Optimal Resource Allocation in Full-Duplex Ambient Backscatter Communication Networks for Green IoT

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Abstract—This paper considers an ambient backscatter communication (AmBC) network in which a full-duplex access point (FAP) simultaneously transmits downlink orthogonal frequency division multiplexing (OFDM) signals to its legacy user (LU) and receives uplink signals backscattered from multiple wireless-powered backscatter devices (BDs) in a time-division-multiple-access manner. To maximize the system throughput and ensure fairness, we aim to maximize the minimum throughput among all BDs by jointly optimizing the backscatter time and reflection coefficients of the BDs, and the FAP’s subcarrier power allocation, subject to the LU’s throughput constraint, the BDs’ harvested-energy constraints, and other practical constraints. However, the formulated problem is non-trivial to solve in general, since the variables are mutually coupled and result in non-convex constraints. We thus propose an iterative algorithm by leveraging the block coordinated descent and successive convex optimization techniques. We further show the convergence performances of the proposed algorithm and analyze its complexity. Finally, extensive simulation results show that the proposed joint design achieves significant throughput gain as compared to the benchmark schemes.

I. INTRODUCTION

Internet of Things (IoT) is a key application paradigm for the forthcoming fifth-generation (5G) and future wireless communication systems. IoT devices in practice have strict limitations on energy, cost, and complexity, thus it is highly desirable to design energy- and spectrum-efficient communication technologies [1]. Recently, ambient backscatter communication (AmBC) has emerged as a promising candidate to fulfill such demand. On one hand, AmBC enables wireless-powered backscatter devices (BDs) to modulate their information symbols over ambient radio-frequency (RF) carriers (e.g., TV, WiFi, or cellular signals) without using any costly and power-hungry RF transmitter [2]. On the other hand, no dedicated spectrum is needed for AmBC due to the spectral sharing between the backscatter transmission and the ambient transmission [3].

The AmBC systems can be divided into three categories, namely the traditional AmBC (TABC) system with separated backscatter receiver and ambient transmitter (and its legacy receiver) [3]–[7], the cooperative AmBC (CABC) system with co-located backscatter receiver and legacy receiver [8], [9], and the full-duplex AmBC (FABC) system with co-located backscatter receiver and ambient transmitter [7], [10]. For TABC systems, one of the key challenges is the strong direct-link interference from the ambient transmitter received at the backscatter receiver, which is avoided by frequency-shifting method proposed in [5], and cancelled out through using the specific feature of the ambient signals in [6]. For CABC systems, the signals from the ambient transmitter are recovered at the backscatter receiver instead of being treated as interference. The optimal maximum-likelihood detector and suboptimal detectors for a CABC system with a single BD are derived in [8]. The transmit beamformer is optimized for a CABC system with a multi-antenna ambient transmitter in [9].

In FABC systems, the backscatter receiver and ambient transmitter are co-located, thus the signals from the ambient transmitter can be cancelled out [7], [10]. The authors in [7] analyze the capacity performances of both the backscatter communication and the legacy communication for an FABC system over orthogonal frequency division multiplexing (OFDM) carriers. The authors in [10] build an FABC system prototype in which the WiFi access point (AP) decodes the received backscattered signal while simultaneously transmitting WiFi packages to its legacy client. However, only a single BD is considered in [7] and [10], which simplifies the analysis and implementation but limits the applicability in practice. To our best knowledge, the existing literature still lacks fundamental analysis and performance optimization for a general FABC system with multiple BDs.

In this paper, we consider a full-duplex AmBC network (F-ABCN) over ambient OFDM carriers as illustrated in Fig. 1, consisting of a full-duplex access point (FAP) with two antennas for simultaneous signal transmission and reception, respectively, a legacy user (LU), and multiple BDs. The FAP transmits downlink signal which not only carries information to the LU but also transfers energy to the BDs; while at the same time all BDs perform uplink information transmission via backscattering in a time-division-multiple-access (TDMA) manner. One typical smart-home application example is described as follows: a WiFi AP simultaneously sends data to its client like a laptop and
receives information from multiple domestic sensors. We aim to optimize the throughput performance for a generic F-ABCN in this paper, where its main contributions are summarized as follows:

- First, to ensure fairness, we formulate a problem to maximize the minimum throughput among all BDs by jointly optimizing three blocks of variables including the BDs’ backscatter time allocation, the BDs’ power reflection coefficients, and the FAP’s subcarrier power allocation, subject to the LU’s throughput requirement and the BDs’ harvested-energy constraints, together with other practical constraints.
- Second, to solve the formulated non-convex problem, we propose an iterative algorithm by leveraging the block coordinated decent (BCD) and successive convex optimization (SCO) techniques. The three blocks of variables are alternately optimized in each iteration. Also, we show the convergence of the proposed algorithm and analyze its complexity.
- Third, numerical results show that significant throughput gain is achieved by our proposed joint design, as compared to the benchmark scheme of F-ABCN with equal resource allocation and that of half-duplex AmBC network (H-ABCN) with optimal resource allocation. The BDs-LU throughput trade-off is also revealed.

The rest of this paper is organized as follows. Section II presents the system model for an F-ABCN over ambient OFDM carriers. Section III formulates the minimum-throughput maximization problem. Section IV proposes an efficient iterative algorithm by applying the BCD and SCO techniques. Section V presents the numerical results. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

As illustrated in Fig. 1, we consider two coexisting communication systems: the legacy system which consists of an FAP with two antennas for simultaneous information transmission and reception, respectively, and its dedicated LU, and the AmBC system which consists of the FAP and \( M (M \geq 1) \) BDs. The FAP transmits OFDM signals to the LU. We are interested in the AmBC system in which each BD transmits its modulated signal back to the FAP over its received ambient OFDM carrier. Each BD contains a backscatter antenna, a switched load impedance, a micro-controller, a signal processor, an energy harvester, and other modules (e.g., battery, memory, sensing). The BD modulates its received ambient OFDM carrier by intentionally switching the load impedance to vary the amplitude and/or phase of its backscattered signal, and the backscattered signal is finally decoded by the FAP.

The block fading channel model is assumed. As shown in Fig. 1, let \( f_{m,l} \) be the \( L_f \)-path forward channel response from the FAP to the \( m \)-th BD, for \( m = 1, \ldots, M \), \( g_{m,l} \) be the \( L_g \)-path backward channel response from the \( m \)-th BD to the FAP, \( h_l \) be the \( L_h \)-path direct-link channel response from the FAP to the LU, and \( v_{m,l} \) be the \( L_v \)-path interference channel response from the \( m \)-th BD to the LU. Let \( N (N \geq 1) \) be the number of subcarriers of the transmitted OFDM signals. For each channel, define the frequency response at the \( k \)-th subcarrier as \( F_{m,k} = \sum_{l=0}^{L_f-1} f_{m,l} e^{-j2\pi kl/N} \), \( G_{m,k} = \sum_{l=0}^{L_g-1} g_{m,l} e^{-j2\pi kl/N} \), \( V_{m,k} = \sum_{l=0}^{L_v-1} v_{m,l} e^{-j2\pi kl/N} \), \( H_k = \sum_{l=0}^{L_h-1} h_l e^{-j2\pi kl/N} \), for \( k = 0, \ldots, N - 1 \).

We consider a frame-based protocol as shown in Fig. 2. The frame duration of \( T \) (seconds) is within the channel block length. In each frame consisting of \( M \) slots, the FAP simultaneously transmits downlink OFDM signals to the LU, and receives uplink signals backscattered from all BDs in a TDMA manner. The \( m \)-th slot of time duration \( \tau_m T \) (with time proportion \( \tau_m \) \((0 \leq \tau_m \leq 1)\)) is assigned to the \( m \)-th BD. Denote the backscatter time allocation vector \( \tau = [\tau_1 \tau_2 \ldots \tau_M]^T \). In the \( m \)-th slot, BD \( m \) reflects back a portion of its incident signal for transmitting information to the FAP and harvests energy from the remaining incident signal, and all other BDs only harvest energy from their received OFDM signals.

Let \( S_{m,k}(n) \in \mathcal{C} \) be the FAP’s information symbol at the \( k \)-th subcarrier, \( \forall k \), in the \( n \)-th OFDM symbol period of the \( m \)-th slot. After inverse discrete Fourier transform at the FAP, a cyclic-prefix (CP) of length \( N_{cp} \) is added at the beginning of each OFDM symbol. The transmitted time-domain signal in each OFDM symbol period is

\[
s_{m,l}(n) = \frac{1}{N} \sum_{k=0}^{N-1} \sqrt{P_{m,k}} S_{m,k}(n) e^{j2\pi \frac{kl}{N}},
\]
for the time index $t = 0, 1, \ldots, N - 1$, where $P_{m,k}$ is the allocated power at the $k$-th subcarrier in the $m$-th slot. Denote the subcarrier power allocation matrix $\mathbf{P} = [p_1 p_2 \ldots p_M]$, where $p_m$ is the subcarrier power allocation vector in the $m$-th slot.

In the $m$-th slot, the incident signal at BD $m$ is $s_{m,t}(n) \otimes f_{m,t}$, where $\otimes$ means the convolution operation. Let $\alpha_m$ ($0 \leq \alpha_m \leq 1$) be the $m$-th BD's power reflection coefficient, and denote the vector $\alpha = [\alpha_1 \alpha_2 \ldots \alpha_M]^T$.

Let $\eta_m$ ($0 \leq \eta_m \leq 1$), $\forall m$, be the energy-harvesting efficiency constant [11] of BD $m$. According to the aforementioned energy-harvesting scheme and from [12], the total energy harvested by BD $m$ in all slots is thus

$$E_m(\tau, \alpha, \mathbf{P}) = \eta_m \sum_{n=0}^{N-1} [F_{m,k}]^2 \left[ \tau_m P_{m,k}(1-\alpha_m) + \sum_{r=1, r \neq m}^{M} \tau_r P_{r,k} \right].$$

Let $X_m(n) \in C$ be the $m$-th BD's information symbol, whose duration is designed to be the same as the OFDM symbol period. We assume that each BD can align the transmission of its own symbol $X_m(n)$ with its received OFDM symbol$^1$. In the $m$-th slot, the backscattered signal from the $m$-th BD is thus

$$y_{m,t}(n) = \sqrt{\alpha_m s_{m,t}(n)} \otimes f_{m,t} \otimes g_{m,t} X_m(n) + w_{m,t}(n),$$

where the additive white Gaussian noise (AWGN) is assumed, i.e., $w_{m,t}(n) \sim \mathcal{CN}(0, \sigma^2)$.

After CP removal and discrete Fourier transform operation at the FAP, the received frequency-domain signal is

$$Y_{m,k}(n) = \sqrt{P_{m,k} \alpha_m F_{m,k} G_{m,k} S_{m,k}(n)} X_m(n) + W_{m,k}(n),$$

where the frequency-domain noise $W_{m,k}(n) \sim \mathcal{CN}(0, \sigma^2)$.

The FAP performs maximum-ratio-combining (MRC) to recover the BD symbol $X_m(n)$ as follows

$$\hat{X}_m(n) = \frac{1}{N} \sum_{k=0}^{N-1} Y_{m,k}(n) / \sqrt{P_{m,k} \alpha_m F_{m,k} G_{m,k} S_{m,k}}.$$  (5)

The $m$-th BD's throughput normalized to $T$ can be further derived from (4) and (5) as follows

$$R_m(\tau, \alpha, \mathbf{P}, m) = \frac{\tau_m}{N} \log \left( 1 + \frac{\alpha_m}{\sigma^2} \sum_{k=0}^{N-1} |F_{m,k} G_{m,k}|^2 P_{m,k} \right).$$  (6)

$^1$BD can practically estimate the arrival time of OFDM signal by some methods like the scheme that utilizes the repeating structure of CP [6].

Similar to (4), the received frequency-domain signal at the LU can be written as follows

$$Z_{m,k}(n) = \sqrt{P_{m,k} H_{k} S_{m,k}(n)} + \ldots$$

where the frequency-domain noise $\tilde{W}_{m,k}(n) \sim \mathcal{CN}(0, \sigma^2)$.

By treating backscatter-link signal as interference, the total throughput of the LU is given by

$$\tilde{R}(\tau, \alpha, \mathbf{P}) = \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} \log \left( 1 + \frac{|H_{k}|^2 P_{m,k}}{\alpha_m |F_{m,k} V_{m,k}|^2 P_{m,k} + \sigma^2} \right).$$  (7)

### III. Problem Formulation

Our objective is to maximize the minimum throughput among all BDs, by jointly optimizing the BDs’ backscatter time allocation (i.e., $\tau$), the BD’s power reflection coefficients (i.e., $\alpha$), and the FAP’s subcarrier power allocation (i.e., $\mathbf{P}$). Mathematically, the optimization problem is equivalently formulated as follows,

$$\max_{\tau, \alpha, \mathbf{P}} Q$$

s.t. $\tau_m N \log \left( 1 + \frac{\alpha_m}{\sigma^2} \sum_{k=0}^{N-1} |F_{m,k} G_{m,k}|^2 P_{m,k} \right) \geq Q, \forall m$  (9a)

$$\sum_{m=1}^{M} \sum_{k=0}^{N-1} \log \left( 1 + \frac{|H_{k}|^2 P_{m,k}}{\alpha_m |F_{m,k} V_{m,k}|^2 P_{m,k} + \sigma^2} \right) \geq D$$  (9b)

$$\eta_m \sum_{k=0}^{N-1} |F_{m,k}|^2 \left[ \tau_m P_{m,k}(1-\alpha_m) + \sum_{r=1, r \neq m}^{M} \tau_r P_{r,k} \right] \geq E_{\min, m}, \forall m$$  (9c)

$$\sum_{m=1}^{M} \sum_{k=0}^{N-1} \tau_m P_{m,k} \leq \bar{P}$$  (9d)

$$\sum_{m=1}^{M} \tau_m \leq 1$$  (9e)

$$\tau_m \geq 0, \forall m$$  (9f)

$$0 \leq P_{m,k} \leq P_{\text{peak}}, \forall m, k$$  (9g)

$$0 \leq \alpha_m \leq 1, \forall m.$$  (9h)

Note that (9b) is the common-throughput constraint for each BD, (9c) is the LU’s requirement of a given minimum throughput $D$; (9d) is each BD’s requirement of a given minimum energy $E_{\min, m}$; (9e) is the FAP’s maximum (total) transmission-power (i.e., a given value $P$) constraint; (9f) is the total backscatter-time constraint, and (9g) is the non-negative and peak-power (i.e., a given value $P_{\text{peak}}$) constraint for each subcarrier power; and (9h) is the
constraint for each power reflection coefficient.

Notice that problem (9) is non-convex and thus challenging to solve in general, since the optimization variables are all coupled and the constraint function in (9c) is non-convex over \( P_{m,k} \).

IV. PROPOSED ALGORITHM

In this section, we first propose an efficient iterative algorithm for problem (9), by applying the BCD technique [14] to solve the challenge of coupled optimization variables and applying the SCO technique [15] to address the non-convexity issue of the constraint function in (9c), respectively. Then, we show the convergence of the proposed algorithm and analyze its complexity.

A. Backscatter Time Allocation Optimization

In iteration \( j \), for given power reflection coefficients \( \alpha^{(j)} \) and subcarrier power allocation \( P^{(j)} \), the backscatter time portions \( \tau \) can be optimized by solving the problem

\[
\max_{Q,\tau} \quad Q \\
\text{s.t.} \quad (9b), (9c), (9d), (9e), (9f), (9g),
\]

where the variables \( P_{m,k} \)'s and \( \alpha_m \)'s are replaced by given \( P_{m,k}^{(j)} \)'s and \( \alpha_m^{(j)} \)'s, respectively. Notice that problem (10) is a standard linear programming (LP), it can be solved efficiently by existing optimization tools such as CVX [16].

B. Reflection Power Allocation Optimization

For given backscatter time portions \( \tau^{(j)} \) and subcarrier power allocation \( P^{(j)} \), the power reflection coefficients \( \alpha \) can be optimized by solving the following problem

\[
\max_{Q,\alpha} \quad Q \\
\text{s.t.} \quad (9b), (9c), (9d), (9i),
\]

where the variables \( P_{m,k} \)'s and \( \tau_m \)'s are replaced by given \( P_{m,k}^{(j)} \)'s and \( \tau_m^{(j)} \)'s, respectively. Since the left-hand-side of the constraint (9c) with given \( P_{m,k} \) and \( \tau_m \) is a decreasing and convex function of \( \alpha_m \), the constraint is convex. Hence, problem (11) is a convex optimization problem that can also be efficiently solved by CVX [16].

C. Subcarrier Power Allocation Optimization

For given backscatter time portions \( \tau^{(j)} \) and power reflection coefficients \( \alpha^{(j)} \), the subcarrier power allocation \( \tilde{P} \) can be optimized by solving the following problem

\[
\max_{Q,\tilde{P}} \quad Q \\
\text{s.t.} \quad \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} \log \left( 1 + \frac{\left| H_{k}^{(j)} \right|^{2} P_{m,k}}{\alpha_{m}^{(j)} F_{m,k} V_{m,k}^{2} P_{m,k} + \sigma^2} \right) \geq D
\]

where the variables \( \tau_m \)'s and \( \alpha_m \)'s are replaced by given \( \tau_m^{(j)} \)'s and \( \alpha_m^{(j)} \)'s, respectively. Since the constraint function \( \tilde{R}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)}} \) in (12b) is non-convex with respect to \( P_{m,k} \), problem (12) is non-convex. Notice that \( \tilde{R}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)}} \) can be rewritten as follows

\[
\tilde{R}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)}} = \sum_{m=1}^{M} \tau_{m}^{(j)} \sum_{k=0}^{N-1} \left[ -\log \left( \alpha_{m}^{(j)} F_{m,k} V_{m,k}^{2} P_{m,k} + \sigma^2 \right) + ... \right]
\]

To handle the non-convex constraint (12b), we exploit the SCO technique [15] to approximate the second logarithm function in (13). Recall that any concave function can be globally upper-bounded by its first-order Taylor expansion at any point. Specifically, let \( \tilde{P}_{m,k}^{(j)} \) denote the subcarrier power allocation in the last iteration. We have the following concave lower bound at the local point \( P_{m,k}^{(j)} \)

\[
\tilde{R}^{lb}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)},P^{(j)}} \geq \sum_{m=1}^{M} \tau_{m}^{(j)} \sum_{k=0}^{N-1} \left[ -\log \left( \alpha_{m}^{(j)} F_{m,k} V_{m,k}^{2} P_{m,k}^{(j)} + \sigma^2 \right) + ... \right]
\]

With given local points \( P^{(j)} \) and lower bound \( \tilde{R}^{lb}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)},P^{(j)}} \) in (14), by introducing the lower-bound minimum-throughput \( Q_{tpa}^{lb} \) problem (12) is approximated as the following problem

\[
\max_{Q_{tpa},\tilde{P}} \quad Q_{tpa}^{lb} \\
\text{s.t.} \quad \tilde{R}^{lb}(\tilde{P})|_{\tau^{(j)},\alpha^{(j)},P^{(j)}} \geq D
\]

where the variables \( \tau_m \)'s and \( \alpha_m \)'s are replaced by given \( \tau_m^{(j)} \)'s and \( \alpha_m^{(j)} \)'s, respectively. Problem (15) is a convex optimization problem which can also be efficiently solved by CVX [16]. It is noticed that the lower bound adopted in (15b) implies that the feasible set of problem (15) is always a subset of that of problem (12). As a result, the optimal objective value obtained from problem (15) is in general a lower bound of that of problem (12).

D. Overall Algorithm

We propose an overall iterative algorithm for problem (9) by applying the BCD technique [14]. Specifically, the entire variables in original problem (9) are partitioned into three blocks, i.e., \( \tau, \alpha, \) and \( P \), which are alternately
Algorithm 1 Iterative Algorithm for solving problem (9)

1: Initialize $\tau^{(0)}$, $\alpha^{(0)}$, $P^{(0)}$, $Q^{(0)}$ with $\tau_m^{(0)} = \frac{1}{M}$, $\alpha_m^{(0)} = \frac{1}{M}$, $P_{m,k}^{(0)} = \frac{1}{MN}$, $\forall k, m$, and small threshold constant $\epsilon = 10^{-4}$. Let $j = 0$.
2: repeat
3: Solve problem (10) for given $\alpha^{(j)}$ and $P^{(j)}$, and obtain the optimal solution as $\tau^{(j+1)}$.
4: Solve problem (11) for given $\tau^{(j+1)}$ and $P^{(j)}$, and obtain the optimal solution as $\alpha^{(j+1)}$.
5: Solve problem (15) for given $\tau^{(j+1)}$, $\alpha^{(j+1)}$, and $P^{(j)}$, and obtain the optimal solution as $P^{(j+1)}$.
6: Update iteration index $j = j + 1$.
7: until The increase of the objective value is smaller than $\epsilon$
8: Return the optimal solution $\tau^* = \tau^{(j-1)}$, $\alpha^* = \alpha^{(j-1)}$, and $P^* = P^{(j-1)}$.

The increased objective value is smaller than $\epsilon$.

V. NUMERICAL RESULTS

We consider an F-ABCN with $M = 2$ BDs. Suppose that the FAP-to-BDI distance and FAP-to-BD2 distance are 2.5 meters (m) and 4 m, respectively, the FAP (BD1, BD2)-to-LU distances are all 15 m [10]. We assume independent Rayleigh fading channels, and the power gains of multiple paths are exponentially distributed. For each channel link, its first-path channel power gain is assumed to be $10^{-3}d^{-2}$, where $d$ denotes the transmitter-to-receiver distance in m. Let the number of paths $L_t = L_q = 4$, $L_h = 8$, and $L_v = 6$ [6]. Other parameters are set as $N = 64$, $N_{cp} = 16$, $P = 1$, $\epsilon = 10^{-4}$, and $\eta_m = 0.5, \forall m$. The average receive SNR at the FAP is defined as $\bar{\gamma} = \frac{P}{a} \sum_{l=0}^{L_t-1} E[|g_{l1}|^2]$. Let $E_{min,1} = E_{min,2} = E_{min}$. The convex subproblems (10), (11) and (15) are efficiently solved by the CVX tool [16]. All results are obtained based on 100 random channel realizations.

For performance comparison, we consider two benchmark schemes. The first one is the case of an F-ABCN with equal resource allocation. The second benchmark is the case of a half-duplex AmBC network (H-ABCN), in which a half-duplex access point first transmits dedicated OFDM signal to the LU to satisfy its throughput constraint in the first phase, then sends dedicated OFDM signal to receive backscattered information from BDs in a TDMA manner in the second phase. The durations of each phase (and slot) together with other variables are jointly optimized.

Fig. 3 plots the max-min throughput of all BDs versus the LU’s throughput requirement $D$ under different SNRs $\gamma$s. As in [12], we fix $E_{min} = 10 \mu$ and $P_{peak} = 20P_{ave}$. First, the max-min throughput decreases as $D$ increases, which reveals the throughput trade-offs between the BDs and the LU. Second, compared to both benchmark schemes, we observe that the max-min throughput performance is significantly enhanced by using the proposed joint design. This performance gain justifies the advantages of the proposed F-ABCN over the H-ABCN benchmark.
higher throughput is achieved for lower harvested-energy gain as compared to the benchmark schemes. Second, the proposed joint design achieves significant throughput under different BDs’ energy requirements when the receive SNR at the FAP is higher. Cancellation operation. Also, higher max-min throughput harvested-energy constraints.

**Fig. 4:** Max-min throughput versus SNR with different harvested-energy constraints.

although the FAP in an F-ABCN requires higher processing complexity resulting from the self-interference-cancellation operation. Also, higher max-min throughput is achieved when the receive SNR at the FAP is higher.

Fig. 4 plots the max-min throughput versus the SNR under different BDs’ energy requirements \( E_{\text{min}} \)'s. We fix \( D = 1 \) bps/Hz and \( P_{\text{peak}} = 20 P_{\text{ave}} \). First, we observe that the proposed joint design achieves significant throughput gain as compared to the benchmark schemes. Second, higher throughput is achieved for lower harvested-energy requirement \( E_{\text{min}} \) with given \( P_{\text{peak}} \), which reveals the BDs’ throughput-energy trade-off.

**VI. CONCLUSION**

This paper has investigated a full-duplex AmBC network over ambient OFDM carriers. The minimum throughput among all BDs is maximized by jointly optimizing the BDs’ backscatter time allocation, the BDs’ power reflection coefficients, and the FAP’s subcarrier power allocation. By utilizing the block coordinated decent and successive convex optimization techniques, an efficient iterative algorithm is proposed for solving the non-convex joint optimization problem, which is guaranteed to converge to at least a locally optimal solution. Numerical results show that significant throughput gains are achieved as compared to the benchmark of equal resource allocation and that of half-duplex AmBC network, due to the proposed multi-dimensional resource allocation joint optimization and the efficient full-duplex operation at the FAP. The BDs’ throughput-energy trade-off and the throughput trade-off between the BDs and the LU are also revealed.

**ACKNOWLEDGEMENTS**

This work was supported in part by the National Natural Science Foundation of China under Grants 61601100, 61631005, and 61571100.

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![Fig. 3: Max-min throughput versus LU’s throughput requirement at different SNRs.](image1)

![Fig. 4: Max-min throughput versus SNR with different harvested-energy constraints.](image2)