Energy-Efficient Prefix Code Based Backscatter Communication for Wirelessly Powered Networks

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***Abstract*—Backscatter communications have been widely applied in wirelessly powered networks. Energy constraint forces the nodes to only backscatter a few bits once, causing backscatter communications unable to be applied in the applications that require to deliver more data (e.g., an image). It is significant to save energy for backscatter communications so that the nodes can deliver more data with the limited energy. In this letter, the energy-efficient code based backscatter communication (CBBC) is proposed, which makes use of the energy consumption disparity between transmitting/receiving bit 0 and bit 1 in the existing backscatter communications. The energy-efficient prefix codebook is derived from the formulated energy consumption minimization problem. In the CBBC, the codebook is shared by the sender and the receiver of a backscatter link, and the sender breaks the original bit stream into equal-length blocks and delivers the energy-consuming blocks by using their corresponding codewords from which the receiver decodes the original data. The experiments show that the proposed CBBC can save energy for backscatter communication.**

***Index Terms*—Backscatter communication, wirelessly powered networks, energy conservation, prefix code.**

I. Introduction

THE NODES in wirelessly powered networks are powered by dedicated wireless chargers or harvest energy from the environment. Backscatter communications, emerged as a promising solution to achieve green communication for future Internet of Things (IoT) [1], have been widely applied in delivering data in wirelessly powered networks. The applications of backscatter communications include radio frequency identification (RFID) systems [2], the backscatter sensors [3], and more. In the RFID systems, tags are powered by a reader and transmit their data to the reader through backscatter communications. Energy constraint causes the nodes to only backscatter a few bits once. This prevents backscatter communications from being applied in the applications that require to deliver more data, such as backscattering image. Therefore, it is important to let the energy-restricted nodes deliver more data through backscatter communications.

In backscatter communications, data are transmitted bit by bit. FM0 baseband encoding (a bi-phase space baseband encoding) and Miller modulation have been widely adopted in the RFID systems [2]. We found that there exists Energy Consumption Disparity (ECD) between transmitting/receiving bit 0 and bit 1 under the backscatter communications adopting FM0 due to an additional mid-symbol phase inversion in backscattering bit 0 [4]. That is, the energy consumed in delivering a single bit 0 almost suffices to deliver two bit 1 s. In fact, ECD is also present in Miller modulation. To cope with the ECD, the Energy-Efficient Data Delivery Scheme (EEDDS) was proposed in our previous work [4] that reduces energy consumption by using a codebook shared by the sender and the receiver. Under the EEDDS, the sender breaks original bit stream into multiple m-bit data blocks, finds the corresponding codewords of the blocks, and then transmits the codewords from which the receiver recovers the original data. There exist the following shortcomings in the EEDDS. Firstly, for a smaller ECD, say less than 2, the EEDDS almost does not save energy when $m<12$. That is, it requires a greater m to gain energy saving. Thus, the number of the codewords (i.e., codebook size) in the EEDDS may be too large to be contained in the nodes' tightly-constrained memory since the codebook size is 2^m, which makes the EEDDS hard to be implemented. In fact, it is unnecessary to encode all the m-bit data blocks because some of them contain many bit 1 s, which can be directly delivered with less energy consumption. Secondly, each codeword has length greater than m, which causes each data block to be delivered with a longer delay. Hence, it is critical to develop an energy-efficient and easy-implementation scheme for the backscatter communications used in the wirelessly powered networks. This is the main motivation of this letter.

The main contributions of this letter are as follows. 1) We propose the prefix code based backscatter communication (CBBC) scheme, which supports to directly deliver the original data blocks with number of bit 0 s less than an encoding threshold in addition to delivering codewords. To inform the receiver of whether a data block is backscattered using its codeword or not, we let the sender adopt two different data rates. 2) We formulate the energy consumption minimization problem to derive the codebook, in which only the blocks with the number of energy-consuming bits being equal to or greater than the threshold are encoded. This leads to a smaller codebook size so that the codebook can be entirely stored in the nodes' memory. That is, we emphasize the number of energy-consuming bits in designing the codebook and only encode the blocks that bring in energy saving. 3) We experiment the CBBC on wireless identification sensing platform (WISP) [5], a programmable, sensing and computationally enhanced platform compatible with GS1 RFID protocols [2]. The CBBC extremely extends the EEDDS and outperforms the EEDDS

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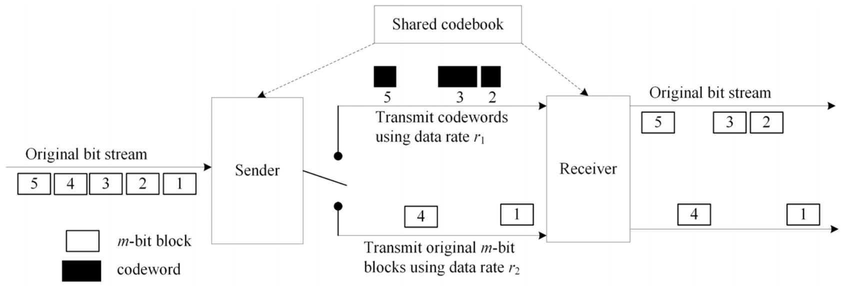

Fig. 1. Block diagram of the proposed CBBC.

in terms of the number of bits transmitted by the WISP with the same amount of energy.

The remainder of this letter is organized as follows. We outline the CBBC in Section II, design the prefix codebook in Section III, evaluate the performance of the CBBC in Section IV, and conclude this letter in Section V.

II. The CBBC

The proposed CBBC consists of procedures of Proc_sender and Proc_receiver, which are applied in the sender and the receiver, respectively. The CBBC delivers m bits from the sender to the receiver once a time. An m-bit block is transmitted using a codeword in the designed codebook if it contains z or more bit 0 s, where z is a preset constant called *encoding threshold*. Under the CBBC, the sender uses two different data rates r_1 and r_2 to transmit codewords and uncoded m-bit blocks, respectively. The sender and the receiver share the designed codebook, which will be derived in Section III.

The procedure Proc_sender contains the following steps:

Step 1. The sender sets the optimal z, denoted by z^*, which is determined by the optimization problem (OP) in (11).

Step 2. The sender divides the original data into multiple m-bit blocks.

Step 3. For each m-bit block, if it contains the number of bit 0 s equal to or greater than z^*, the sender searches for its corresponding codeword in the designed codebook, and then transmits the found codeword using data rate r_1. Otherwise, it transmits the original m-bit block using data rate r_2.

The procedure Proc_receiver is as follows. When the receiver receives a packet, it considers the received packet as a codeword if the packet is received with data rate r_1 and as an original m-bit block otherwise. For a received codeword, the receiver searches in the codebook for its corresponding original m-bit block.

The CBBC is illustrated in Fig. 1. In the figure, the sender can deliver data either in the coding mode or in the non-coding mode. For instance, blocks 1 and 4 are directly delivered, whereas blocks 2, 3, and 5 are delivered via the corresponding codewords in the designed codebook.

III. Codebook Design

We use e_{t0} and e_{t1} to represent the energy consumptions of transmitting bit 0 and bit 1, respectively. In addition, e_{r0} and e_{r1} stand for the energy consumptions of receiving bit 0 and bit 1, respectively. Considering ECD is a constant for a given backscatter communication, we use constant $\alpha(>1)$ to reflect the ECD between transmitting/receiving bits 0 and 1 such that $e_{t0} = \alpha e_{t1}$ and $e_{r0} = \alpha e_{r1}$. Denoting the energy consumptions of delivering bits 0 and 1 by ε_0 and ε_1, respectively, we have $\varepsilon_0 = e_{t0} + e_{r0}$, $\varepsilon_1 = e_{t1} + e_{r1}$, and

$$\varepsilon_0 = \alpha\varepsilon_1. \tag{1}$$

For a given m, there are 2^m different m-bit data blocks, from which we choose and encode the ones that have the number of bit 0 s being equal to or greater than the encoding threshold z. Therefore, the codebook contains the number of codewords as follows:

$$N_c = \sum_{u=z}^{m} \binom{m}{u}. \tag{2}$$

Necessarily, there exists one-to-one corresponding between the encoded m-bit blocks and the codewords in the codebook. Then, the number of m-bit blocks without being encoded is $2^m - N_c$. Accordingly, the original m-bit blocks can be classified into encoded and uncoded ones. Assume the probabilities of bit 0 and bit 1 occurring in the original data are identical. Then, the probabilities of the sender transmitting a codeword and an uncoded m-bit block can be expressed in (3) and (4), respectively.

$$P_c = \frac{N_c}{2^m} = \frac{1}{2^m}\sum_{u=z}^{m} \binom{m}{u}, \tag{3}$$

$$P_{uc} = 1 - P_c = 1 - \frac{1}{2^m}\sum_{u=z}^{m} \binom{m}{u}. \tag{4}$$

A. Energy Consumption of the Common Backscatter Communication

We first calculate the energy consumption for the common backscatter communication (ComBC). For a given m, there are totally 2^m m-bit blocks, in which the numbers of bit 0 s and bit 1 s are each equal to $(2^m m)/2 = m2^{m-1}$. Hence, the average energy consumption of the sender and the receiver in delivering one m-bit block under the ComBC is

$$E_{cbc} = \frac{m2^{m-1}\varepsilon_0 + m2^{m-1}\varepsilon_1}{2^m} = \frac{1}{2}m(1+\alpha)\varepsilon_1. \tag{5}$$

B. Energy Consumption of Delivering Uncoded Data Blocks Under the CBBC

Before deriving the codebook, we consider the energy consumption under the CBBC without using any codebook. With the CBBC, there are totally $2^m - N_c$ uncoded m-bit blocks delivered without using codebook. These uncoded blocks include $\sum_{u=1}^{z-1} u\binom{m}{u}$ bit 0 s and $(2^m - N_c)m - \sum_{u=1}^{z-1} u\binom{m}{u}$ bit 1 s. Thus, using (1), we obtain the average energy consumption of the sender and the receiver in delivering one *m*-bit block as follows

$$E_{uc} = \frac{\varepsilon_0 \sum_{u=1}^{z-1} u\binom{m}{u} + \varepsilon_1[m(2^m - N_c) - \sum_{u=1}^{z-1} u\binom{m}{u}]}{(2^m - N_c)} = \varepsilon_1 m + \frac{\varepsilon_1(\alpha-1)}{(2^m - N_c)} \sum_{u=1}^{z-1} u\binom{m}{u}. \quad (6)$$

C. Average Energy Consumption of Delivering Encoded Data Blocks Under the CBBC

The CBBC applies an energy-efficient prefix codebook $\mathbb{C}$ that includes N_c prefix codewords. Here, prefix codewords are also called prefix-free codewords, which have the property that any codeword is not a prefix of the other ones.

For a codeword $c_i \in \mathbb{C}$, we use $|c_i|$ to represent the number of the bits in c_i such that the codeword can be expressed as $c_i = b_{i,1}b_{i,2}\cdots b_{i,|c_i|}$, where $b_{i,j} \in \{0,1\}$, $i = 1,2,\ldots,N_c$, $j = 1,2,\ldots,|c_i|$. Thus, codeword c_i has $n_{i,1} = \sum_{j=1}^{|c_i|} b_{i,j}$ bit 1 s and $n_{i,0} = |c_i| - \sum_{j=1}^{|c_i|} b_{i,j}$ bit 0 s. Hence, delivering c_i causes the sender and the receiver to expend energy of $n_{i,1}\varepsilon_1 + n_{i,0}\varepsilon_0 = [|c_i|\alpha + (1-\alpha)n_{i,1}]\varepsilon_1$. As a result, energy consumption per codeword is

$$E_c = \frac{\varepsilon_1}{N_c} \sum_{i=1}^{N_c} \left[|c_i|\alpha + (1-\alpha) \sum_{j=1}^{|c_i|} b_{i,j} \right]. \quad (7)$$

Therefore, the expected energy consumption in the CBBC using the prefix codebook is $E_{cbbc} = P_c E_c + P_{uc} E_{uc}$, i.e.,

$$E_{cbbc} = \frac{\varepsilon_1}{2^m N_c} \sum_{u=z}^{m} \binom{m}{u} \sum_{i=1}^{N_c} \left[|c_i|\alpha + (1-\alpha) \sum_{j=1}^{|c_i|} b_{i,j} \right] + \frac{2^m - \sum_{u=z}^{m}\binom{m}{u}}{2^m} \left\{ \varepsilon_1 m + \frac{\varepsilon_1(\alpha-1)}{2^m - N_c} \sum_{u=1}^{z-1} u\binom{m}{u} \right\}. \quad (8)$$

Clearly, to benefit from using codebook, we need

$$E_{cbbc} < E_{cbc}. \quad (9)$$

In the case when the original data blocks are delivered through codewords, each *m*-bit block corresponds to a unique one of the N_c codewords in $\mathbb{C}$. Hence, we obtain the average delivery time of an *m*-bit block as $\frac{1}{r_1}(\sum_{i=1}^{N_c} |c_i|/N_c)$ so that the average delivery time per bit is $\frac{1}{m r_1 N_c} \sum_{i=1}^{N_c} |c_i|$, where r_1 is the data rate applied in the sender and the receiver. Additionally, in the case when the original data blocks are delivered directly (the blocks are uncoded), the delivery time per bit in the *m*-bit block is $1/r_2$. Hence, the average transmission time per bit in the original block under the CBBC is

$$t_b = P_c \frac{1}{m r_1 N_c} \sum_{i=1}^{N_c} |c_i| + P_{uc} \frac{1}{r_2} = \frac{1}{r_2} + \frac{1}{2^m r_1} \left(\frac{1}{m} \sum_{i=1}^{N_c} |c_i| - \frac{r_1}{r_2} N_c \right). \quad (10)$$

We use OP (11) to generate prefix codebook $\mathbb{C}$, where notation $\oplus$ stands for the bitwise exclusive-OR (i.e., XOR) operation. In the OP, Constraint (11a) is obtained by substituting (5) and (8) into (9). Eq. (11b) reflects prefix property, where $\underline{c}_{i,j} = \min\{|c_i|, |c_j|\}$. Eq. (11c) is the Kraft inequality. Eqs. (11b) and (11c) are required in designing prefix code [6]. Constraint (11d) comes from $t_b \leq \theta/r$ using (10), where $\theta > 0$ is a preset constant and $r = \max\{r_1, r_2\}$. Here, $1/r$ represents the duration of a bit transmitted using the higher rate in r_1 and r_2. Hence, Constraint (11d) aims to limit bit duration t_b so that it does not exceed θ multiples of the bit duration $1/r$. Aiming to accelerate delivering the original data over the link, we set $r_1 = r$ if $\sum_{i=1}^{N_c} |c_i| > m(2^m - N_c)$ (i.e., the number of bits in the codebook is larger than that in the uncoded blocks), and $r_2 = r$ otherwise. In Constraint (11e), $\hat{m}$ is the upper bound of *m* to ensure that the derived codebook can be stored in nodes' restricted memory. In (11f), $z = 0$ causes all the *m*-bit data blocks to be encoded, and $z = m + 1$ makes no data block encoded.

$$\min E_{cbbc}$$
$$w.r.t.\!: m, z, b_{i,k}\, (i = 1,2,\ldots,N_c; k = 1,2,\ldots,|c_i|) \quad (11)$$
$$s.t.\!:$$
$$\left\{ \frac{1}{N_c} \sum_{i=1}^{N_c} \left[|c_i|\alpha + (1-\alpha) \sum_{j=1}^{|c_i|} b_{i,j} \right] - \frac{\alpha-1}{2^m - N_c} \sum_{u=1}^{z-1} u\binom{m}{u} - m \right\} \sum_{u=z}^{m} \binom{m}{u} + \frac{2^m(\alpha-1)}{2^m - N_c} \sum_{u=1}^{z-1} u\binom{m}{u} < 2^{m-1} m(\alpha-1); \quad (11a)$$
$$\sum_{k=1}^{\underline{c}_{i,j}} b_{i,k} \oplus b_{j,k} \neq 0, \forall i,j \in \{1,2,\ldots,N_c\} (i \neq j); \quad (11b)$$
$$\sum_{i=1}^{N_c} \frac{1}{2^{|c_i|}} \leq 1; \quad (11c)$$
$$\frac{1}{r_2} + \frac{1}{2^m r_1} \left(\frac{1}{m} \sum_{i=1}^{N_c} |c_i| - \frac{r_1}{r_2} N_c \right) \leq \frac{\theta}{r}; \quad (11d)$$
$$1 \leq m \leq \hat{m}; \quad (11e)$$
$$b_{i,k} \in \{0,1\}, i = 1,2,\ldots,N_c;\ k = 1,2,\ldots,|c_i|; \quad z \in \{0,1,\ldots,m+1\}. \quad (11f)$$

Noticing a prefix codebook corresponds to a binary tree, we use the pruning and expanding (PEO) operation [6] on binary trees to find the solution of OP (11). It has been proved in [6] that the PEO is with complexity of $O(N_c^4)$ in the worst case. In solving the OP, the PEO is conducted for each pair of *z* and *m*, where $z \in \{0,1,\ldots,m+1\}$, $m \in \{1,2,\ldots,\hat{m}\}$. That is, the times of the PEO being conducted is $(m+2)\hat{m} \leq \hat{m}(\hat{m}+2)$. Thus, the complexity of solving the OP is $O(\hat{m}^2 N_c^4)$. This complexity is acceptable because $\hat{m}$ is usually very small in practice and the OP can be solved offline without strictly time constraint.

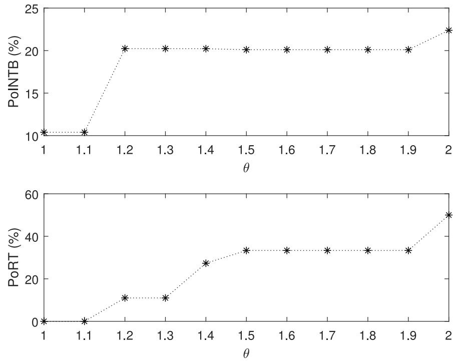

Fig. 2. PoINTB and PoRT vs θ when $\hat{m} = 12$.

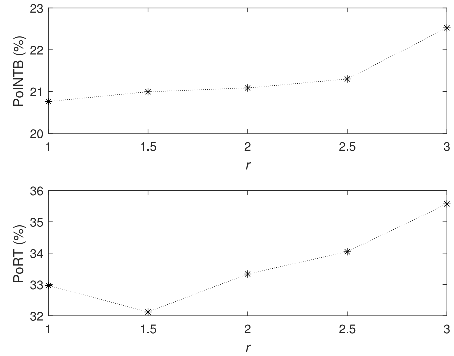

Fig. 3. PoINTB and PoRT vs r when $\hat{m} = 12$ and $\theta = 1.6$.

We note that the codebook designed in [4], which is applied in the EEDDS, consists of equal-length codewords. Obviously, equal-length codebook is a special prefix codebook since they satisfy the conditions of prefix codewords. Therefore, the prefix code based CBBC outperforms the EEDDS presented in [4], which is validated by simulations but we omit the simulation results due to space limitation.

IV. Performance Evaluation

We conduct the experiments on two WISPs, in which one WISP backscatters its data to the other. To evaluate the performance of the CBBC, in each experiment, the capacitor in the WISP is fully charged (i.e., its voltage reaches 4.25 V) and then the WISP transmits to the other WISP until the capacitor exhausts its energy (i.e., its voltage drops to 2.0 V). We focus on the effect of the CBBC on the sender. From the experiments, we obtain $\alpha = 1.64$, and thus we set $\varepsilon_1 = 1$ unit of energy (UoE) and $\varepsilon_0 = 1.64$ UoE. All the experimental results shown below are the average of 10 experiments.

To compare the CBBC with the ComBC, we choose percentage of increased number of transmitted bits (PoINTB) and percentage of reduced throughput (PoRT) as metrics. Here, the PoINTB is defined as the ratio of $(a_1 - a_2)/a_2$, where a_1 and a_2 stand for the numbers of bits transmitted with the CBBC and the ComBC, respectively; and the PoRT is similarly defined.

First, we apply data rates of 1 and 3 kbps in the CBBC. For fair comparison, we, in the ComBC, let the sender transmit with the maximum data rate $r = 3$ (in kbps). Impact of θ on PoINTB and PoRT is shown in Fig. 2. From the upper part of the figure, we have the following two observations. Firstly, the CBBC can gain the PoINTB higher than 20% when $\theta \geq 1.2$. That is, with the same amount of energy, the CBBC can deliver 20% more bits than the ComBC. This observation indicates the proposed CBBC consumes less energy than the ComBC. Secondly, the number of transmitted bits increases as θ grows. In other words, more bits can be delivered when the limitation on bit duration (i.e., t_b) is relaxed. The lower part of the figure illustrates that the gain in the number of transmitted bits is at cost of throughput. The reason is that the CBBC needs to apply two different data rates, the lower rate leads to throughput reduction.

Next, we consider impact of data rates on PoINTB and PoRT by using data rate pair of (r, r/3). We set the higher data rate $r = 1.0, 1.5, \ldots, 3.0$. The experimental results are shown in Fig. 3. The upper part of the figure indicates that PoINTB increases slightly as r grows, i.e., a higher rate brings in a higher number of transmitted bits, while the lower one illustrates that PoRT stays closely (i.e., the errors between them are less than 4%). This is because the ratio of the two applied data rates, i.e., r_1/r_2, remains unchanged when the higher rate r varies. Additionally, we experiment by varying $\hat{m}$, which leads to the observation that too greater a $\hat{m}$ does not bring more energy saving (e.g., no more energy saving is gained when $\hat{m} > 4$ for $r = 3$ kbps).

In summary, the proposed CBBC can improve energy-efficiency in backscatter communications, which is measured by the number of the bits transmitted with the same amount of energy consumption.

V. Conclusion

Backscatter communications are widely used in wireless powered networks. The proposed CBBC makes use of the ECD in backscattering bits 0 and 1 so as to save energy by delivering codewords instead of the original data block containing considerable energy-consuming bits. The CBBC can be applied in the nodes with restricted memory. It is extremely suitable for the popular RFID systems. In future we will study how to apply the CBBC in WISPCam, a battery-free RFID camera, to energy-efficiently backscatter image.

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