A New Energy Efficient MAC Protocol based on Redundant Radix for Wireless Networks

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Abstract—In this paper, we first propose a redundant radix based number (RBN) representation for encoding the data to be transmitted in a wireless network. This RBN encoding uses three possible values - 0, 1 and \( \bar{1} \), for each digit to be transmitted. We then propose to use silent periods (zero energy transmission) for transmitting the 0’s in the RBN encoded data thus obtained. This is in contrast to most conventional communication strategies that utilize energy based transmission (EbT) schemes, where energy expenditure occurs for transmitting both 0 and 1 bit values. The binary to RBN conversion algorithm presented here offers a significant reduction in the number of non-zero bits in the resulting RBN encoded data. As a result, it provides a highly energy-efficient technique for data transmission with silent periods for transmitting 0’s. We simulated our proposed technique with ideal radio device characteristics and also with parameters of various commercially available radio devices. Experimental results on various benchmark suites show that with ideal as well as some commercial device characteristics, our proposed transmission scheme requires 69% less energy on an average, compared to the energy based transmission schemes. This makes it very attractive for application scenarios where the devices are highly energy constrained. Finally, based on this transmission strategy, we have designed a MAC protocol that would support the communication of such RBN encoded data frames.

I. INTRODUCTION

During recent years, wireless ad hoc networks have received considerable attention of researchers for their increasing applications in various fields, e.g. military communications, disaster relief, rescue operations, etc. There exist different schemes for transmitting data in a wireless network. Depending on the situation, either both 0 and 1 are represented by non-zero voltage levels, or one of the bit values is represented by a zero voltage level while a non-zero voltage level is used to distinguish the other bit value. An example of the latter is the polar return-to-zero (polar-RZ) transmission scheme, where a 0 corresponds to a zero voltage level, while a 1 is represented by a non-zero voltage level. However, most existing transmission schemes utilize non-zero voltage levels for both 0 and 1 so as to distinguish between a silent and a busy channel. Communication strategies that require energy expenditure for transmitting both 0 and 1 bit values are known as energy based transmission (EbT) schemes. For example, in order to communicate a value of 278, a node will transmit the bit sequence \(<1, 0, 0, 0, 1, 0, 1, 1, 0>\), consuming energy for every bit it transmits. Thus, if the energy required per bit transmitted is \( e_b \), the total energy consumed to transmit the value 278 would be \( 9e_b \).

In this paper, we propose a communication technique that first recodes a binary data in redundant radix based number (RBN) representation [10] and then uses silent periods to communicate the bit value of ‘0’. We show that by using the redundant binary number system (RBNS) that utilizes the digits from the set \{-1, 0, 1\} to represent a number with radix 2, we can significantly reduce the number of non-zero digits that need to be transmitted. The transmission time remains linear in the number of bits used for data representation, as in the binary number system. We finally propose a MAC protocol that would support the communication of such RBN encoded data frames with a significant amount of energy savings.

We have simulated our proposed transmission algorithm with both ideal device characteristics and parameters of several commercially available radio devices. The results of these experiments show that, for ideal device characteristics and even for some commercial device characteristics, the increase in energy savings with our proposed algorithm over the existing energy based transmission schemes is, on an average, equal to 69%.

II. RELATED WORK

Recent research efforts on reducing energy consumption have mainly been focussed on the MAC layer design [5], optimizing data transmissions by reducing collisions and re-transmissions [6] and through intelligent selection of paths or special architectures for sending data [7]. A survey of routing protocols in wireless sensor networks can be found in [5]. In all such schemes, the underlying communication strategy of sending a string of binary bits is energy based transmissions (EbT) [3], [4], which implies that the communication of any information between two nodes involves the expenditure of energy for the transmission of data bits. In [3], a new communication strategy called Communication through Silence (CtS) has been proposed that involves the use of silent periods as opposed to energy based transmissions. CtS, however, suffers from the disadvantage of being exponential in time. An alternative strategy, called Variable-base tacit communication (VarBaTaC) has been proposed in [4] that uses a variable radix-based information coding coupled with CtS for communication.

III. PRELIMINARIES AND PROPOSED COMMUNICATION SCHEME

The redundant binary number system (RBNS) [10] utilizes the digits from the set \{-1, 0, 1\} for representing numbers
using radix 2. In the rest of the paper, for convenience, we denote the digit ‘-1’ by $\bar{1}$. In RBNS, there can be more than one possible representation of a given number. For example, the number 7 can be represented as either 111 or 1001 in RBNS. In this work, we utilize this property of RBNS to recode a message string so as to reduce the number of 1’s in the string while transmitting the message \(|11\). The original binary message can, however, be obtained at the receiver end by reconverting the received message from RBN to binary number system \(10^2\).

The basic idea of our recoding scheme is as follows: Consider a run of \(k\) 1’s, \(k > 1\). Let \(i\) be the bit position for the first 1 in this run, \(i \geq 0\) (bit position 0 refers to the least significant bit at the rightmost end). Let \(v\) represent the value of this run of \(k\) 1’s. Then,

\[
v = 2^i + 2^{i+1} + 2^{i+2} + \ldots + 2^{k+i-1}
\]  
(1)

Alternatively, we can rewrite equation (1) as,

\[
v = 2^{k+i} - 2^i
\]  
(2)

Equation (2) can be represented in RBNS by a ‘1’ at bit position \((k+i)\) and a $\bar{1}$ at bit position \(i\), while all the intermediate 1’s between them are converted to 0’s. Thus, a long run of 1’s can equivalently be replaced by a run of 0’s and only two non-zero digits, 1 and $\bar{1}$.

Observe that for a run of \(k\) 1’s, \(k > 1\), the savings in terms of the number of non-zero digits is \(k - 2\). However, the number of non-zero digits remain unchanged for \(k = 2\).

Thus, if we keep the transmitter switched-off for 0 bit-values, the power consumption of the transmitter will be less than that in energy based transmission (EbT) schemes. Hence, by combining this approach of silent zero transmission with our RBNS-based recoding strategy, a significant reduction in the energy expenditure during data transmission can be achieved when compared to the energy based transmission (EbT) of binary data.

Our proposed low energy transmission strategy involves the execution of the following two steps:

**Algorithm TransmitRBNDData**

**Step 1**: Recode the \(n\)-bit binary data frame to its equivalent RBNS data frame using steps 1.1 and 1.2 stated below.

**Step 1.1**: Starting from the least significant bit (lsb) position, scan the string for a run 1’s of length \(> 1\). A run of \(k\) 1’s \((k > 1)\) starting from bit position \(i\), is replaced by an equivalent representation consisting of a ‘1’ at bit position \(k + i\) and a \(\bar{1}\) at bit position \(i\), with 0’s in all intermediate bit positions.

**Step 1.2**: Every occurrence of the bit pattern \(\bar{1}1\) in a string obtained after step 1.1, is replaced by the equivalent bit pattern \(0\bar{1}\).

**Step 2**: Transmit the RBNS data frame obtained from step 1 above.

Note that the encoding process of an \(n\)-bit binary string to its equivalent RBNS representation can result in a RBNS string of length of either \(n\) or \(n+1\) symbols. If a run of 1’s of length \(> 1\) ends in the most significant bit (msb), then by virtue of step 1.1 of TransmitRBNDData algorithm, the symbol 1 is placed at the position \(msb + 1\). Otherwise, if the msb was 0, then the RBNS string also has exactly \(n\) symbols.

**Example 1**: Consider a given binary string, a substring, say 110111, with only one ‘0’ trapped between runs of 1’s. Then following step 1.1, we would get the string 1011001. Note the presence of the pattern \(1\bar{1}\) for this trapped ‘0’. Application of step 1.2 of algorithm TransmitRBNDData to the bit pattern \(1\bar{1}\) replaces it by 01, thus resulting in a further reduction in the number of non-zero symbols to be transmitted.

We now present the receiver side algorithm to receive a RBNS data frame and convert it back to binary:

**Algorithm ReceiveRBNDData**

**Step 1**: Receive the RBNS data frame in a buffer, say \(recv\_buf\).

**Step 2**: Set \(runflag \leftarrow false\). Now starting from lsb, scan the RBNS string in \(recv\_buf\) sequentially to obtain the binary equivalent using steps 2.1 through 2.3:

**Step 2.1**: If the \(i^{th}\) bit, \(recv\_buf[i] = 1\) then execute steps 2.1.1 and 2.1.2, otherwise execute step 2.2:

**Step 2.1.1**: If \(runflag = false\) then the corresponding output binary bit is 1. Also set \(runflag \leftarrow true\).

**Step 2.1.2**: If \(runflag = true\) then the corresponding output binary bit is 0.

**Step 2.2**: If the \(i^{th}\) bit, \(recv\_buf[i] = 1\) then execute steps 2.2.1 and 2.2.2, otherwise execute step 2.3:

**Step 2.2.1**: If \(runflag = true\) then the corresponding output binary bit is 0. Also set \(runflag \leftarrow false\).

**Step 2.2.2**: If \(runflag = false\) then the corresponding output binary bit is 1.

**Step 2.3**: If the \(i^{th}\) bit, \(recv\_buf[i] = 0\) then execute steps 2.3.1 and 2.3.2:

**Step 2.3.1**: If \(runflag = true\) then the corresponding output binary bit is 1.

**Step 2.3.2**: If \(runflag = false\) then the corresponding output binary bit is 0.

**Step 3**: Set \(i \leftarrow i + 1\) and repeat from step 2 until the entire received RBNS data frame is scanned and converted to the binary equivalent. The equivalent binary data is then passed onto the higher layers of the network stack.

We note that the application of steps 1.1 and 1.2 of the TransmitRBNDData algorithm ensures that the bit patterns \(1\bar{1}\) and \(\bar{1}1\) can not occur in the transmitted data. Hence, there is only a unique way of converting the received RBNS data into its binary equivalent.

**IV. ANALYSIS OF THE ENERGY SAVINGS**

We denote a run of 1’s of length \(k\) by \(R_k\). Let us append a zero on left of each such \(R_k, 1 \leq k \leq n\) and denote the symbol 0 by \(y_k\). We also denote a single zero by the symbol \(y_0\). Then each such \(y_k, 0 \leq k \leq n\), will be a string of length \(k + 1\). To find out the total number of occurrences of \(R_k\), \(1 \leq k \leq n\), in all possible \(2^n\) strings of length \(n\), we would first compute the total number of occurrences of exactly \(i_k\) number of \(y_k\)’s. Let this number be denoted by the symbol \(N_{n,k}^{i_k}\).
We use a generating function based approach to derive an expression for $N^{i_k,k}_n$ in all possible binary strings of length $n$. The detailed analysis is given in [1]. We have omitted it here for the sake of brevity and state only the final result as follows:

For a given $n$ and $k \geq 1$, $N^{i_k,k}_n$ is given by,

$$N^{i_k,k}_n = \sum_{r=1}^{n+1-(k+1)i_k} \binom{r+i_k}{i_k} \sum_{q=0}^{r} \sum_{j=0}^{q} (-1)^{q+j} \times$$

$$\left( \frac{r + m - 1 - kq - j}{m - kq - j} \right)^{\binom{r}{q}} \binom{q}{j}$$

**Example 2**: For $n = 8$, $k = 2$ and $i_k = 2$, we get the number:

$$N^{2,2}_8 = 2(3) \left[ \left( \frac{2}{2} \left( \frac{1}{0} \right) \left( \frac{1}{0} \right) \right) - \left( \frac{0}{1} \left( \frac{1}{0} \right) + \left( \frac{-1}{1} \left( \frac{1}{1} \right) \right) \right) + 2 \left( \frac{4}{2} \left( \frac{2}{1} \left( \frac{0}{0} \right) - 0 + 0 \right) \right) + 2 \left( \frac{5}{2} \left( \frac{2}{0} \left( \frac{3}{0} \right) - 0 + 0 \right) \right) = 2(0 + 12 + 10) = 44$$

For a given $k \geq 1$, if we now sum the expression $N^{i_k,k}_n$ for all possible values of $i_k$, $1 \leq i_k \leq \lfloor(n+1)/(k+1) \rfloor$, then we get the total number of occurrences of $R_k$ in all possible strings of length $n$. Table I shows the total number of occurrences of all possible runlengths of 1’s in all possible binary strings of length 8 bits. It was shown in [1] that considering all possible $2^n$ binary strings of length $n$ each, the total number of 1’s and 1’s in the RBN coded message after applying both the steps 1.1 and 1.2 of the algorithm TransmitRBNData would be $(n+2)2^{n-2}$.

**V. Experimental Results**

Experimental results demonstrate that algorithm TransmitRBNData significantly reduces the energy consumption required for transmission, for different types of application scenarios. We tested our algorithm on several popular compression benchmark test suites [8], [9]. The results for these test suites are presented in figure [1]. We have omitted the detailed results for each file of the individual benchmark suites for the sake of brevity. For the purpose of the experiments, we assumed a data frame size of 1024 bits. All the reported values in figure [1] are with respect to energy based transmission schemes where the transmission of both '0' and '1' bit values require the expenditure of energy. The column “SiZe” mentioned in the tables and figures, refers to a silent zero (SiZe) transmission scheme introduced in [1].

Considering the mean of the values reported for the SiZe protocol, we find that binary encoded files consists of 42.5% zeroes on an average which thus translates into an increased energy savings of 42.5%, as compared to an EbT transmission scheme. Application of algorithm TransmitRBNData on binary encoded files to create RBN encoded files cause on an average, an increased savings in energy from 42.5% to 69%, when averaged over the values reported in figure [1].

Experimental results also showed that increasing the data frame size increases the fractional savings in energy as longer runs of ones can then be reduced. It increases steeply with the increase in frame size, when the size of the frames is small (8, 16, 32, 64, . . . bits) and plateaus out for larger frame sizes. We observed that in general, for frame sizes larger than 1024 bits, the increase in fractional savings is either very small or none.

The results show that the maximum increase in energy savings (34.4%) with our proposed algorithm over the SiZe protocol is obtained for the Maximum Compression test suite [9], while the minimum (21.8%) is for the Large Canterbury suite [8]. From the results in figure [1] we see that there is an increase of $69\% - 42.5\% = 26.5\%$ in transmission energy savings, when averaged over all benchmark suites considered in the figure, by using the proposed TransmitRBNData algorithm over the SiZe protocol.

**A. Results Considering Device Characteristics**

The effect of real life device characteristics on the energy savings was studied in details in [2]. It was shown in [2] that the fractional energy savings generated by the TransmitRBNData algorithm over EbT transmission scheme is,

$$\gamma_{dev} = \left(1 - \frac{n + 2}{4n}\right) \left(1 - \frac{I_{low}}{I_{high}}\right)$$

while the fractional energy savings generated by the SiZe protocol compared to an EbT transmission scheme is given by,
TABLE II
THEORETICAL ENERGY SAVINGS RESULTS FOR DIFFERENT RADIOS, \( n = 1024 \)

| Vendor | Maxim 2820 | Chipcon CC2510Fx | RFM TR1000 | Maxim 1479 |
|--------|-------------|------------------|-------------|-------------|
| part no. |            |                  |            |             |
| Data rate (kbps) | 50 | 2.5 | 25 | 2.0 |
| Symbol duration (\( \mu s \)) | 20 | 400 | 40 | 500 |
| \( V_{cc} \) (volts) | 2.7 | 3.0 | 3.0 | 2.7 |
| TX state, \( I_{high} \) (mA) | 70.0 | 23.0 | 12.0 | 7.3 |
| Active state, \( I_{low} \) (mA) | 25.0 | 7.5 | 7.0x10^{-4} | 0.2x10^{-6} |
| \( \gamma_{\text{SiZe}} \) | 32.14% | 33.69% | 50.0% | 50.0% |
| \( \gamma_{\text{dev}} \) | 48.18% | 50.51% | 74.95% | 74.95% |

\[ \gamma_{\text{SiZe}} = \frac{I_{\text{high}} - I_{\text{low}}}{2I_{\text{high}}} = \frac{1}{2} - \frac{I_{\text{low}}}{2I_{\text{high}}} \]  

where, \( I_{\text{high}} \) and \( I_{\text{low}} \) denote the current drawn in the transmit (TX) and the active states, respectively. In order to evaluate the performance of our TransmitRBNData algorithm on real-life devices, we considered some of the commercially available radios for our simulation purpose. The results of our simulation are presented in table II. In table II, \( \gamma_{\text{SiZe}} \) and \( \gamma_{\text{dev}} \) refer to the values obtained by substituting the corresponding device parameter values in equations 4 and 5 respectively.

Table II shows that \( \gamma_{\text{dev}} \) is higher than \( \gamma_{\text{SiZe}} \) by at least 16% for Maxim 2820 and Chipcon CC2510Fx chips, while it is higher by nearly 25% for RFM TR1000 and Maxim 1479. The values of \( \gamma_{\text{SiZe}} \) and \( \gamma_{\text{dev}} \) in figures 2 and 3 refer to the energy saving results with the SiZe transmission scheme and our proposed algorithm respectively, obtained by running the simulation on the benchmark suites with the corresponding device parameters. The results show that for the TransmitRBNData algorithm, the performance in energy savings is always much better than the SiZe transmission scheme. However, while the graphs of RFM TR1000 and the Maxim 1479 devices show savings that are nearly equal to those reported in figure 1, the savings are somewhat lower for the CC2510Fx and Maxim 2820, due to the fact that the current drawn in the active state for both of these devices is not negligible compared to the current in the TX state.

VI. MEDIUM ACCESS CONTROL

We present in this section a medium access control for the TransmitRBNData algorithm. Issues related to the design of a MAC protocol such as representation of RBN encoded numbers in the internal buffers at the MAC layer, consideration of suitable modulation schemes for the TransmitRBNData algorithm and receiver-transmitter synchronization for the duration of transmission of a data packet were addressed in [2].

A. RBN-SiZeMAC - Asynchronous MAC Protocol

We now present RBN-SiZeMAC - an asynchronous MAC protocol that allows the transmission of RBN encoded data, for single channel wireless networks. In order to transmit a frame successfully, a node must compete with other nodes within its neighborhood to win the channel for the time duration it requires to transmit its frame. It is important to prevent simultaneous transmission to the same receiving node as that would garble the frames beyond recovery.

Our protocol uses two classes of frames: data and control. The format of the data frame is shown in figure 4. The data frame consists of three parts: i) a header, ii) payload and, iii) a frame trailer. The frame header and the trailer are in binary while the payload is in RBN. The header part consists of a preamble, destination and source addresses, type, length and sync fields. Each frame starts with a Preamble of 2 bytes, each containing the bit pattern 10101010, similar to that of the IEEE 802.3 MAC header. The receiver synchronizes its
clock with that of the sender on this preamble field \([11]\). The next two fields in the frame header are the destination and the source addresses respectively, each 6 bytes long. As in the 802.3 standard, the high order bit of the destination address is a 0 for ordinary addresses and 1 for group addresses. A frame with destination address consisting of all 1s is accepted by all nodes in the neighborhood of the transmitter. Next comes a 2 bit type field which indicates whether this is a data or a control frame. The value '00' is used to indicate a data frame while the remaining 3 possible bit patterns (01, 10 and 11) are reserved for the control frames. The 2 byte length field gives the length of the payload part of the frame. Finally, there are another 2 bytes of sync field, each consisting of the binary bit pattern 10101010 to ensure that the receiver and the sender clocks remain synchronized during the entire period of transmission of the payload. This is necessary as we assume that no signal is transmitted by the sender for the symbol 0 in the RBN encoded payload. As our proposed algorithm TransmitRBNData can lead to the creation of long runs of 0's in the RBN encoded data, it is important to ensure that the sender and receiver clocks remain synchronized for the entire duration of the transmission of the payload. The payload field can be maximum 1500 bytes, again similar to the 802.3 frame. The payload part is followed by the binary encoded frame trailer which consists of a 4 byte checksum field computed only on the binary equivalent of the payload of the frame. The checksum algorithm is the standard cyclic redundancy check (CRC) used by IEEE 802.
The format of the control frame is shown in Figure 5. The control frame is binary. It consists of a 2 byte preamble, source and the type fields respectively. The size and interpretation of these three fields are same as in the data frame. The type field is set according to the type of the intended control message, namely RTS, CTS or ACK. The way these three message types are used is exactly the same as in the 802.11 MAC protocol. This is followed by a length field which indicates the length of the payload that a node wishes to send in the data frame. In the case of a CTS or ACK frame from a receiving node, if the receiver too has some data to send to the sender, it sets the length field accordingly, otherwise it is set to zero. The last field is the usual 4 byte checksum computed over the rest of the control frame fields.

Each node in the network is assumed to possess channel status sensing capability - i.e., whether the channel is idle or busy. The protocol that we propose here is a CSMA/CA (CSMA with collision avoidance) protocol, very similar to the 802.11 protocol. When a node A wants to transmit, it senses the channel. If it remains idle for a time period of $b$, where $b$ is the maximum possible duration of a frame transmission in an RBN protocol, A sends an RTS (Request to Send) control message to the receiver (say B). The reason for waiting for at least $b$ time is to avoid interrupting any ongoing frame transmission. Due to encoding of the payload in RBN, it is possible that there may be a long run of the symbol 0 in the data which may otherwise be wrongly interpreted as the channel being idle without any ongoing transmission. If $B$ receives the RTS, it may decide to grant permission to A to transmit, in which case it sends a CTS frame back. If A does not receive any CTS from $B$ or a collision occurs for the RTS frame, each of the colliding nodes waits for a random time, using the binary exponential back-off algorithm, and then retry. The behavior of other nodes in the vicinity of both A and B on hearing the RTS or CTS frames is the same as in 802.11.

After a frame has been sent, there is a certain amount of dead time before any node may send a frame. We define two different intervals, similar to the 802.11 protocol, for the RBN protocol:

1) The shortest interval is SIFS (Short InterFrame Spacing) that is used in exactly the same way as in 802.11. After a SIFS interval, the receiver can send a CTS in response to an RTS or an ACK to indicate a correctly received data frame.

2) If there is no transmission after a SIFS interval has elapsed and a time NIFS (Normal InterFrame Spacing) elapses, any node may attempt to acquire the channel to send a new frame in the manner described previously. We use NIFS in exactly the same way as the 802.11 protocol

VII. Conclusion

The redundant binary number system can be used instead of the binary number system in order to increase the number of zero bits in the data. Coupled with this, the use of silent periods for communicating the 0’s in the bit pattern provides a significant amount of energy savings in data transmissions. The transmission time also remains linear in the number of bits used for data representation, as in the binary number system. Simulation results on various benchmark suites show that with ideal as well as some commercial device characteristics, our proposed algorithm offers a reduction in energy consumption of 69% on average, when compared to existing energy based transmission schemes. Based on this transmission strategy, we have designed a MAC protocol that would support the communication of such RBN encoded data frames for asynchronous communication in a wireless network.

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Energy Savings for EEC Benchmark

![Bar chart showing energy savings for different file types.](image)

- **pdf**
- **ps**
- **html**
- **doc**
- **text**
- **bin**
- **mpeg**
- **stream**
- **jpeg**
- **mp3**

Legend:
- SiZe
- SiZe + RR1
- SiZe + RR1 + RR2
Maximum Compression Test Suite

| Device     | Energy Savings (%) |
|------------|--------------------|
| Maxim 2820 |                    |
| CC2510     |                    |
| TR1000     |                    |
| Maxim 1479 |                    |

- Size
- TransmitRBNDATA
Energy Savings for EEC Benchmark

- File Type
- Energy Savings (%)

- pdf, ps, html, doc, text, bin, mpeg, stream, jpeg, mp3

Energy Savings:
- SiZe
- SiZe + RR1
- SiZe + RR1 + RR2
Large Canterbury Test Suite

Energy Savings (%)

| Device   | SiZe  | TransmitRBNData |
|----------|-------|-----------------|
| Maxim 2820 |       |                 |
| CC2510   |       |                 |
| TR1000   |       |                 |
| Maxim 1479 |     |                 |
Canterbury Test Suite

![Bar chart showing energy savings for different devices. The x-axis represents the devices (Maxim 2820, CC2510, TR1000, Maxim 1479), and the y-axis represents energy savings (%). The bars are color-coded to indicate different categories: black for "Size" and yellow for "TransmitRBNDData."](image-url)
Required SNR for Given BER

- \( \text{Signal to Noise Ratio (SNR)} \)

\( -\log_{10}(\text{BER}) \)

- \( \text{RBNS} \)
- \( \text{FSK} \)
Data frame size in bits

Percentage energy savings ($\gamma_e$)

Reduction Rule 1
Reduction Rules 1 and 2