DOI: 10.19729/j.cnki.1673-5188.2018.04.007
http://kns.cnki.net/kcms/detail/34.1294.TN.20181210.0836.002.html, published online December 10, 2018

Energy Efficiency for NPUSCH in NB-IoT with Guard Band

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Abstract

Narrowband Internet of Things (NB-IoT) has been proposed to support deep coverage (in building) and extended geographic coverage of IoT. In this paper, a power control scheme for maximizing energy efficiency (EE) of narrowband physical uplink shared channel (NPUSCH) with the guard band is proposed. First, we form the optimization problem based on the signal model with the interferences of narrowband physical random access channel (NPRACH) which are caused by the non-orthogonality of NPUSCH and NPRACH. Then, a method of reserving guard bands is proposed to reduce these interferences. Based on it, an efficient iterative power control algorithm is derived to solve the optimization problem, which adopts fractional programming. Numerical simulation results show that NPUSCH with the guard band has better performance in EE than that without the guard band.

Keywords

NB-IoT; energy efficiency; NPUSCH; NPRACH; interference; guard band

1 Introduction

To support some specific scenarios of Internet of Things (IoTs), e.g. deep coverage (in building) and extended geographic coverage, the Narrowband Internet of Things (NB-IoT) was standardized at the Third-Generation Partnership Projects (3GPPs) Radio Access Network Plenary Meeting 69 [1]. This new technology can improve network coverage, support massive number of low throughput devices, and provide low delay sensitivity and high energy efficiency (EE). This technology includes three mode operations: 1) stand-alone as a dedicated carrier, 2) in-band within a normal Long Term Evolution (LTE) carrier, and 3) guard bands within a LTE carrier [1].

The uplink of NB-IoT mainly includes two physical channels: narrowband physical uplink shared channel (NPUSCH) and narrowband physical random access channel (NPRACH). They support different subcarriers, i.e., 15 kHz and 3.75 kHz subcarriers for NPUSCH and only single-tone with 3.75 kHz subcarrier for NPRACH. Once the 15 kHz subcarrier for NPUSCH is deployed close to NPRACH, there will be interference between them due to the non-orthogonal signal. If there is no filters in the receivers of NPUSCH, the symbol of NPRACH will interfere with the subcarriers of NPUSCH after discrete Fourier transform (DFT). Such phenomenon can be regarded as narrow-band interference (NBI) [2], which will increase the transmission power cost of NPUSCH and reduce the EE of NPUSCH [3]. We can also adopt the method of reserving guard bands in LTE to ease the interference from NPRACH and improve EE of NPUSCH. Reserving guard bands is an efficient method to avoid the interference from the non-orthogonal subcarriers, which means reserving an idle subcarrier between NPUSCH and NPRACH. At the same time reserving guard bands also means the loss of frequency spectrum of the NB-IoT system. Therefore, researching on the relationship between the guard band and interference is an important issue for adopting this method.

In the last decade, due to economic, operational, and environmental concerns [4], EE has emerged as a new prominent figure of merit for communication networks design. As a result, the research on EE (bit/Joule) has drawn much attention. In [5], the authors studied the energy-efficient resource scheduling with quality of service (QoS) guarantees in multi-user orthogonal frequency division multiple access network. In [6], an energy-efficient resource control problem which is subject to constraints in service quality requirements, total power, and probabilistic interference was modeled as a chance-constrained programming for multicast cognitive orthogonal frequency division multiplexing (OFDM) network. An energy-efficient resource control problem for device-to-device (D2D) links was studied in [7], which aims to maximize the minimum weighed EE of D2D links while guaranteeing minimum data rates for cellular links. Using a two-level dynamic scheme, energy-efficient resource control and inter-cell interference management were both considered in heterogeneous networks [8]. The authors in [9] investigated the fundamental tradeoff between EE and spectral efficiency for interference-limited wireless networks. All of the works mentioned above focus on EE with considering the constraints of QoS, power, interference, etc. However, to the best of our knowledge, the guard band as a factor that influences EE in some certain scenes has not been

This work was supported by the National Natural Science Foundation of China under Grant No. 61501056, National Science and Technology Major Project of China under Grant No. 2016ZX03001012, and ZTE Industry-Academia-Research Cooperation Funds.

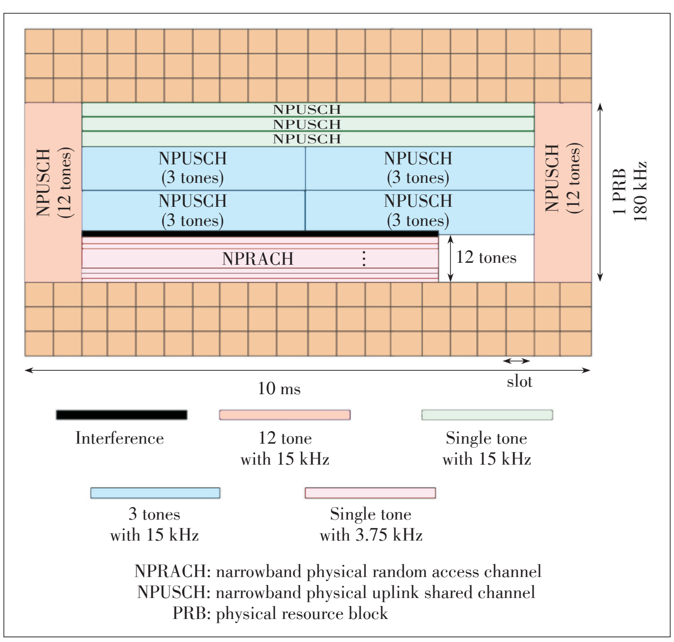
studied yet.

Motivated by the aforementioned observation, we have proposed a power control algorithm optimized for maximizing EE of NPUSCH in NB-IoT with the guard band. The main contributions of this study are as follows: 1) A signal model with NPRACH interference is introduced; 2) A method of reserving guard bands is designed to reduce the interference from NPRACH; 3) Based on the above two points, an energy efficient power control using iterative algorithm with the guard band is proposed.

The rest of the paper is organized as follows. Section 2 describes the system model and focuses on problem formulation. Section 3 introduces a method of reserving guard bands for easing the interference from NPRACH and elaborates the power control algorithm for EE maximization. The simulation results are presented in Section 4, while a conclusion is drawn in Section 5.

2 System Model and Problem Formulation

In this paper, we discuss the situation where the 15 kHz subcarrier for NPUSCH is deployed adjacently to NPRACH. **Fig. 1** is an example for this deployment in the mode of in-band operation which utilizes one resource block as its bandwidth. In the figure, the black long rectangle is the interference from NPRACH to NPUSCH; the rectangles of different colors are used to describe the mapping of the NPUSCH to resource elements, which is called resource unit (Ru) including consecutive Single-Carrier Frequency Division Multiple Access (SC-FDMA) symbols in the time domain and consecutive orthogonal subcarriers in the frequency domain. Different from the PRACH in LTE, NPRACH transmits preambles based on single-subcarrier frequency-hopping symbol groups and the frequency location of its transmission is constrained within 12 subcarriers, i.e., frequency hopping shall be used within the 12 subcarriers [10].



▲**Figure 1. Example for NB-IoT design of uplink (in-band).**

2.1 Signal Model

Suppose that a NPUSCH contains M consecutive orthogonal subcarriers, while a NPRACH only contains one subcarrier n. Let p_m denote the transmitted power of subcarrier $m \in \{1, \cdots M\}$. The received symbol R_m at the Fast Fourier Transform Algorithm (FFT) output can be described by

$$R_m = X_m H_m \sqrt{p_m} + N_m + I_m, \tag{1}$$

where X_m and H_m are the transmitted symbol and transfer factor of subcarrier m, respectively. N_m is additive while Gaussian noise at $m-$th subcarrier and I_m is the interference from NPRACH on the subcarrier m.

The interference from NPRACH can be regarded as a narrow band interference (NBI) [2], [11]. NPRACH with single tone can be described by

$$x(k) = a \cdot e^{j(2\pi f_c k + \phi)}, \tag{2}$$

where a, f_c and ϕ are the corresponding amplitudes, frequencies and a random phase, respectively. At the receiver, the interferer goes through the N point DFT and appears on the OFDM spectrum when $f_c \in \{m < f < m+1, m = 1, \dots M\}$. The result of this operation on the subcarrier m is described by

$$I_m = \sum_{k=0}^{N-1} x(k) e^{-j2\pi km/N}, k = 0, \dots, N-1. \tag{3}$$

Then, the amplitude spectrum of the interference on each subcarrier m applying a rectangular window is given by

$$I_m = a.e^{j\phi} e^{j(N-1)(\pi f_c - \pi m/N)} \frac{\sin N(\pi f_c - \pi m/N)}{\sin(\pi f_c - \pi m/N)}. \tag{4}$$

The derivation of the equation can be found in Appendix A. The received Signal to Interference plus Noise Ratio (SINR) of the subcarrier m is γ_m:

$$\gamma_m = \frac{p_m |H_m|^2}{|I_m|^2 + \sigma_m^2}, \tag{5}$$

where $|I_m| = \left| a \cdot \frac{\sin N(\pi f_c - \pi m/N)}{\sin(\pi f_c - \pi m/N)} \right|$ and $\sigma_m^2 = E|W_m|^2$.

2.2 Problem Formulation

Using (5), the data rate of the subcarrier m can be written as follow:

$$R_m = \log_2(1 + \gamma_m). \tag{6}$$

Correspondingly, the sum rate is

$$R=\sum_{m=1}^{M}R_m, \tag{7}$$

and the total power consumption of NPUSCH is

$$P=\varepsilon\cdot\sum_{m=1}^{M}p_m+P_0, \tag{8}$$

where the coefficient ε is a constant power-amplifier inefficiency factor of NPUSCH, and P_0 is the circuit power consumption [4].

We formulate the optimization problem as maximizing the EE of one NPUSCH, in which "bit per Joule" is defined as the metric subject to the constraints of the target rate and total transmit power. The problem can be written as:

$$\max \eta_{EE}=\frac{R}{P}, \tag{9a}$$

$$s.t.\ R_m>r_m, \tag{9b}$$

$$\sum_{m=1}^{M}p_m\leqslant P_{\max}, \tag{9c}$$

$$p_m\geqslant 0, \tag{9d}$$

where r_m and $P_{\max}$ are the minimum rate requirements for the subcarrier m and the total transmit power of the NPUSCH, respectively. Here we assume $r_1=r_2...=r_M=r_0.$ The constraint (9d) guarantees the feasible sets of p_m .

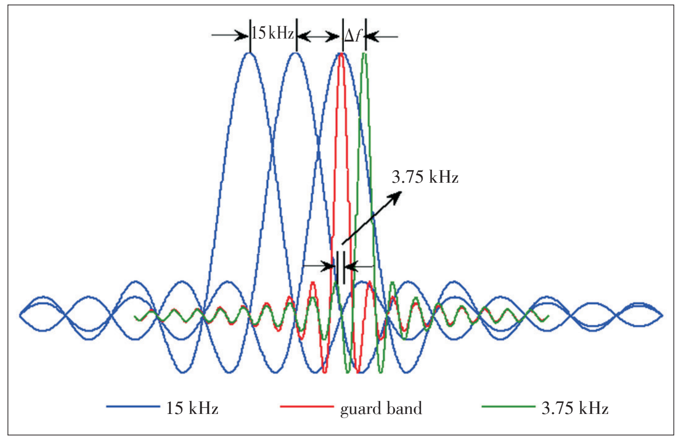
3 Design for Guard Band and Power Control

In this section, we will elaborate the method of reserving guard bands, based on which a power control algorithm is also proposed to solve the optimization problem.

3.1 Guard Band

In LTE, the physical random access channel (PRACH) transmits preambles generated from Zadoff-Chu sequences using a certain amount of subcarriers. By designing the number of subcarriers, one physical uplink shared channel (PUSCH) is set respectively at the two edges of PRACH as guard bands to avoid the interference between PUSCH and PRACH [10]. We can adopt the method of reserving guard bands to reduce the inference from NPRACH, like the method for LTE.

In this paper, the size of a guard band is depend on the interference from NPRACH. From (3), we know that the signal transmitted on NPRACH appears on the OFDM spectrum of the subcarrier m of NPUSCH due to their overlapped frequency band. **Fig. 2** is an example of the guard band between NPRACH and NPUSCH. In the figure, the three blue ones are the subcarriers of NPUSCH, i.e., $M=3$; the red waveform represents the subcarrier of NPRACH, i.e., $n=1$; the green one



▲ **Figure 2. Guard band for the narrowband physical random access channel (NPRACH) and narrowband physical uplink shared channel (NPUSCH).**

denotes the subcarrier n when the guard band Δf is deployed between the NPUSCH and NPRACH. As we can see, before reserving the guard band, the crest of red waveform overlaps the blue ones, i.e., there is interference between NPUSCH and NPRACH due to the non-orthogonal signal. Compared with the primary NPRACH, reserving Δf means the center frequency of the subcarrier n is varied from the red one to the green one with Δf . As we mentioned above, NPRACH only supports single tone and (2) can be rewritten with Δf as follow

$$x(k)=a\cdot e^{j(2\pi(f_c+\Delta f/f_s)k+\phi)}. \tag{10}$$

When $\left(f_c+\Delta f/f_s\right)\in\left\{f\,|\,m<f<m+1,m=1,...,M\right\}$, the interference on each subcarrier m can be written by

$$I'_m=a\cdot e^{j\phi}e^{j(N-1)(\pi m/N)}\frac{\sin N(\pi f'-\pi m/N)}{\sin(\pi f'-\pi m/N)}, \tag{11}$$

where $f'=f_c+\Delta f/f_s$ and f_s is the sample rate. Then, SINR with guard band is

$$\gamma'_m=\frac{p_m|H_m|^2}{|I'_m|^2+\sigma_m^2}. \tag{12}$$

As defined in (6), we will get a new data rate of the subcarrier m and sum rate R' with guard band, i.e., we can also form the EE problem with η'_{EE} as defined in (9), which can be solved by power control.

3.2 Power Control for EE

Fractional programming [12] and Convex (CVX) will be used for problem transformation and obtaining optimal power, respectively.

We first change the fractional formula (9) with η'_{EE} and

$R^{'}(\mathbf{P})$ into a compact form

$$\max_{P\in\Omega} \eta^{'}_{EE} = \frac{R^{'}(\mathbf{P})}{P(\mathbf{P})}, \quad s.t.\ R^{'}_m > r_0,\ (9c),\ (9d), \tag{13}$$

where $\mathbf{P}$ is a $1\times M$ matrices with elements p_m, $R^{'}(\mathbf{P})$ and $P(\mathbf{P})$ are the numerator and denominator in $(9a)$ with $\eta^{'}_{EE}$, respectively. While Ω is the feasible domain defined by the constraints in (13).

Moreover, (13) can be written in the following form:

$$\max_{P\in\Omega} \left\{R^{'}(\mathbf{P}) - \eta^{'}_{EE} \cdot P(\mathbf{P})\right\}, \quad s.t.\ R^{'}_m > r_0,\ (9c),\ (9d). \tag{14}$$

Many previous works [8], [11] have proven the following equivalence

$$\max_{P\in\Omega} \left\{R^{'}(\mathbf{P}) - \eta^{'}_{EE^*} \cdot P(\mathbf{P})\right\} = R^{'}\left(\mathbf{P}^*\right) - \eta^{'}_{EE^*} \cdot P(\mathbf{P}^*) = 0, \tag{15}$$

where $\eta^{'}_{EE^*}$ and $\mathbf{P}^*$ are the optimal value and the optimal solution of (14), respectively. That means if and only if (15) is satisfied, the maximum EE $\eta^{'}_{EE^*}$ can be achieved.

$T(\eta^{'}_{EE}) = \max\left\{R^{'}(\mathbf{P}) - \eta^{'}_{EE} \cdot P(\mathbf{P})\right\}$ is strictly monotonic decreasing and continuously proved in [11]. Besides, $R^{'}(\mathbf{P})$ and $P(\mathbf{P})$ are concave function and convex function, which are judged by their second-order conditions. With all these properties, an iterative algorithm can be designed to get $\eta^{'}_{EE^*}$, which is described in **Algorithm 1**. In the algorithm, $\mathbf{P}^{(t)}$ and $\eta^{'(t)}_{EE}$ are the t-th iteration value of $\mathbf{P}$ and $\eta^{'}_{EE^*}$, respectively. The optimization problem is concluded in the following

$$T(\eta^{'(t)}_{EE}) = \max_{P\in\Omega} \left\{R^{'}(\mathbf{P}) - \eta^{'(t)}_{EE} \cdot P(\mathbf{P})\right\}. \tag{16}$$

Algorithm 1: Energy-efficient power scheduling with guard band (EP-GD)

Initialization:

Set any feasible $\mathbf{P}^{(0)}$ with $R^{'}(\mathbf{P}^{(0)})/P(\mathbf{P}^{(0)})$, maximum iteration $T_{\max}$ and maximum tolerance $\tau > 0$.

1: $\eta^{'(t)}_{EE} = R^{'}(\mathbf{P}^{(0)})/P(\mathbf{P}^{(0)})$ proceed to 2 with $t = 1$.

2: CVX to obtain $\mathbf{P}^{(t)}$ by solving equation (16).

3: **if** $T(\eta^{'(t)}_{EE}) \leqslant \tau$ then

4: $\eta^{'}_{EE^*} = \eta^{'(t)}_{EE}$ Break.

5: **else if** $T(\eta^{'(t)}_{EE}) > \tau$ then

6: Evaluate $\eta^{'(t)}_{EE} = R^{'}(\mathbf{P}^{(0)})/P(\mathbf{P}^{(0)})$ and go to 3 replacing $\eta^{'(t)}_{EE}$ by $\eta^{'(t+1)}_{EE}$, $t = t + 1$.

7: **end if**

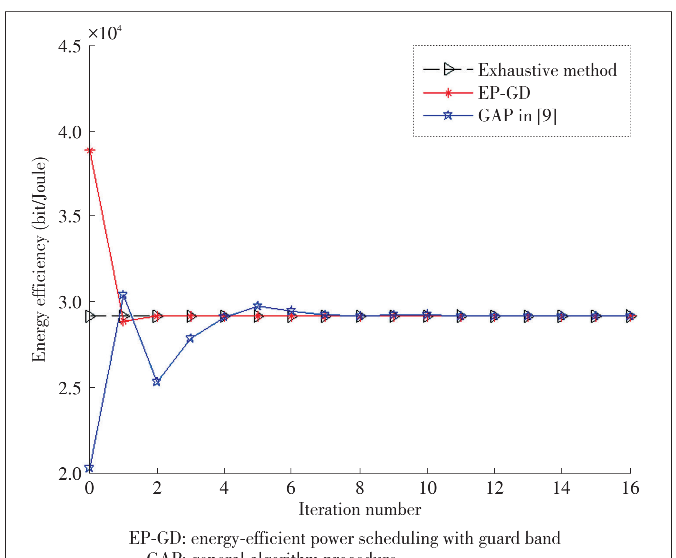
The convergence of EP-GD has been proven in Appendix B.

4 Numerical Simulation

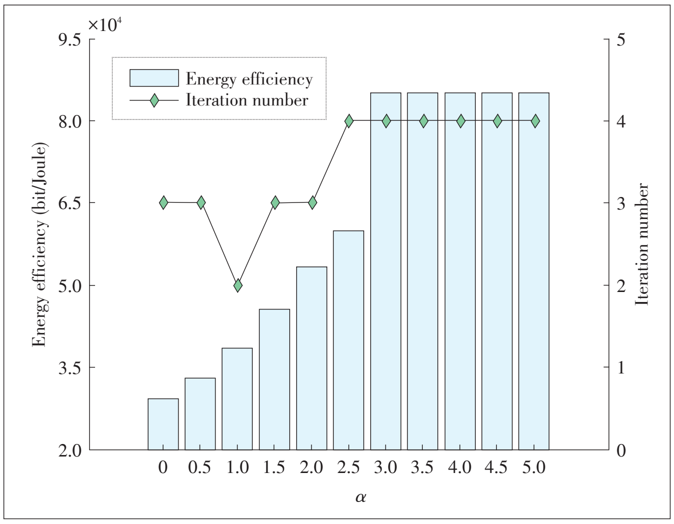
This section presents several numerical results to evaluate EE of NPUSCH using power control with the guard band. The total number of subcarriers for NPUSCH and points for DFT are set 3 and 4, respectively. The amplitude value and phases for NPRACH are set 1 and 0, respectively. Without loss of generality, we assume the value of sample rate is $1/(15\ \text{kHz}\times 4)$. The channel gains for subcarriers of NPUSCH are assumed to be rayleigh fading and noise power $\sigma^2_m = 0.1\,\mu W$.

Fig. 3 verifies the correctness of EP-GD without guard band by exhaustive method, which is denoted by black line. It was also compared with the general algorithm procedure (GAP) [9] which is denoted by blue line. In this comparison, $P_{\max} = 0.5$ mW, $r_0 = 0.5$ bit/s/Hz, $P^{(0)} = [0.3\ 0.2\ 0.3] \times P_{\max}$, and $P_0 = 0.1$ mW. From Fig. 3, we can see EP-GD converges to the exhaustive method which can be regarded as the theoretical optimality after a few iterations, so does GAP which adopts a bisection method. The overlap line also demonstrates the convergence of EP-GD. Moreover, approaching to the exhaustive method after a few iterations, EP-GD has better performance than GAP.

Fig. 4 gives the relationship between EE and Δf with an iteration number. Since NB-IoT supports the single-tone with 3.75 kHz subcarrier and we can reserve 3.75 kHz subcarrier to avoid the interference, we define $\Delta f = \alpha \cdot 3.75$ kHz. We then choose different values of α to show the variation of EE. As the blue bar in Fig. 4 shows, EE increases greatly at the beginning, but then it holds steady. The reason is that more Δf will result in less interference, but when Δf is large enough, the frequency bands of NPRACH and NPUSCH will not overlap,



▲Figure 3. Comparison of energy efficiency of EP-GD, the exhaustive method, and GAP.



▲**Figure 4. Energy efficiency of different Δf with the iteration number.**

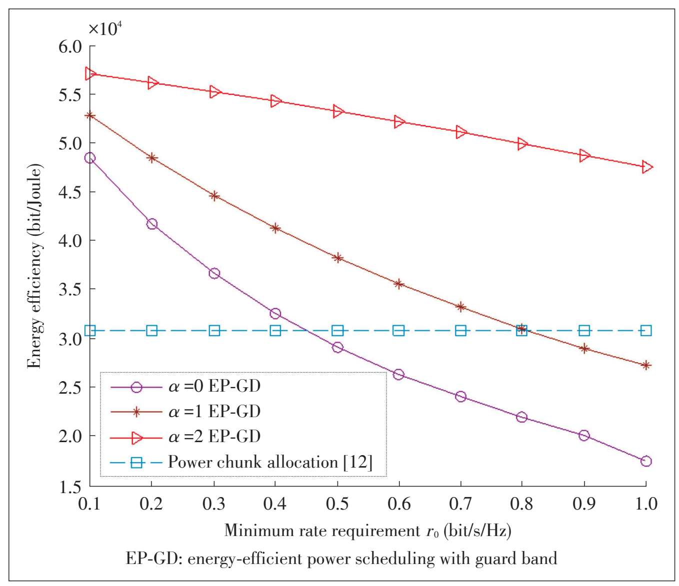
i.e., the interference is inexistence. The black line in Fig. 4 represents the iteration number which still holds a lower level when Δf increases.

Limited by space, we choose three values of Δf that is defined as $\Delta f = \alpha \cdot 3.75$ kHz and illustrate their variations under different r_0 in **Fig. 5**. For comparison, we bring our interference expression into the power chunk allocation in [12] which obtained the optimal sum throughput. We then calculate the EE with the same simulation parameters. As Fig. 5 shows, the EE of our EP-GD decreases monotonically as r_0 increases on the whole trend. The reason is that the larger r_0 is, the more power subcarrier m needs, which results in EE performance degradation. Particularly, when $\alpha = 0$, EE decreases more quickly than the other two cases. The reason is that no guard band means more interference and more power is allocated to subcarriers to satisfy their QoS requirements. This implies that if we need higher data rate communications, we can choose more guard bands to reduce the interference from NPRACH. Compared with the power chunk allocation, EP-GD has a better performance at the beginning, but it descends obviously after $r_0 = 0.4$ bit/s/Hz, when $\alpha = 0$. However, this situation will be improved when $\alpha = 1$, and the descended point will be pushed to $r_0 = 0.8$ bit/s/Hz. EE of EP-GD will greatly increase and outperform the power chunk allocation for any minimum data rate when $\alpha = 0$. In summary, EP-GD has a higher EE at lower data rate communications, which is suitable for NB-IoT. Moreover, higher data rate communications will be realized at the cost of bandwidth.

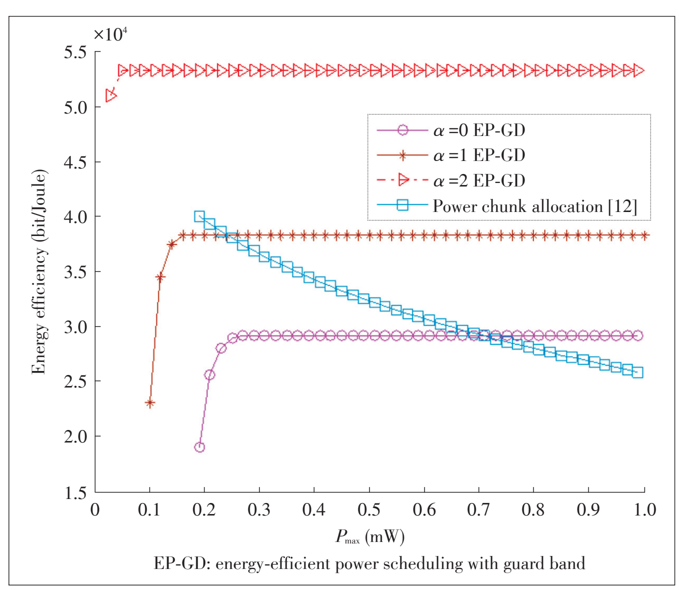
Fig. 6 shows the effect of $P_{\max}$ on EE, and we also choose three values of Δf to see the variations of EE. It can be seen EE increases greatly with more guard bands in the same $P_{\max}$. The beginning of EE with different Δf is also worth observing, which can be explained that the more guard bands are chosen, the less interference will be suffered and the least $P_{\max}$ can be obtained. Besides, when $P_{\max}$ is large enough, EE approaches a constant value since the algorithm will not consume more power. The power chunk allocation outperforms the proposed EP-GD at the beginning when $\alpha = 1$ and $\alpha = 2$. Then, EE of the power chunk allocation has a sharp descent with the increasing of $P_{\max}$, while EP-GD holds a higher steady level after a modest rise. At last, EP-GD outperforms the power chunk allocation after two intersections.

5 Conclusions

In this paper, based on the signal model with NPRACH interference, we formulate the EE of NPUSCH in NB-IoT as an optimization problem, in which the circuit power consumption



▲**Figure 5. Energy efficiency vs. minimum rate requirement r_0 under different Δf.**



▲**Figure 6. Energy efficiency of different Δf under different $P_{\max}$.**

and minimum data rate requirement were taken into consideration. A method of reserving guard bands is proposed to reduce the interference from NPRACH, based on which an efficient iterative power control algorithm is derived for maximization of the optimization issue. The simulation results show that the asymptotically optimal power solutions could be obtained after a few iterations by using the proposed algorithm. Moreover, we find EP-GD has a higher EE for lower data rate communications, which is suitable for NB-IoT. Higher data rate communications will be realized at the cost of bandwidth. Since reserving the guard band means losing the frequency spectrum, and the relation between EE and spectral efficiency (SE) of the whole NB-IoT is our further study.

Appendix A

From (3),

$$
\begin{aligned}
I_m &= \sum_{k=0}^{N-1} x(k) e^{-j2\pi km/N} = \\
& a \cdot e^{j\phi} \sum_{k=0}^{N-1} e^{2\pi jk(f_c - m/N)} = \\
& a \cdot e^{j\phi} \frac{1 - e^{2\pi jk(f_c - m/N)}}{1 - e^{j(2\pi f_c - 2\pi m/N)}} = \\
& a \cdot e^{j\phi} \frac{1 - \cos(2\pi N(f_c - m/N) - \sin(2\pi N(f_c - m/N))}{1 - \cos(2\pi(f_c - m/N)) - \sin(2\pi(f_c - m/N))} = \\
& a \cdot e^{j\phi} e^{j(N-1)(\pi f_c - \pi m/N)} \frac{\sin N(\pi f_c - \pi m/N)}{\sin(\pi f_c - \pi m/N)}.
\end{aligned} \tag{17}
$$

Appendix B

We follow a similar approach with [11] for proving the convergence of the proposed algorithm. The proof is divided into two steps:

Step 1: Prove $\eta'^{(t+1)}_{EE} > \eta'^{(t)}_{EE}$ for all t with $T(\eta'^{(t)}_{EE}) > \tau$.

Let $P^{(t)}$ be an arbitrary feasible solution and $\eta'^{(t)}_{EE} = R'(P^{(t)}) / P(P^{(t)})$, and then $T(\eta'^{(t+1)}_{EE}) = \max\left\{R'(P) - \eta'^{(t)}_{EE} P(P)\right\} \geqslant R'(P) - \eta'^{(t)}_{EE} P(P) = 0$. By the definition in the algorithm, we have $\eta'^{(t+1)}_{EE} = R'(P^{(t)}) / P(P^{(t)})$, hence $T(\eta'^{(t)}_{EE}) = R'(P^{(t)}) - \eta'^{(t+1)}_{EE} P(P^{(t)}) - \eta'^{(t)}_{EE} P(P^{(t)})$, since $P(P^{(t)}) > 0, T(\eta'^{(t)}_{EE}) > 0$, and $\eta'^{(t+1)}_{EE} > \eta'^{(t)}_{EE}$.

Step 2: $\lim_{x \to \infty} \eta'^{(t)}_{EE} = \eta'_{EE^*}$

As we mentioned above, $T(\eta'_{EE}) = \max_{P \in \Omega} \left\{R'(P) - \eta'_{EE} \cdot P(P)\right\}$ is strictly monotonic decreasing and $\max_{P \in \Omega} \left\{R'(P) - \eta'_{EE^*} \cdot P(P)\right\} = R'(P^*) - \eta'_{EE^*} \cdot P(P^*) = 0$, i.e., if $T(\eta'^{(t+1)}_{EE}) < T(\eta'^{(t)}_{EE})$, combined with Step 1, we have $T(\eta'^{(t)}_{EE}) < T(\eta'_{EE^*})$. The elementary function and their four operations are continuous on the domain of $\eta'^{(t)}_{EE}$, and we then have $\lim_{x \to \infty} \eta'^{(t)}_{EE} = \eta'_{EE^*}$.

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Manuscript received: 2017-11-27

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