RBNSiZeComm and TSS: An Energy Efficient Communication Schemes for Wireless Networks

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Abstract – **Wireless sensor networks typically require low cost devices and low power applications. Hence, such networks usually employ radios with only simple modulation techniques such as ASK, OOK and FSK [9]. We present in this paper, a two energy efficient communication schemes for wireless sensor networks which are a redundant radix based number (RBN) representation i.e. RBNSiZeComm (Redundant Binary Number Silent through Zero digit Communication) scheme and a ternary number system encoding of data TSS (Ternary with Silent Symbol) communication scheme. In this, we see how both the schemes may implemented, the similarities and differences. We propose a transceiver design that uses a hybrid modulation scheme utilizing FSK and ASK so to keep the cost/complexity of the radio devices low. Also, discuss the physical implementation issues.**

Keywords – **Energy – efficient communication, redundant binary number system, silent symbol communication, ternary encoding, wireless sensor networks.**

I. INTRODUCTION

Wireless sensor networks (WSNs) typically utilize highly energy constrained, low cost sensor devices that are deployed (often in an ad hoc manner) in areas that are difficult to access and with little or no network infrastructure. They are characterized by battery-powered sensor devices that are expected to operate over prolonged periods of time. Because of the difficulties in replacing the batteries of these devices quickly and regularly and communication being a major source of power drain in such networks, energy efficient communication protocols that can be implemented with low hardware and software cost/complexity are thus of paramount importance in WSNs to reduce the device recharging cycle periods and hence provide connectivity for longer durations at a stretch.

Most existing transmission schemes not only utilize non- zero voltage levels for both 0 and 1 so as to distinguish between a silent and a busy channel, they also keep both the transmitter and the receiver switched on for the entire duration of the transmission of a data frame. Communication strategies that require energy expenditure for transmitting both 0 and 1 bit values are known as energy based transmission (EbT) schemes. In other words, if the energy required per bit transmitted is e_b, the total energy consumed to transmit an n-bit data would be $n \cdot e_b$. For example, in order to communicate a byte of value 124, a node will transmit the bit sequence < 0,1,1,1,1,1,0,0 >, 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 124 would be 8 e_b.

In contrast to EbT based communication schemes, a new communication strategy called Communication through Silence (CtS) was proposed in [6] that involves the use of silent periods as opposed to energy based transmissions. CtS, however, suffers from the disadvantage of being exponential in communication time. An alternative strategy, called Variable- Base Tacit Communication (VarBaTaC) was proposed in [7] that uses a variable radix-based information coding coupled with CtS for communication. However, for an n-bit binary string, the duration of transmission is in general significantly longer than n. Neither [6] nor [7] talk about the amount of energy saved by CtS and VarBaTaC for noisy channels and considering real-life device characteristics.

A new communication technique was proposed in [3], [4] that recodes a binary coded data using a redundant radix based number representation and then uses silent periods to communicate the bit value of '0'. The authors in [3] showed 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, it is possible to significantly reduce the number of non-zero digits that need to be transmitted. Considering an n-bit data representation, it was proved that the theoretically obtainable fraction of energy savings by recoding the binary string of length n in RBNS and using the proposed RBNSiZeComm transmission protocol from [3], [4] is, on an average, $1 - [(n + 2) / 4n]$. Another new communication scheme based on recoding data from binary to the ternary radix and the silent symbol strategy, with the aim of generating energy savings simultaneously at the transmitter and the receiver.

II. RBNSIZECOMM PRELIMINARIES

The redundant binary number system (RBNS) as used in [3], [4] 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 $\overline{1}$. 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 $100\overline{1}$. The basic idea of the RBNSiZeComm 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 υ represent the value of this run of k 1's. Then,

$$\begin{aligned}\upsilon &= 2^{i} + 2^{i+1} + 2^{i+2} + \ldots + 2^{k+i-1} \\ &= 2^{k+i} - 2^{i} \qquad \ldots\ldots (1)\end{aligned}$$

Equation (1) 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 remains 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 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.

The proposed RBNSiZeComm transmission strategy in [3], [4] involves the execution of the following two steps:

Algorithm TransmitRBNData

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 of 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 TransmitRBNData 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 in 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 $10\bar{1}100\bar{1}$. Note the presence of the pattern $\bar{1}1$ for this trapped '0'. Application of step 1.2 of algorithm TransmitRBNData to the bit pattern $\bar{1}1$ replaces it by $0\bar{1}$, thus resulting in a further reduction in the number of non-zero symbols to be transmitted.

The receiver side algorithm to receive a RBNS data frame and convert it back to binary involves executing the reverse process of TransmitRBNData. It is to be noted that the application of steps 1.1 and 1.2 of the TransmitRBNData 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.

[3], [4] assumes that for every transmission of data between a pair of nodes, the receiver and the transmitter are synchronized in time during the period of the transmission. A possible way of achieving this would be to synchronize on the packet header, such as in IEEE 802.3 protocol.

III. TSS PRELIMINARIES

Let a given binary message B be represented by an n-bit binary string $b_{n-1}b_{n-2}...b_2b_1b_0$. Let T be its equivalent m-digit ternary representation given by $T = t_{m-1}t_{m-2}...t_2t_1t_0$. We assume that n is even, otherwise we pad the message with a 0 bit at the leftmost (msb) position.

For conversion from binary to ternary, we successively scan every two bits of the binary message starting from its msb position and then convert the leftmost part of the binary message (starting from its msb to the currently scanned bit position) to its equivalent ternary representation. To do this, we replace the currently scanned two bits (bit-pair) by either a single ternary digit (0, 1 or 2 depending on whether the binary bit-pair is 00, 01 or 10), or by two ternary digits $(10)_3$ (if the binary bit-pair is 11), and then add it to four times the so far obtained ternary number T from all the previous bit positions (on the left of this bit-pair). Note that this addition will be in ternary number system, and the multiplying factor four is to adjust the weight of T with respect to the currently scanned bit-pair. Also, since this addition will be in ternary number system, the weight of four can be assigned to T by adding the two ternary numbers $T0$ and $0T$. Thus, the equivalent ternary representation of the part of the binary message from its msb to the currently scanned bit-pair will then be obtained as $T0 \oplus 0T \oplus x$, where $\oplus$

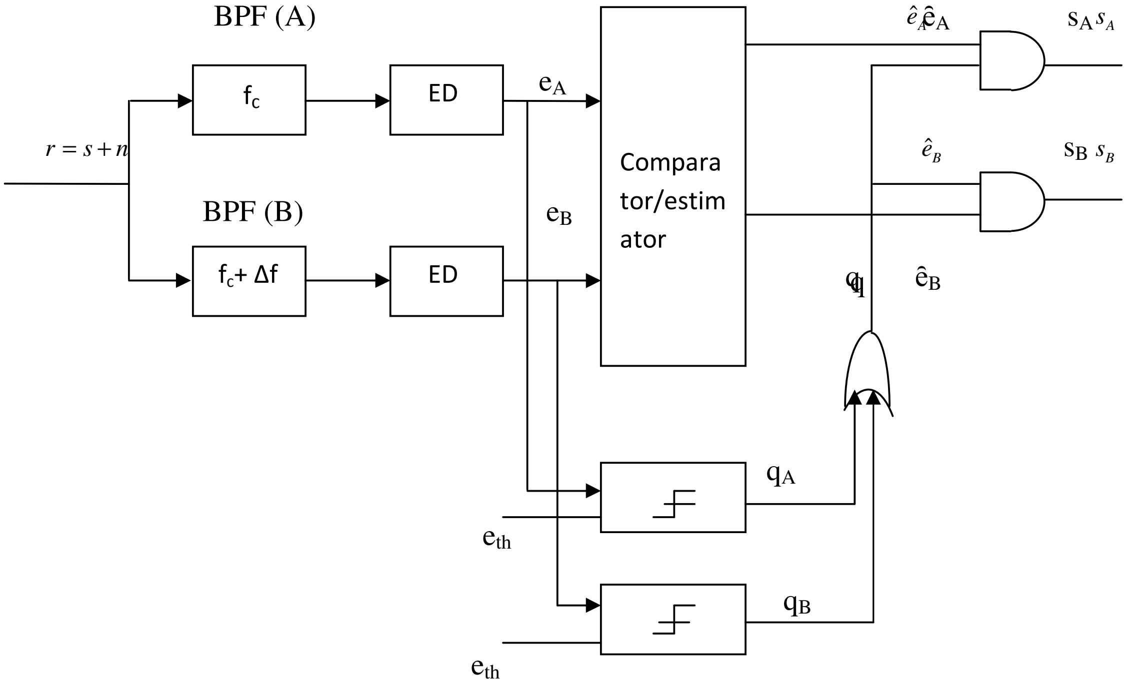

Fig.1. Representative non-coherent FSK Receiver

represents a ternary addition operator, and x is the ternary number equal to 0, 1, or 2 (when the scanned bit-pair is 00, 01 or 10, respectively), or equal to $(10)_3$ (when the scanned bit-pair is 11).

Example 1: Consider the binary number 10011100. First, we get $T = 2$ from the leftmost two bits 10. Then, for the next two bits, the equivalent ternary digit is 1. So we add (in ternary) the three numbers $(20)_3$, $(02)_3$ and $(1)_3$ to get the changed value of $T = (100)_3$ (which is equal to 9 in decimal corresponding to the binary digits 1001 scanned so far). Then for the next two bits, we get the equivalent ternary representation as $(10)_3$, which is added to $(1000)_3 (= T0)$ and $(0100)_3 (= T0)$ in ternary to get the changed value of $T = (1110)_3 = (39)_{10}$. Finally, for the bit-pair 00, we add $(11100)_3$ to $(01110)_3$ to get the equivalent ternary number as $(12210)_3 = (156)_{10}$.

Algorithm *Binary2Ternary* outlines the steps required to convert a number from binary to ternary.

In a similar manner, we can reconvert the received m- digit ternary message to its equivalent binary form by using algorithm *Ternary2Binary*, where again we scan the given ternary number from its most significant (leftmost) digit position in a digit by digit manner, and convert the part of the so far scanned ternary digits to its equivalent binary representation. In the algorithm, we denote a ternary digit by t_i and the converted binary number by B . As in the previous *Binary2Ternary* algorithm, we need to adjust the weight of the binary representation of the previously scanned ternary digits, by attaching a weight of three to it, with respect to the currently scanned ternary digit, and this is achieved by adding $B0$, $0B$ and the equivalent binary representation of the currently scanned ternary digit (note that, this time it is a binary addition).

Example 2: Let the given ternary number T = 2102. The leftmost digit is 2 whose binary representation is 10. So we initially form the binary number as $B = 10$. The next ternary digit is 1. We add the three binary numbers $100 (= B0), 010 (= 0B)$ and 1 to get the changed value of $B = 111$. The next scanned ternary digit is 0. So we add 1110 to 0111 to get the changed value of B as 10101. Finally, for the rightmost ternary digit 2, we add 101010, 010101 and 10 to get 1000001 as the equivalent binary representation B of the given ternary number T .

Binary to ternary conversion of data provides us with the advantage of reduction in the total number of symbols to be transmitted and hence saves on the total transmission duration. As both the transmitter and the receiver consume energy proportional to the duration for which they are switched on, regardless of the symbol transmitted, this recoding to a higher radix will lead to a savings in energy at both the transmitter and the receiver simultaneously. Additional energy savings can be obtained at the transmitter by adopting the silent symbol strategy proposed in [4], [4] for one of the 3 possible ternary digits. Our proposed *ternary with silent symbol* (TSS) communication strategy combines these two strategies to derive an energy efficient communication scheme that saves energy at both the transmitter and the receiver. Assuming equal likelihood of all the three symbols, without any loss of generality we assume 0 to be our silent symbol. In practice however, the relative frequencies of the three symbols will depend on the nature of the data to be transmitted and hence a better strategy would be to assign the most frequent symbol as the *silent symbol* - the relative frequencies of the symbols determined either statistically or for each message to be transmitted.

The transmission protocol of TSS thus consists of the following two steps:

Protocol TransmitTSS

Step 1: Recode the binary data to ternary using the *Binary2Ternary* protocol.
Step 2: Transmit the ternary data symbol by symbol, obtained by the recoding process from step 1 using the following rules:
  Step 2.1: If the symbol to be transmitted is a 0, then switch off the transmitter for the symbol period.
  Step 2.2: Otherwise, switch on the transmitter and transmit the symbol (1 or 2) in the time slot.

The receiver side protocol would be the reverse of the transmitter:

Protocol ReceiveTSS

Step 1: Receive the ternary encoded data symbol by symbol as follows:
  Step 1.1: If a signal is received in the given time slot (symbol period), then the received symbol is either a 1 or a 2, depending on the predetermined received signal to symbol mapping .
  Step 1.2: Otherwise, if the channel is quiet, then the received symbol is a 0.
Step 2: Convert the received ternary message to binary using the *Ternary2Binary* protocol.

IV.PROPOSED IMPLEMENTATION

We consider the theoretical analysis of the energy savings generated at the transmitter for noisy channels. We assume that the channel noise is *additive white gaussian noise* (AWGN). Without any loss of generality, we assume that the transmitter uses FSK modulation with two frequencies - f_c and $f_c + \Delta f$ corresponding to the symbols 1 and $\overline{1}$ respectively in RBNSiZeComm protocol and symbols 1 and 2, respectively in TSS protocol and is switched off during the 0's. Effectively this will be a hybrid modulation scheme involving FSK and ASK. As a representative example for showing the energy savings, we use here a non-coherent detection based receiver presented in [2] with a schematic structure as shown in figure 1.

In figure 1, r is the signal received at the input of the receiver which consists of the transmitted signal s as well as the channel noise n, *i.e.*, $r = s + n$. The received signal r is first passed through two bandpass filters (BPF) as shown in the figure, with center frequencies at f_c and $f_c + \Delta f$ (corresponding to 1 and $\overline{1}$ respectively for RBNSiZeComm protocol and 1 and 2 respectively for TSS protocol)

A. RBNSIZECOMM IMPLEMENTATION

In the figure 1, the outputs q_A and q_B of the threshold detectors are ORed to get the value q. If the transmitted symbol is 0 and if e_{th} is correctly chosen, then the outputs of each of the threshold detectors will be zero, making q equal to 0. On the other hand, if the transmitted symbol is 1 or $\overline{1}$, and the threshold value e_{th} is correctly chosen, it will generate the desired output symbol 1 or $\overline{1}$ at the output $\hat{s}$ of the receiver. Thus, the desired output $\hat{s}$ of the receiver is given as follows:

i) If $q = 0$, then $\hat{s} = 0$, corresponding to $s_A = s_B = 0$

ii) If $q = 1$ then,

$$\hat{s} = \{ 1 \quad \text{if } e_A > e_B, \ (i.e., \ s_A = 1, \ s_B = 0)$$

$$\overline{1} \quad \text{if } e_B > e_A, \ (i.e., \ s_B = 1, \ s_A = 0) \} \quad ....(2)$$

Error Analysis

Let P_0, P_1 and $P_{\overline{1}}$ be the probabilities of occurrences of the symbols 0, 1 and $\overline{1}$, respectively in the transmitted message. Hence, the bit error rate *BER* can be written as,

$$\begin{aligned} BER &= P_0(1 - P\{q = 0 \mid 0\}) \\ &+ P_1[1 - P\{q = 1 \text{ and } e_A > e_B, \forall e_A \mid 1\}] \\ &+ P_{\overline{1}}[1 - P\{q = 1 \text{ and } e_B > e_A, \forall e_B \mid \overline{1}\}] \quad ..(3) \end{aligned}$$

Where $P\{q = 0 \mid 0\}$ is the probability that the symbol 0 is detected at the receiver, given that 0 was transmitted. Now,

$$P\{q = 0 \mid 0\} = P\{q_A = 0 \mid 0\}.P\{q_B = 0 \mid 0\}$$

$$= [P\{q_A = 0 | 0\}]^2 \text{ (by symmetry)...(4)}$$

Note that $P\{q_A = 0 | 0\}$ follows Rayleigh distribution. Hence, assuming a zero mean and standard deviation of σ, we can write,

$$P\{q_A = 0 | 0\} = \int_0^{e_{th}} \frac{e_A}{\sigma^2} e^{-e_A^2/2\sigma^2} .de_A$$
$$= (1 - e^{-e_{th}^2/2\sigma^2}).u(e_A)$$

Hence, we have $P\{q = 0 | 0\} = (1 - e^{-e_{th}^2/2\sigma^2})^2$.

Now, let $X = P\{q = 1 \text{ and } e_A > e_B, \forall e_A | 1\}$. Then we can say,

$$X = P\{q = 1 | 1\} P\{e_A > e_B, \forall e_A | 1\}$$
$$= X_1 X_2 \qquad \text{(say)}$$

where $X_1 = P\{q = 1 | 1\}$ and $X_2 = P\{e_A > e_B, \forall e_A | 1\}$. From the schematic diagram of the receiver in figure 1, it follows that X_1 can be written as,

$$X_1 = \int_0^{\infty} [1 - P\{q_A = 0 | 1\} P\{q_B = 0 | 1\}] p_1(e_A).de_A,$$

where $P\{q_B = 0 | 1\}$ is governed by a Rayleigh distribution, while $P\{q_A = 0 | 1\}$ is governed by a Rician distribution. Thus,

$$P\{q_A = 0 | 1\} = \int_0^{e_{th}} \frac{e_A}{\sigma^2} e^{-\frac{e_A^2 + s_A^2}{2\sigma^2}} I_0(\frac{s_A e_A}{\sigma^2}) de_A \text{ and,}$$

$$P\{q_B = 0 | 1\} = \int_0^{e_{th}} \frac{e_B}{\sigma^2} e^{-e_B^2/2\sigma^2} .de_B$$

$$= 1 - e^{-e_{th}^2/2\sigma^2}$$

Hence, solving for X_1 and X_2 we get,

$$X_1 = \int_0^{\infty} [1 - (1 - e^{-e_{th}^2/2\sigma^2})$$
$$\times \; (\int_0^{e_{th}} \frac{e_A}{\sigma^2} e^{-\frac{e_A^2 + s_A^2}{2\sigma^2}} I_0(\frac{s_A e_A}{\sigma^2}) de_A) \frac{e_A}{\sigma^2} e^{-\frac{e_A^2 + s_A^2}{2\sigma^2}}$$
$$\times \; I_0(\frac{s_A e_A}{\sigma^2})].de_A \qquad \text{...... (5)}$$

$$X_2 = \int_0^{\infty} \left[\left(1 - e^{-e_A^2/2\sigma^2}\right) \frac{e_A}{\sigma^2} e^{-\frac{e_A^2 + s_A^2}{2\sigma^2}} \times I_0(\frac{s_A e_A}{\sigma^2}) u(e_A) \right]$$
$$. de_A \qquad \text{...... (6)}$$

and, $BER = P_0[1 - (1 - e^{-e_{th}^2/2\sigma^2})^2]$
$$+ P_1(1 - X_1 X_2) + P_{\bar{1}}(1 - X_1 X_2) \quad \text{...... (7)}$$

From [4], [5], $P_0 = 0.69$ and $P_1 + P_{\bar{1}} = 0.31$. Thus,

$$BER = 0.69[1 - (1 - e^{-e_{th}^2/2\sigma^2})^2] + 0.31(1 - X_1 X_2) \qquad \text{..(8)}$$

In [4], they introduced the concept of *frame error rate* (FER) instead of the conventional bit error rate for an accurate performance analysis.

B.TSS IMPLEMENTATION

While combining ternary encoding with the silent symbol transmission strategy increases the total energy savings at the transmitter, for the detection of the silence of any carrier waveform in presence of bandpass noise, the instantaneous power levels of both non-silent symbols may have to be increased appropriately. This is because of the relatively inferior (higher) SNR requirements of ASK for the same BER value. Thus, although apparently some energy is saved during silent symbols, the detection of symbols in both non-silent and silent intervals with acceptable BER performance might increase the transmit power for the non-silent symbols employing PSK/FSK modulation scheme. Consequently, while one can indeed have some energy saving during silence transmission, there might as well be a need to increase the instantaneous power level for the non-silent intervals in order to achieve an overall energy savings for the system. For a successful strategy, the difference (in dB) between the energy saved due to silence and the additional amount of energy needed for the increased instantaneous power for FSK needs to be positive. An analysis of the net savings in energy generated by TSS at the transmitter is given below.

Without any loss of generality, let q_A and q_B be the outputs of the threshold detectors corresponding to the symbols 1 and 2 respectively. q_A and q_B are ORed to get the value q. If the transmitted symbol is 0 and if e_{th} is correctly chosen, then the outputs of each of the threshold detectors will be zero, making q equal to 0. On the other hand, if the transmitted symbol is 1 or 2, and the threshold value e_{th} is correctly chosen, it will generate the desired output symbol 1 or 2 at the output $\hat{s}$ of the receiver. Thus, the desired output $\hat{s}$ of the receiver is given as follows:

i) If $q = 0$, then $\hat{s} = 0$, corresponding to $s_A = s_B = 0$

ii) If $q = 1$ then,

$\hat{s} = \{1$ if $e_A > e_B$, (*i.e.*, $s_A = 1$, $s_B = 0$)

2 if $e_B > e_A$, (*i.e.*, $s_B = 1$, $s_A = 0$) $\}$ ....(9)

Error Analysis

The computation of the BER in AWGN channels for the TSS protocol is the same as for the RBNSiZeComm protocol as explain above.

V. PHYSICAL IMPLEMENTATION ISSUES

We now considering various issues arising out of the practical implementation of the proposed protocol as discussed below.

A. Representation of Numbers

In order to internally represent the three symbols ({$\overline{1}$, 0, 1}) in case of RBNSiZeComm protocol at the MAC layer, we can use two bits to encode each digit of the redundant binary number (RBN). As an example, the RBN digit 0 may be encoded using the bit-pair 00, while 1 and $\overline{1}$ using the bit-pairs 01 and 10 respectively. Similarly, in TSS protocol, to internally represent the three symbols (0, 1 and 2) at the MAC layer, we can use two bits to encode each ternary digit. As an example, the ternary digit 0 may be encoded using the bit-pair 00, while 1 and 2 using the bit-pairs 01 and 10 respectively.

Thus, we can use the MAC buffer for an n – bit binary data frame would have to be 2n – bit wide to hold the equivalent data. The system would read every bit pair to determine whether the corresponding transmitted data is to be $\overline{1}$, 0 or 1in RBNSiZeComm protocol or 0, 1 or 2 in TSS protocol and accordingly switch on / off the radio circuit. We also assume that the data in higher layers of the network stack are represented in binary only and a conversion of binary to RBN or ternary and vice versa occurs exclusively at the MAC layer. Only the digits 1 and $\overline{1}$ or 2 require transmissions, while the transmitter's radio circuit is switched off the digit 0 and the receiver (assumed to have already been synchronized with the transmitter for this data packet transmission) interprets each silent symbol period as the ternary digit 0.

B. Synchronization Issues

A necessary underlying requirement for the correct detection of silent symbol in both protocol is the presence of clock synchronization between the transmitter and the receiver. We assume that the receiver and transmitter are i) either synchronized for every packet on the MAC packet header - as commonly done in most wireless and wired communication protocols (*e.g.*, in IEEE 802.3 protocol the preamble field in the MAC frame header is utilized for synchronization between the sender and the receiver) or, ii) there exists a global clock source - for example, protocols such as the *Network Time Protocol* (NTP), which disseminate *International Atomic Time* (TAI) in the form of *Coordinated Universal Time* (UTC) to provide network-wide clock synchronization. For WSNs, there exists a number of low overhead clock synchronization protocols in the literature [15], [16]. The transmission time of the payload of the packet is assumed to be small enough so as not to lose synchronization between the receiver and the transmitter during the transmission of consecutive silent symbols. The exact implementation of maintaining synchronization between nodes is left to the data link layer designer.

C. Collision Avoidance Issues

For contention based medium access protocols, an issue that arises with the use of silence-based symbols in the transmitted data is how do the neighbouring nodes determine whether the channel is actually free for transmission or whether there is an ongoing transmission containing a run of 0's. An erroneous interpretation of the absence of any signal on air (carrier and/or baseband) can lead to either corruption of an ongoing transmission (thus leading to retransmission and hence, an increase in energy consumption by the communicating node pair) or unnecessary increase in communication delay due to waiting, when the channel is actually free.

One way to avoid the above mentioned issue would be to utilize only designated time slots in a predetermined trans- mission schedule for data communication. For example, in the 802.15.4protocol, one may choose to employ RBNSiZeComm based data transmission only during the contention free period (CFP).

For contention based medium access, we propose three possible MAC layer schemes for handling the issues of collision and correctly detecting the channel status.

The first one is based on a longer carrier sensing time, equal to the duration of the maximum allowable number of bits in the message as determined by the protocol, by a neighbouring node (that wishes to transmit over the same channel) so that collision is avoided altogether.

The second scheme is based on inserting an invalid pair of symbols (not containing any 0's) - similar to bit stuffing - after every run of 0's of a predefined length. This avoids collision altogether, but the overhead would be a small increase in transmission time and energy. This idea is actually in line with similar techniques used in protocols like IEEE 802.15.4.

Our third scheme is based on waiting for some w symbol periods to get a non-zero symbol and then trying to retransmit which may, however, cause a collision with a probability as a function of w. If a collision is detected, standard back-off techniques similar to those used in IEEE 802.3, IEEE 802.15.4, etc. may be used to tackle the situation.

Thus, depending on the typical application environment, one may choose any one of the above three schemes to handle collisions while using RBNSiZeComm or TSS in contention based medium access protocols.

D. Effect of Device Characteristics

For most commercially available radio devices, the power drawn in the transmit or receive state is considerably more than the idle or active state - i.e., when the radio is in low power operation mode [9]. The penalty paid for this low power operational state is the switching time from the active to transmit state and vice versa. However, this does not, in fact, put any limitation on the applicability of RBNSiZeComm protocol in a WSN, which essentially is a low data rate one. With chips having faster switching time, the data rate can be increased. the maximum data rate at which we can transmit using the TSS protocol is dependent on the time it takes to turn the radio circuit on or off. the energy expenditure for transmitting the equivalent ternary data frame using the TSS can be represented as the sum of the following three terms,

1) A base energy value that exists throughout the duration of the transmission, which is equal to the energy required when the device is in the active state.
2) Extra energy in addition to the base energy required to transmit a 1 or $\overline{1}$ or 2 in TX state.
3) Extra energy in addition to the base energy required during the edge transitions between a symbol 0 and the symbols 1, $\overline{1}$, and 2, which corresponds to switching from the active to TX state and vice versa.

For the sake of simplicity of computation, we can consider the radio circuit as a single stage low pass RC circuit for the transition from the active state to transmit state and vice versa, given the fact that for most devices this transition time is of the order of microseconds. We assume that the radio is deactivated on the trailing edge of a 1 or $\overline{1}$ or 2 that is followed by a 0, while it is activated on the rising edge a 1 or $\overline{1}$ or 2 following a 0. Under these assumptions, it is not unreasonable to assume that the rise time of the RBN symbol pulse is almost equal to the fall time of the pulse and in turn to the turn-on time of the radio circuit from the active to the transmit state.

It was shown in [3] that under the above assumptions, the effect of the radio device characteristics on the performance of their RBNSiZeComm protocol can be neglected for several of the commercially available low cost, low power radios popularly used in wireless sensor networks. As TSS protocol also uses 3 symbols similar to the RBNSiZeComm protocol, hence their results are applicable for TSS.

V. CONCLUSION

We have presented in this paper an energy efficient communication schemes one based on encoding the source data in Redundant Binary Number System (RBNS), coupled with the use of silent period for communicating the 0's in the encoded message and another that can generate energy saving simultaneously at the transmitter and the receiver which is not done in RBNSiZeComm protocol. A low cost and low complexity implementation scheme based on a hybrid modulation utilizing FSK and ASK has also been presented. For analysis, we calculate the BER in AWGN channel.

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