FRESH*), is proposed to minimize the update energy consumption subject to information freshness constraints. We theoretically show that *FRESH* can make the energy saving arbitrarily close to that of the optimal scheduling decision. Simulation results demonstrate the necessity and effectiveness of implementing *FRESH* for cellular IoT systems.**

I. Introduction

The Internet of Things (IoT) will revolutionize our physical world into digitalized world [1]. To realize this vision, low power wide area (LPWA) networks have drawn great attention primarily because of their unique features offering wide-area connectivity to low-power terminals [2]. To support LPWA networks, existing cellular systems are evolving to more advanced cellular IoT systems with ratifications, such as EC-GSM (Extended Coverage GSM), LTE-M (LTE for machine-type communication) and NB-IoT (Narrowband IoT) [2]–[4]. The distinct advantages of these cellular IoT systems, such as global reach, high quality-of-service (QoS), low cost of ownership, scalability and diversity, etc., have attracted great commercial potentials [1]–[6]. For instance, in [5] and [6], the two typical and well-developed commercial cellular IoT prototype systems, smart waste bins and smart grid, are respectively introduced.

In cellular IoT systems, the performance of applications depends on the sensing/monitoring data collected from massive terminals. Thus, the freshness of the collected data becomes a vital concern. Meanwhile different applications may possess distinct freshness requirements, where time-critical applications like smart tracking demand more stringent requirement than non-time-critical applications like environment monitoring [1]–[4]. To properly measure the freshness of the collected data, we adopt the metric age-of-information (AoI), which is defined as the elapsed time of the latest update since its generation [7], [8]. In cellular IoT systems, the AoI of a terminal characterizes the freshness of its updated data as illustrated in Fig.1. Unlike the delay metric that measures the timeliness of a packet, AoI is constantly evolving to measure the timeliness of a terminal's update. Specifically, assuming a terminal's data generated at time t_g is the latest updated data at time t, the AoI of this terminal is $t - t_g$. In cellular IoT systems, considering the freshness of collected data, the ideal scheduling is to immediately update the new arrival packets. Nevertheless, some packets are likely to be queued due to the dynamic packet generation and the limited cellular resources. Therefore, this work is well motivated to design a freshness-aware uploading scheduler for cellular IoT systems, which has not been well explored yet.

The aforementioned issue touches upon uplink transmissions, and thus the energy consumption of terminals becomes the fundamental concern [1]–[4]. Especially towards achieving ultra-long battery life in cellular IoT systems, the uploading scheduler should take energy saving into account. According to the uploading power trace presented in [9], [10], except the energy consumed by data transmissions, each radio activation also costs additional energy. Specifically, the additional energy includes promotion and tail energy, where the promotion (pre-send) energy is consumed before data transmission to transform the low-power idle state into the high-power transmission state, and the tail (post-send) energy is used to maintain a short high-power state after data transmission [9], [10]. To improve the energy efficiency of IoT terminals, it is reasonable to avoid frequent radio activations by scheduling packets in batches. As a result, how to balance the freshness of information updates and the energy consumption becomes a challenge. To the best of our knowledge, none of existing work focuses on upload scheduling considering both the freshness awareness and the energy saving.

In this paper, to address the aforementioned issues, we propose an online upload scheduler, namely FReshness-aware Energy efficient ScHeduler (*FRESH*), for cellular IoT systems. To accommodate the dynamics of packet generation and wireless channel, a general Lyapunov framework is adopted to min-

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imize the long-term energy consumption while guaranteeing the information freshness requirement. We theoretically prove that both the energy consumption bound and the information freshness, i.e., AoI, bound under varying packet arrivals and wireless conditions, can be achieved by implementing *FRESH*. In addition, we design a coarse-grained fixing algorithm with low complexity to derive a feasible scheduling decision for the non-linear integer problem (NIP) in *FRESH*. Extensive simulations are developed to demonstrate the necessity and effectiveness of implementing *FRESH* for cellular IoT systems. The results also show impacts of diverse IoT characteristics, such as information freshness requirements and data arrival rate, on energy-efficient cellular IoT design.

The rest of this paper is organized as follows. In Section II, we present the system model and formulate the freshness-aware energy minimization problem. In Section III, *FRESH* is proposed to address this problem including online optimization design and the coarse-grained fixing scheduling. The simulation results are illustrated in Section IV. Section V finally concludes this paper.

II. System Model

In this section, we first present the system model, and then formulate the freshness-aware energy minimization problem.

A. Basic Cellular IoT Transmission Model

As a family of cellular IoT standardizations, EC-GSM, LTE-M and NB-IoT respectively target at different use cases and deployment scenarios [2]–[4]. Although their uplink multiplexing techniques are different, either time-division multiple access (TDMA) for EC-GSM or single-carrier frequency-division multiple access (SC-FDMA) for LTE-M and NB-IoT, the uploading resources are centrally scheduled by BSs. In each scheduling time $t \in \tilde{t} = \{1, 2, 3, ...\}$, a BS makes decisions for the following transmission interval Δt. To clarify our design, this work explores NB-IoT scenario as a typical cellular IoT scheduling example. Our scheduler can be implemented in LTE-M with larger resource unit (RU) granularity and in EC-GSM as a special case under single frequency band. Denote the number of uploading RUs by $N_{ru} = \tau_{tot} f_{tot}$, where τ_{tot} and f_{tot} are respectively the numbers of time and frequency units. The size of a time unit $\Delta\tau = \Delta t/\tau_{tot}$ is either 0.5ms with 15KHz frequency unit or 2ms with 3.75KHz frequency unit [4].

The physical architecture of a cellular IoT system is illustrated in Fig.1. Under the coverage of a BS, there are multiple IoT applications (APP 1-APP N). Denote the set of serving applications by $\tilde{N}_d$. Each application $n \in \tilde{N}_d$ may exhibit different packet generation rate λ_n, packet size s_n and freshness requirement ϕ_n. Denote the set of terminals in application n by $\tilde{K}_n$. The total number of terminals belonging to all applications $n \in \tilde{N}_d$ is given by $\sum_{n\in\tilde{N}_d} \left|\tilde{K}_n\right|$. Each terminal buffers the dynamically generated packets in the packet queue, and waits for its upload schedule. Without loss of generality, this work explores the radio transceiver with a popular packet queuing discipline, first-in-first-out (FIFO) [7], [8]. Due to the channel variations, different modulation and coding schemes (MCS) may be applied to each serving terminal. We assume that the channel condition during a transmission interval $[t, t+1]$ is static, and the capacity of a single RU for terminal $k \in \tilde{K}_n, n \in \tilde{N}_d$ is denoted by $c_{n,k}(t)$. Thus, the number of RUs for transmitting one packet at scheduling interval $[t, t+1]$ can be given by

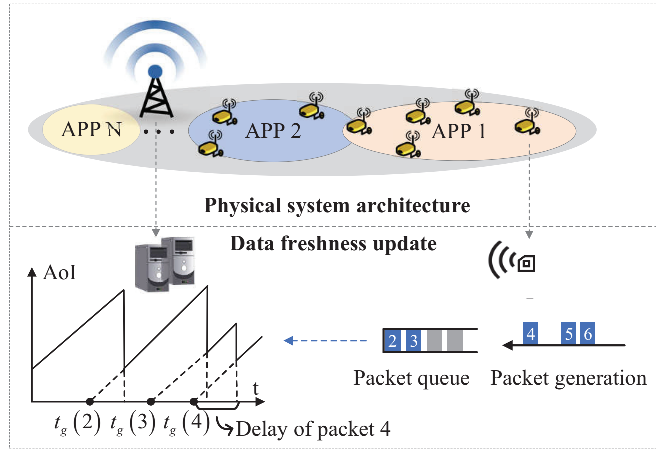

Fig. 1. The physical cellular IoT system architecture and the corresponding data freshness updates.

$$\tau_{n,k}(t) = \left\lceil \frac{s_n}{c_{n,k}(t)} \right\rceil, \forall k \in \tilde{K}_n, n \in \tilde{N}_d.$$

where s_n is the packet size of application n. Note that the channel selective fading among different frequency units is limited and thus ignored in our model[1]. At any scheduling point $t \in \tilde{t}$, denote the number of the scheduled RUs by

$$m_{n,k}(t) = \mu_{n,k}(t)\,\tau_{n,k}(t), k \in \tilde{K}_n, n \in \tilde{N}_d, \tag{1}$$

where $\mu_{n,k}(t)$ is the number of its packets scheduled to be transmitted, and thus we have

$$\mu_{n,k}(t) \in [0, N_{ru}] \subset \mathbb{N}, k \in \tilde{K}_n, n \in \tilde{N}_d. \tag{2}$$

Due to the limitation of cellular IoT resources, the resource constraint at any scheduling point $t \in \tilde{t}$ can be given by

$$\sum_{n\in\tilde{N}_d} \sum_{k\in\tilde{K}_n} m_{n,k}(t) \le N_{ru}, \tag{3}$$

where N_{ru} is the aforementioned total number of the available uploading RUs in cellular IoT systems.

B. Information Freshness

Most cellular IoT applications are based on the information collected from massive IoT terminals. To characterize the information freshness, we adopt the metric, age-of-information (AoI) [7], [8], which measures the time elapsed since the generation of its latest received packet by the BS as illustrated

[1]The total available bandwidth of NB-IoT equals to the bandwidth of a single carrier (the frequency unit) of legacy LTE. Since the fading inside a carrier is usually regarded as the same, the selective fading is ignored in NB-IoT [4].

in Fig.1. Thus the value of AoI depends on both the packet generation and the uploading processes. For any terminal $k \in \tilde{K}_n, n \in \tilde{N}_d$, denote the set of packets that are generated since schedule point $t = 0$ by $U_{n,k} = \{1, 2, 3, ...\}$. Thus, the latest received packet at the BS at scheduling point t is given by

$$u_{n,k}(t) = U_{n,k}\left(\sum_{i=0}^{t-1} \mu_{n,k}(i)\right).$$

where $\sum_{i=1}^{t-1} \mu_{n,k}(i)$ is the number of previously received packets accumulated until scheduling point t, which is determined by the previous scheduling decisions at the BS. Thus, the AoI of terminal $k \in \tilde{K}_n, n \in \tilde{N}_d$ at scheduling point t is given by

$$A_{n,k}(t) = t \cdot \Delta t - t_g(u_{n,k}(t)),$$

where $t_g(u)$ records the generation time of packet u. Note that the AoI evolution is based on discrete time slots, and $t_g(u)$ is correlated with a terminal's packet generation rate λ, which is transmitted as part of the overhead signaling to the BS. Due to different freshness requirements of different applications, the AoI constraints are introduced. Instead of the instantaneous value, we consider the long-term averaged AoI for the flexible management of massive terminals under dynamic channel environment and packet generation, where the instantaneous constraints for all terminals are hard to guarantee. Therefore, we have the freshness constraint as follows,

$$\lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} A_{n,k}(t) \le \phi_n,\ \forall k \in \tilde{K}_n,\ \forall n \in \tilde{N}_d, \quad (4)$$

where ϕ_n is the long-term freshness requirement of IoT application $n \in \tilde{N}_d$. In order to satisfy the above freshness constraint, a virtual age queue $Q_{n,k}^{A}(t)$ is introduced for each terminal [12], [13]. The updating equation of this virtual queue can be given by

$$Q_{n,k}^{A}(t+1) = \left[Q_{n,k}^{A}(t) - \phi_n\right]^{+} + t \cdot \Delta t - t_g(u_{n,k}(t)), \quad (5)$$

where $[x]^{+} = \max\{x, 0\}$. To satisfy the freshness constraint (4), the virtual queue $Q_{n,k}^{A}(t)$ should be kept stable at each terminal, where its long-term averaged input rate must be lower than the long-term averaged output [13].

C. Upload Energy Consumption

According to the trace of upload power [9], [10], either the data transmission duration or the promotion and tailing (pre/post-send) duration costs high energy. In a cellular IoT system, the upload energy consumption during a scheduling interval $[t, t+1]$ depends on the number of the scheduled RUs $m_{n,k}(t), k \in \tilde{K}_n, n \in \tilde{N}_d$ at scheduling point t. Assuming that the power of a data transmission is P_{data}, the energy consumption of a data transmission is given by

$$E_{n,k}^{data}(t) = m_{n,k}(t) P_{data}.$$

Denote the energy consumed during each promotion (pre-send) and tail (post-send) duration by E_{RA}, which is utilized for radio activation. Thus, the energy consumption for radio activation is given by

$$E_{n,k}^{active}(t) = \mathbf{1}(m_{n,k}(t) > 0) E_{RA}, \quad (6)$$

where $\mathbf{1}(X) = 1$ when event X is true, otherwise $\mathbf{1}(X) = 0$. Thus we have the upload energy consumption for one terminal during scheduling interval $[t, t+1]$, and that for all terminals can be given by

$$E_{total}(t) = \sum_{n\in\tilde{N}_d}\sum_{k\in\tilde{K}_n}\left\{E_{n,k}^{data}(t) + E_{n,k}^{active}(t)\right\}. \quad (7)$$

Since the upload energy consumption is dynamically determined by scheduling decisions at each scheduling point, the energy performance is evaluated by the average upload energy, which is given by

$$E(T) = \frac{1}{T}\sum_{t=1}^{T} E_{total}(t).$$

Thus, we consider the long-term averaged upload energy consumption $\lim_{T\to\infty} E(T)$, which can be utilized as the objective function for realizing the energy-efficient cellular IoT systems.

D. Freshness-aware Energy Minimization Problem

Our objective is to schedule the number of transmitted packets $\mu_{n,k}(t)$ for all terminals $k \in \tilde{K}_n, n \in \tilde{N}_d$ at each scheduling point $t \in \tilde{t}$ that can minimize the upload energy consumption while guaranteeing the AoI performance. Then the freshness-aware energy minimization problem is formulated as follows:

$$\begin{aligned} &\min_{\mu_{n,k}(t)} \quad \lim_{T\to\infty} E(T) \\ &\text{subject to } (2), (3) \text{ and } (4). \end{aligned} \quad (8)$$

Given the corresponding channel variations, the number of the scheduled RUs $m_{n,k}(t)$ and the number of the packets $\mu_{n,k}(t)$ are correlated based on (1). Due to the integer optimization variants and the long-term performance both in the objective function and the constraint (4), our problem can be transformed from NP-hard partition problem [11]. For the long-term performance, the statistical information is required. Unfortunately, it is challenging and inaccurate to obtain the statistics of massive terminals considering the dynamic wireless channel condition and packet generation in real systems. To address this issue, an online optimal scheduler is developed in Section III, where the long-term benefits can be obtained at each scheduling point $t \in \tilde{t}$ without requiring future network information.

III. Freshness-Aware Energy Efficient Scheduler

In this section, we propose an online scheduler named *FRESH* (FReshness-aware Energy efficient ScHeduler) for our scheduling problem in (8). Aiming at achieving a long-term benefit, *FRESH* can be easily implemented by a BS to effectively and efficiently schedule the packet transmissions without requiring future system information. In the following, we present its online optimization design, followed by the coarse-grained fixing schedule.

A. Online Optimization Design

Considering the long-term benefit, we adopt the Lyapunov optimization tool [12]–[14]. According to the Lyapunov framework [13], our Lyapunov function is given by $L(t) \triangleq \frac{1}{2} \sum_{n \in \tilde{N}_d} \sum_{k \in \tilde{K}_n} \left(Q^A_{n,k}(t)\right)^2$. Denote the AoI performance constraint at each scheduling point by $\mathcal{Q}^A(t) = \left\{Q^A_{n,k}(t) \mid \forall k \in \tilde{K}_n, \forall n \in \tilde{N}_d\right\}$. Thus, the Lyapunov drift function can be given by

$$\Delta L(t) \triangleq \mathbb{E}\left[L(t+1) - L(t) \middle| \vec{Q}^A(t)\right]. \quad (9)$$

Considering the energy minimization objective, we further develop the Lyapunov drift function into Lyapunov drift-plus-penalty function, $\Delta L(t) + V\mathbb{E}\left[E_{total}(t) \middle| \vec{Q}^A(t)\right]$, where $V \geq 0$ is a pre-defined constant that is utilized to balance the tradeoff between information freshness and system energy consumption [12]. Specifically, the increasing of V will lead to better energy saving while sacrificing the AoI performance. Based on Lyapunov drift-plus-penalty function, we obtain the following Lemma 1.

Lemma 1. *Assume that the freshness improvement of each terminal during one scheduling interval $G(n,k,t) = t_g(u_{n,k}(t+1)) - t_g(u_{n,k}(t))$ has finite expectation, i.e., $\forall n \in \tilde{N}_d, k \in \tilde{K}_n, \mathbb{E}[G(n,k,t)] \leq \mathcal{G}$. We have*

$$\begin{aligned} &\Delta L(t) + V\mathbb{E}\left[E(t) \middle| \vec{Q}^A(t)\right] \\ &\leq B + \sum_{n \in \tilde{N}_d} \sum_{k \in \tilde{K}_n} Q^A_{n,k}(t)\{\Delta t - G(n,k,t)\} + VE_{total}(t), \end{aligned} \quad (10)$$

where $B \triangleq \frac{1}{2} \cdot \sum_{n \in \tilde{N}_d} \left|\tilde{K}_n\right| \left(\Delta t^2 + \phi_n^2 + \mathcal{G}^2\right)$, and $E_{total}(t)$ is given in (7).

Lemma 1 can be proved by taking equation (5) into equation (9). According to the Lyapunov optimization principle, the optimal schedule can be derived by minimizing Lyapunov drift-plus-penalty function at each scheduling point [12], [13]. Thus, *FRESH* minimizes the RHS of (10) to guarantee the stability of AoI performance while minimizing the uploading energy consumption. Therefore, problem (8) can be transformed into the following minimization problem:

$$\begin{aligned} \min_{\mu_{n,k}(t)} \quad & \sum_{n \in \tilde{N}_d} \sum_{k \in \tilde{K}_n} Q^A_{n,k}(t)\{\Delta t - G(n,k,t)\} + VE_{total}(t) \\ \text{subject to} \quad & (2) \text{ and } (3) \end{aligned} \quad (11)$$

According to $E_{total}(t)$ in (7), the objective function of problem (11) involves l_0-norm of $\mu_{n,k}(t)$, i.e., $\|\mu_{n,k}(t)\|_0 = \mathbf{1}(\mu_{n,k}(t) > 0)$. Due to the complexity introduced by l_0-norm, we further transform this problem into an equal form by introducing additional auxiliary variables $\xi_{n,k}$ [15]. Therefore, problem (11) can be solved by

$$\begin{aligned} \min_{\mu_{n,k}(t),\ \xi_{n,k}} \quad & \sum_{k \in \tilde{K}_n} \sum_{n \in \tilde{N}_d} \left\{-Q^A_{n,k}(t)\, G(n,k,t) \right. \\ & \left. + VP_{data}\tau_{n,k}(t)\,\mu_{n,k}(t) + VE_{RA}\xi_{n,k}\right\} \\ \text{subject to} \quad & (2) \text{ and } (3) \\ & \mu_{n,k}(t) \leq M\xi_{n,k}, \\ & \xi_{n,k} \in \{0,1\}, \forall k \in \tilde{K}_n, n \in \tilde{N}_d, \end{aligned} \quad (12)$$

where M is the scalar defined as $M = N_{RU} \geq \|\mu^*(t)\|_\infty$ [15]. The optimization variables of problem (12) turn into $\mu_{n,k}(t)$, $\xi_{n,k}$ for all $k \in \tilde{K}_n, n \in \tilde{N}_d$. It is noticeable that our scheduling problem is nonlinear integer programing (NIP) due to the nonlinearity of the freshness improvement $G(n,k,t)$ mentioned in Lemma 1. Since NIP problem is proved to be NP-hard [17] and the difficulty of our problem arises from the integer constraints, we reduce the complexity by relaxing the integer constraints into continuous space. Due to the enlarged solution space (relaxed integer constraints), the solution of this relaxed problem yields an lower bound of our energy minimization problem (8) in Section II-D. Although this lower bound solution may not be feasible for the original problem (8), it can be a benchmark to evaluate the quality of feasible solutions.

B. The Coarse-grained Fixing Schedule

Although the aforementioned lower bound solution can be regarded as the benchmark, it is still necessary to seek integer values representing the number of the scheduled packets, i.e., integer $\mu_{n,k}(t)$-variables. To address this issue, *FRESH* employs the coarse-grained fixing method to effectively and efficiently produce a feasible solution [16]. To determine the values for all $\mu_{n,k}(t)$, a sequence of relaxed optimization problems are iteratively solved. In each iteration, a number of $\mu_{n,k}(t)$-variables are fixed. Specifically, the first iteration relaxes all the integer variables, i.e., $\mu_{n,k}(t)$ and $\xi_{n,k}, k \in \tilde{K}_n, n \in \tilde{N}_d$, which is the same procedure as solving the aforementioned lower bound solution. Then, we select the $\mu_{n,k}(t)$-variables that are very close to integers, i.e., whose decimal places are either close to 0 or 1, and set their values to be the corresponding closest integers. Once the fixed $\mu_{n,k}(t)$ is non-zero value, the corresponding $\xi_{n,k}$ is set to be 1, otherwise to be 0. Given the fixed $\mu_{n,k}(t)$ and $\xi_{n,k}$ variables, we remove their associated terms and update the problem for the second iteration. The second iteration solves the updated problem and then set the values of some unfixed $\mu_{n,k}(t)$ to be integers based on the same process. The iteration terminates when all the $\mu_{n,k}(t)$-values are fixed to be integers. The overall procedure of our coarse-grained fixing schedule is summarized in Algorithm 1.

Note that the computation of the second iteration is lower than that of the first iteration, since the fixed $\mu_{n,k}(t)$-variables by the first iteration are removed and the optimization variables are reduced to be the remaining unfixed $\mu_{n,k}(t)$-variables. Thus in each iteration, the computation complexity is lower than the lower bound solution. Due to the limited number of iterations that is lower than the number of integer optimization variables, i.e., $\sum_{n\in\tilde{N}_d}|K_n|$, our coarse-grained fixing schedule exhibits the same computation complexity compared as that of the lower bound solution. In addition, our coarse-grained fixing schedule scheme yields an upper bound solution of the energy minimization problem (8) in Section II-D. Thus, the quality of our sub-optimal schedule can be assessed by comparing its solution with the lower bound solution.

C. Performance Analysis of *FRESH*

In general, *FRESH* can utilize the instantaneous network settings of each scheduling point to effectively schedule per terminal's packet transmission, which is much more practicable than solving problem (8) based on statistical data. After a long time period operation, the long-term energy saving and freshness performance of problem (8) can be bounded as shown in Theorem 1.

Theorem 1. *Given that the uploading load is strictly within the network capacity, FRESH can stabilize the cellular IoT system, guarantee the freshness requirement and optimize the energy consumption. The time-averaged freshness performance and the time-averaged energy consumption respectively satisfy:*

$$\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\sum_{n\in\tilde{N}_d}\sum_{k\in\tilde{K}_n}\mathbb{E}\left\{Q_{n,k}^{A}\left(t\right)\right\}\leq\frac{B+V\sum\limits_{n\in\tilde{N}_d}\left|\tilde{K}_n\right|E^*}{\varepsilon},\tag{13}$$

$$\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\mathbb{E}\left\{E_{total}\left(t\right)\right\}\leq E^*+\frac{B}{V},\tag{14}$$

where B is the same expression as in Lemma 1, $\varepsilon>0$ is a positive constant, and E^* is the theoretical optimal time-averaged energy consumption during a scheduling interval.

According to Lemma 1 and Lyapunov bound in [13], [14], we derive Theorem 1. Due to the page limit, the detailed proof is ignored here. According to Theorem 1, the virtual queues of both the energy consumption and AoI are stabilized under finite queue length. From (14), the optimal E^* can be arbitrarily approaching with $V\to\infty$. However, from (13), a large V will lead to a decreased freshness performance. Thus we utilize the maximum V that meets the AoI constraint while minimizing the upper bound of time-averaged energy consumption to the optimal value.

Algorithm 1 The Coarse-grained Fixing Schedule

1: Initialization: Relax integer constraints of all $\mu_{n,k}\left(t\right)$ and $\xi_{n,k}$ variables in problem (12) into continuous space;
2: Solve the relaxed nonlinear problem in continuous space.
3: Search for the $\mu_{n,k}\left(t\right)$ with decimal part less than ϵ and more than 1-ϵ among all the unfixed $\mu_{n,k}\left(t\right)$;
4: Respectively fix the above selected $\mu_{n,k}\left(t\right)$ by $\lfloor\mu_{n,k}\left(t\right)\rfloor$ and $\lceil\mu_{n,k}\left(t\right)\rceil$;
5: Set the corresponding $\xi_{n,k}$ to be 0 when the fixed $\mu_{n,k}\left(t\right)$ is 0, otherwise to be 1;
6: **if** all the $\mu_{n,k}\left(t\right)$-variables are fixed **then**
7:     Go to line 12;
8: **else**
9:     Reformulate the relaxed problem by replacing the latest selected $\mu_{n,k}\left(t\right)$ and $\xi_{n,k}$ variables with the corresponding fixed values.
10:     Step to line 2;
11: **end if**
12: Output the values of all integer $\mu_{n,k}\left(t\right)$-variables.

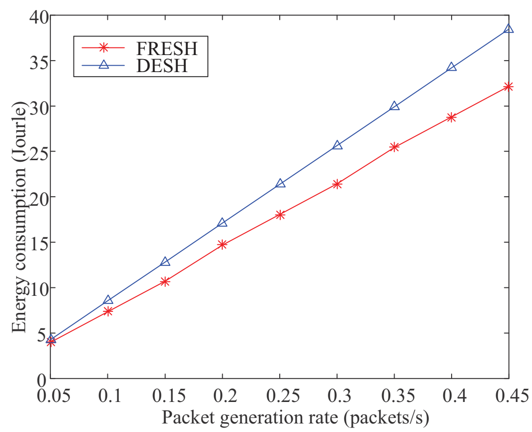

Fig. 2. Energy consumption comparison between *FRESH* and *DESH*.

IV. Performance Evaluation

In this section, we evaluate the performance of *FRESH* in cellular IoT systems. Under the coverage of a BS, we consider several IoT applications with different freshness requirements ϕ. The packet arrival from the same application follows Poisson distribution with the same corresponding arrival rate λ in the range of 0.05 to 0.45. Based on the trace of IoT terminal's uploading energy, a terminal's transmit power P_{data} and radio activation energy E_{RA} are respectively set to be 375mW and 5×10^{-3}Joule [9], [10]. According to NB-IoT standard [4], the number of resource units N_{RU} in one transmission interval is 240. The packet size s is set to be 800 bytes, and the capacity of a single resource unit $c_{n,k}\left(t\right)$ for terminal $n\in\tilde{N}_d$ and $k\in\tilde{K}_n$ is exponentially distributed with the same average. To evaluate the long-term system performance, we run our simulation over 10000 scheduling intervals.

We first evaluate the necessity of implementing a new scheduler *FRESH* for cellular IoT systems. Conventional cellular uplink scheduling focuses on human-type devices, where the QoS constraint of timeliness usually takes the packet-level delay metric into account [18]. Instead of the timeliness of a packet, most IoT applications deal with terminal's monitoring information, i.e., information freshness, and thus we propose *FRESH*. For comparative analysis, we also evaluate conventional delay-aware scheduler, namely, *DESH* [18]. The same system configurations are implemented in the two schedulers for a fair comparison. As illustrated in Fig.2, the averaged per hour energy consumption of a terminal is as a function of packet generation rate λ, where 1000 terminals from an application with freshness requirement $\phi=30$s are considered. We can observe that *FRESH* always outperforms

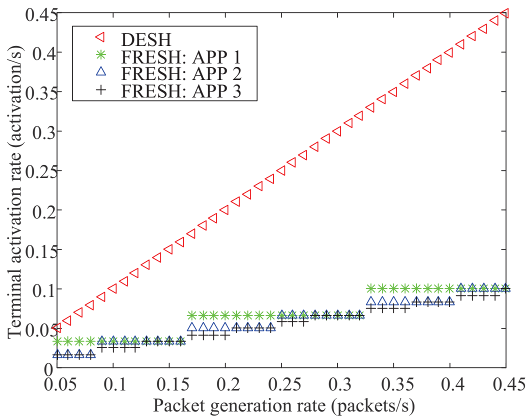

Fig. 3. Terminal activation rate comparison between different cellular IoT applications.

DESH. The energy saving of *FRESH* becomes more significant with more frequent packet arrival, and the largest saving under our configurations can be more than 17%. This is because under human-centric *DESH*, every packet is meaningful for a user, and thus the scheduler has to frequently allocate resources for packet transmissions, which leads to more frequent radio device activation. *FRESH* matches the fact of freshness-awareness in machine-centric IoT applications, which fully utilizes the freshness constraint to buffer packets in FIFO type transceivers, and save energy cost by redundant terminal activations while guaranteeing the freshness requirement.

Based on the aforementioned simulation results that energy saving can be realized by implementing *FRESH*, we further evaluate its impact on applications with different freshness requirements. We consider three applications (APP 1-3) with equal terminal number $\tilde{K} = \{333, 333, 333\}$ and corresponding freshness requirement $\tilde{\phi} = \{30, 60, 120\}$ seconds. According to the above analysis as shown in Fig.2, the benefit of energy saving comes from the reduced radio activations, and thus we directly examine the radio activation rate. Fig.3 illustrates the averaged radio activation rate of a terminal as a function of packet generation rate. We can observe that APP 1 and 3 respectively have the lowest and highest radio activation rate. This indicates that applications with less intensive freshness requirement can achieve more benefits, since the frequent updating requirement supports fewer buffering packets with more radio activations. In addition, compared with the activation rate by implementing *DESH* as the benchmark, we further demonstrate *FRESH* performs better in energy saving. Moreover, since a BS may serve for massive terminals in cellular IoT systems, *FRESH* can also effectively reduce the contentions for random access by reduced radio activation requirements.

V. Conclusions

In this paper, we have proposed an online uploading scheduler *FRESH* for cellular IoT systems by jointly considering the freshness of data updates and the energy constraint of battery-powered terminals. To achieve a long-term energy saving, a general Lyapunov optimization framework has been adopted to realize a practical online scheduling under varying packet arrivals and channel conditions. We have theoretically proved that both the energy consumption bound and the information freshness bound can be obtained by implementing *FRESH*. Simulation results have demonstrated the necessity and effectiveness of the proposed *FRESH*. Besides, the reduced radio activation through our scheme can also address the high contention problem in the random access of cellular IoT systems.

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