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Energy-Efficient Communication for Cognitive Radio Networks

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Corresponding Author:	Ansuman Bhattacharya, M.Tech. Indian Statistical Institute Kolkata, West Bengal INDIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Indian Statistical Institute
Corresponding Author's Secondary Institution:	
First Author:	Ansuman Bhattacharya, M.Tech.
First Author Secondary Information:	
Order of Authors:	Ansuman Bhattacharya, M.Tech.
	Koushik Sinha, Ph.D.
	Debasish Datta, Ph.D.
	Bhabani P. Sinha, Ph.D.
Order of Authors Secondary Information:	

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Energy-Efficient Communication for Cognitive Radio Networks *

Ansuman Bhattacharya · Koushik Sinha · Debasish Datta · Bhabani P. Sinha

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Abstract We propose an elegant source coding technique for encoding the messages to be transmitted, so that the frequencies of different symbols in the encoded messages become highly asymmetric, i.e., some symbol is present at a relatively much higher frequency than any of the others. Keeping this symbol period with the highest frequency of occurrence as silent during transmission, we achieve substantial savings of transmitter and receiver energies by using a hybrid $ASK - FSK$ modulation/demodulation technique. We also design the corresponding protocols for transmission and reception of messages using this coding technique and evaluate its performance to compare with other existing techniques. Our results demonstrate that for *Additive White Gaussian Noise* ($AWGN$) noisy channels, on an average, the transmitter side energy is reduced by about 53%, while at the receiver side there is about 17.2% savings. Due to the savings of transmitter and receiver energies and the low cost/complexity of the proposed transceiver, our proposed scheme is suitable for multi-hop communication in *Cognitive Radio Networks* (CRNs).

Keywords cognitive radio network · energy-efficient communication · non-coherent detection · silent symbol communication · redundant binary number system

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Ansuman Bhattacharya
ACM Unit, Indian Statistical Institute, Kolkata, India.
E-mail: ansuman.bhattacharya@gmail.com

Koushik Sinha
HP Labs, Bangalore, India.
E-mail: sinha_kou@yahoo.com

Debasish Datta
Dept. of Electronics and Electrical Communication Engg., Indian Institute of Technology, Kharagpur, India.
E-mail: ddatta@ece.iitkgp.ernet.in

Bhabani P. Sinha
ACM Unit, Indian Statistical Institute, Kolkata, India.
E-mail: bhabani@isical.ac.in

1 Introduction

Cognitive Radio (CR) has been proposed in recent years to make more efficient use of the wireless spectrum on widely used frequency bands. A key aspect of these radios is the cognition gained through a spectrum scanning process. Cognitive Radio Networks (CRN) are designed to utilize the licensed spectrum when it is not used by the primary (licensed) users. Energy consumption in CRN is important when particularly portable communication devices or remotely located sensor nodes having limited battery-life, are used in the network. Low-power transmissions from sensor nodes may easily be corrupted by channel noise and interferences generated from co-located wireless transmitters leading to packet loss, thus causing increased energy requirement.

The CR network is assumed to operate on a frame-by-frame basis. Power consumption for transmitting a frame arises mainly from two components-spectrum sensing and data transmission. The power used in spectrum sensing depends on the algorithm used for sensing and is usually very small compared to the power consumed for data transmission, which is quite significant depending on the data transmission rate and channel quality as described in [5]. Energy-efficiency for data transmission can be considered in different layers of the communication protocol stack, e.g., in physical layer, MAC layer, network layer and application layer. In conventional *Energy based Transmissions* (EbT) scheme [13,21], energy in spent for bit to be transmitted . Thus, longer the transmission duration, more will be the energy required for communication. Reducing the length of the message by some appropriate source coding technique may reduce the energy requirements for both transmission and reception, as shown by various authors [2, 7, 12, 22]. In addition to this, it has also been shown in [2, 7, 12, 22] that appropriate source coding techniques may lead to highly asymmetric distributions of code symbols, and keeping the symbol with the dominant frequency of occurrence as silent, considerable savings of energy can be achieved during transmission and reception of messages.

2 Our Contribution

We propose here a new source coding technique in order to encode the messages to be transmitted which is based on the *Modified Redundant radix Based Number System* ($MRBNS$). $MRBNS$ is a modified version of the *Redundant radix Based Number System* ($RBNS$) introduced by Sinha et al. [7]. The frequencies of different symbols in the encoded message become highly asymmetric after this encoding, so that some symbol may be present at a relatively much higher frequency than any of the others. Keeping the symbol period with the highest frequency of occurrence as silent during transmission, we achieve substantial savings of both the transmitter and receiver energies. We assume that a CR user can use the required numbers of channels available for message communication based on the channel allocation and deallocation techniques with the help of *Sample Division Multiplexing* (SDM) [23].

The $MRBNS$ encoding uses three symbols -1, 0, 1 as in $RBNS$, but the total number of digits in $MRBNS$ is, on an average, less than that in $RBNS$. The proposed scheme utilizes low cost devices and requires low power operations with a hybrid modulation scheme using FSK and ASK. With a non-coherent detection based receiver and assuming equal likelihood of all possible binary strings of a given length, we show that there is a 53% saving in energy on an average at the transmitter compared to binary FSK for *Additive White Gaussian Noise* ($AWGN$) channels. Also, due to the reduction in message length with $MRBNS$ encoding, we save, on an average 17.2% energy at the receiver end compared to binary FSK as well as the scheme proposed by Sinha et al. [7]. It may be noted that message encoding in $RBNS$ did not result to any reduction in receiver energy. The savings in both transmitter and receiver energies provided by the proposed technique demonstrate the superiority of $MRBNS$ over $RBNS$ for low power CRNs which need multi-hop communications to transmit the messages from a source to a destination node.

3 Related Works

An adaptive energy and spectrum efficient inverse power control method based on the truncated filtered-x LMS ($FxLMS$) algorithm was introduced by Hoyota et al. [10]. Hu et al. [11] has addressed link adaptive transmission for maximization of energy efficiency rather than the throughput. Their scheme adapts both overall transmission power and its allocation according to the states of all subchannels and circuit power consumption to maximize energy efficiency. Their results show an improvement in energy utilization by at least 15%, when frequency is selectivity exploited. Stabellini et al. [6] considered an energy constrained system comprising two sensor nodes that avoid interference by exploiting spectrum holes in the time domain. The algorithm used in [6] for spectrum sensing minimizes the average energy required for successful delivery of a packet resulting in significant energy savings upto 50% for short packets. Energy-efficient spectrum access has been considered for a CRN by Song et al. [16] with distributed power control to manage the co-channel interference when needed due to the non-cooperative behavior among new users.

In *Energy based Transmissions* (EbT) scheme, communication between two nodes involves the expenditure of the same amount of energy for every bit to be transmitted, be it a 0 or a 1. A new communication strategy called *Communication through Silence* (CtS) was proposed by Zhu et al. [13], that used silent periods as opposed to EbT, thereby saving the transmitter energy. However, CtS suffers from the disadvantage of being exponential in time. An alternative strategy called *Variable-Base Tacit Communication* ($VarBaTaC$) was proposed by Chen et al. [21], that used a variable radix-based information coding coupled with CtS for communication. Later on, some communication schemes based on various source coding techniques, e.g., *Compression with Null Symbol* (CNS) [2], *Redundant Binary Number System with Silent Zero Communication* ($RBNSiZeComm$) [7], *Ternary with Silent Symbol*

(TSS) [22] and *Run Zero Encoding* (RZE) [12] were proposed by several authors which provided average transmitter energy savings of about 30%, 53%, 20% and 35.2%, respectively. Also, at the receiver side, while $RBNSiZeComm$ does not generate any saving, CNS, TSS and RZE provide about 50%, 36.9% and 12.5% savings of energy on an average, respectively.

4 Proposed Energy-Efficient Communication Scheme

In this section we describe a new energy-efficient communication scheme based on the *Modified Redundant radix Based Number System* ($MRBNS$) for CRNs, which is a modified version of the *Redundant radix Based Number System* ($RBNS$). $MRBNS$ uses the same digits set $\{-1,\ 0,\ 1\}$ as in $RBNS$ for representing numbers using radix 2. For convenience, we denote the digit '-1' by '$\bar{1}$'.

The basic idea of coding the binary message in $MRBNS$ is two-fold: (i) to reduce the number of non-zero digits as in $RBNS$ and (ii) to eliminate some zeros from the string whose appearances at different positions are predictable. For this, we first convert the given binary message to $RBNS$ by the technique used in [7], and then eliminate the predictable zeros from the $RBNS$ string. The resulting $MRBNS$ string is then transmitted through the channel. At the receiver end, the $MRBNS$ string is reconverted to binary.

4.1 Modified Redundant Radix Based Number System

The encoding scheme of the $MRBNS$ is as follows:

Reduction Rule 1 *A run of k 1s ($k > 1$) 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 0s in all intermediate bit positions.*

Example 1 If we consider a binary string, say 11011101, then after this reduction rule it becomes $10\bar{1}100\bar{1}01$.

Reduction Rule 2 *Every occurrence of the bit pattern $\bar{1}1$ in a string obtained after applying reduction rule 1, is replaced by the equivalent bit pattern $0\bar{1}$.*

Example 2 After this reduction rule, the string $10\bar{1}100\bar{1}01$ from example 1 becomes $100\bar{1}00\bar{1}01$.

Observation 1 *The application of the reduction rules 1 and 2 on the binary data ensures that the digit patterns $\bar{1}\bar{1}$, $1\bar{1}$ and $\bar{1}1$ do not occur in the data.*

Observation 2 *After $RBNS$ coding every occurrence of $0\bar{1}$ is preceded by a 0 on its most significant bit, i.e., the bit pattern $0\bar{1}$ is found at every occurrence of $\bar{1}$.*

Observation 3 *If the original data was an n-bit binary data frame, $RBNS$ encoding can result in a frame of size $n+1$ $RBNS$ digits.*

Reduction Rule 3 *Based on the above observation, we thus propose to recode every occurrence of* $0\bar{1}$ *to only* $\bar{1}$*. In essence just we drop the zero bit before every* $\bar{1}$.

Example 3 After this reduction rule, the string $100\bar{1}00\bar{1}01$ from example 2 becomes $10\bar{1}0\bar{1}01$.

Observation 4 *Applying the reduction rule 3, we may encounter with the digits patterns* $1\bar{1}$ *and* $\bar{1}\bar{1}$ *in the data. But still now the digit pattern* $\bar{1}1$ *will not occur in the data.*

Observation 5 *After reduction rule 3 the* $RBNS$ *data become less in size, i.e., if the original data was an* n*-bit binary data frame, after applying reduction rule* 3*, encoding can result in a frame of size* $\leq n+1$ $RBNS$ *digits.*

Reduction Rule 4 *After reduction rule 3, we recode the bit pattern* $\bar{1}01$ *with the bit pattern* $\bar{1}1$*. In other words we just drop the '*0*' in between the bit pattern* $\bar{1}01$*, so that the bit pattern* $\bar{1}01$ *becomes* $\bar{1}1$.

Example 4 After this reduction rule, the string $10\bar{1}0\bar{1}01$ from example 3 becomes $10\bar{1}0\bar{1}1$.

Observation 6 *The encoding and decoding processes need scanning from the least significant digit position to the most significant digit position, and these can be conveniently overlapped with a pipelined serial transmission/reception of the digits.*

Lemma 1 *For every binary string, there exists a unique* $MRBNS$ *string and vice versa.*

Proof Reduction rules 1 and 2 gives us the $RBNS$ output for a certain binary input. Every $RBNS$ string has a unique binary string and vice versa [7]. It then follows that every $RBNS$ string has a unique $MRBNS$ string because of the reduction rules 3 and 4. Conversely, every $MRBNS$ string has a unique $RBNS$ string. Because, to get the corresponding $RBNS$ string from an $MRBNS$ string, at every occurrence of a $\bar{1}$ in $MRBNS$, we insert a 0 on its left and every occurrence of $\bar{1}1$ in $MRBNS$ is always converted to $\bar{1}01$ in $RBNS$.

4.2 Physical Implementation

We now consider various issues arising out of the practical implementation issues of our proposed $MRBNS$ scheme concerning the representation of the $MRBNS$ symbols in the internal buffers at the MAC layer, hardware consideration of communicating the encoded $MRBNS$ symbols and maintenance of receiver-transmitter synchronization for the duration of transmission of a data packet.

4.2.1 Encoder and Decoder Design

We present here a simple hardware circuit to convert from binary to $MRBNS$. In order to internally represent the three symbols $(\{\bar{1},\ 0,\ 1\})$ at the MAC layer, we use two bits to encode each digit of the

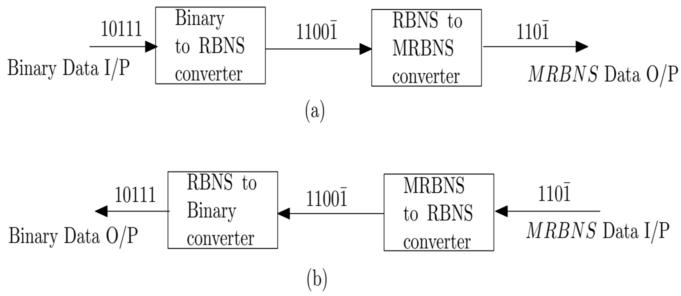

Fig. 1 Block Diagram of (a) encoder and (b) decoder

redundant binary number (RBN). Every digit of $RBNS$ is represented by X and Y bit pair, where X is MSB and Y is LSB. Thus, the $RBNS$ digit 0 may be encoded using the bit-pair 00, while 1 and $\bar{1}$ using the bit-pairs 01 and 10 respectively as in [7]. As shown in Fig. 1(a), the encoder for $MRBNS$ transmitter has two parts. The first part is basically $RBNS$ coder which is already described in [7] and the second part is for selecting removing the 0 bits as explained above. Similarly, as shown in Fig. 1(b), the decoder portion also has two parts - $MRBNS$ to $RBNS$ decoder and $RBNS$ to binary decoder. The $RBNS$ to binary decoder is the same as described in [7]. The $MRBNS$ to $RBNS$ decoder is used for 0 bit stuffing in the appropriate positions. The $MRBNS$ to $RBNS$ encoder and decoder both will work in online mode.

(a) Encoder : In the $RBNS$ to $MRBNS$ encoder we have to drop the zero bit before every $\bar{1}$ and drop the 0 bit in between the bit pattern $\bar{1}01$.

Thus, when a $\bar{1}$ is encountered at the bit position 2, i.e., ($X_2 = 1$) then digit 0 on the left of $\bar{1}$ needs to be deleted. For, this, after we see that $X_2 = 1$, we take the clock pulse off from the flip-flops (FFs) at bit position 2 to n of both MSB and LSB registers. For this, we take help of a control flip-flop F_1 which is a $J - K$ flip-flop with $J = 1$ and $K = C_2$. Let, C_i be the clock input to the flip-flops X_i and Y_i and C be the grand clock. Initially F_1 is set to 1. When $X_2 = 0$, $F_1 = 1$, then C_2 should be equal to C. When $X_2 = 1$, $F_1 = 1$, then we need C_2 to be zero. In the next pulse, F_1 becomes 0 as J and K inputs of F_1 both are equal to 1 and so F_1 toggles to 0 and C_2 should be equal to C, so that the $\bar{1}$ digit at the second digit position will now be shifted right by one position after the clock pulse. In the next clock cycle X_2 becomes 0 (as the digit initially on left of $\bar{1}$ must not be a $\bar{1}$) and also F_1 becomes 1. Thus, the pulse C_2 to be applied to flip-flops X_2 and Y_2 is given by $C_2 = C\bar{X}_2F_1 + CX_2\bar{F}_1$.

Now, $\bar{1}01$ in $RBNS$ needs to be converted to $\bar{1}1$ in $MRBNS$. When such a bit pattern is stored in the X-Y register, $X_1\bar{Y}_2Y_3 = 1$. Under this condition the X_1, Y_1 values will be shifted to right by one position (rewriting over the previous $X_2 = Y_2 = 0$ values) and there will be no movement of data from third bits of the two registers to n^{th} bits of the registers, i.e., none of the other FF outputs will be shifted right from the third bit position onwards. We effect that by taking the immediate next clock pulse off

X_1	X_2	Y_2	Y_3	C'
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	1
0	1	0	0	0
0	1	0	1	0
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	0

Table 1 Truth table for the condition C' to generate C_i $(i \geq 3)$ when $C = 1$

from 3^{rd} bit position onwards to the right, but the clock pulse, will be applied to the left most two FFs of both the MSB and LSB registers.

For generating the clock pulse C_i $(i \geq 3)$ we similarly need another control flip-flop F_2 which is a J-K flip-flop, initially set to 1, with J input always equal to 1 and K input set to C' as given by the truth table 1. Thus, from the truth table 1,

we get,

$$C' = \bar{X}_1\bar{X}_2 + \bar{X}_2 Y_2 + \bar{X}_2\bar{Y}_3 \tag{1}$$

and

$$C_i = CC'\bar{F}_2 + C\bar{C}'F_2. \tag{2}$$

The circuit diagram of the $MRBNS$ encoder is shown in fig. 2.

(b) Decoder : In the $MRBNS$ to $RBNS$ decoder we have to add a zero bit before every $\bar{1}$ and add a 0 in between the bit pattern $\bar{1}1$. The outputs of X_i and Y_i FFs in these shift registers will indicate the value $Q_i (i \geq 1)$ the data to the X_i and Y_i will be decoded by D_i; the D inputs of the flip-flops X_i and Y_i will be denoted by D_{X_i} and D_{y_i} respectively. Thus, for every two $MRBNS$ bits we decode to $RBNS$ bit stream. Let us denote the i^{th} digit of the number in in $RBNS/MRBNS$ by Q_i, where $Q_i \in \{1,\ 0,\ \bar{1}\}$ and Q_i will be encoded by X_iY_i as

$$Q_i = \begin{cases} 1 \implies X_i = 0, Y_i = 1 \\ 0 \implies X_i = 0, Y_i = 0 \\ \bar{1} \implies X_i = 1, Y_i = 0 \end{cases} \tag{3}$$

The decoded data in $RBNS$ will be stored in two shift registers X and Y, as shown in fig. 3(a). Let, C_1 be a boolean variable which assumes the value 1 when $Q_1Q_2 = \bar{1}1$, i.e., $C_1 = X_1\bar{X}_2Y_2$. Thus, with $C_1 = 1$, the decoder should insert a 0 between $\bar{1}$ and 1. To achieve this, after detecting $Q_1Q_2 = \bar{1}1$, the value of Q_2 should appear at the output of FF_5 after the next clock pulse, i.e., the input line of FF_5 (i.e., D_5) should be fed from the output Q_2 when $C_1 = 1$. Also, the inputs of all FF_i $(i \geq 5)$ will receive the

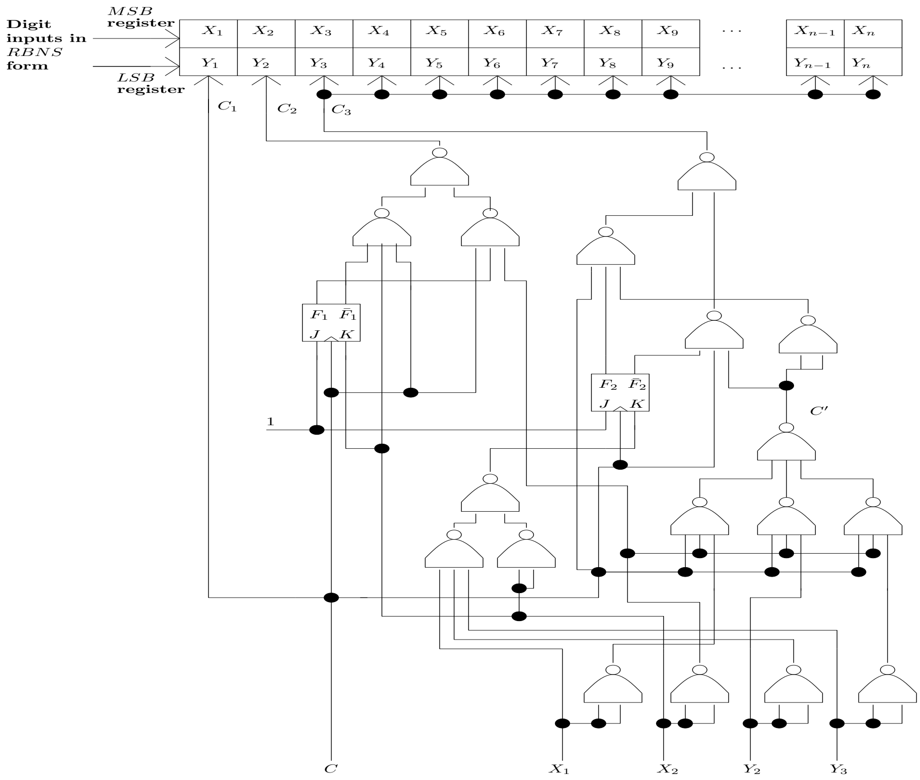

Fig. 2 Circuit Diagram of $MRBNS$ encoder

output values from Q_{i-3} when $C_1 = 1$, i.e., $D_i = C_1.Q_{i-3}$, $i \geq 5$. It implies that the D inputs to X_i and Y_i FFs will be given by $D_{X_i} = C_1 X_{i-3}$ and $D_{Y_i} = C_1 Y_{i-3}$. Further, when $C_1 = 1$, D_2 and D_4 both should be set to 0 and D_3 should get the value from Q_1, i.e., $D_3 = C_1.Q_1$. Let, C_2 be a boolean variable which assumes the value 1 when $Q_1Q_2 = \bar{1}0$, i.e., $C_2 = X_1\bar{Y}_2$. Thus, with $C_2 = 1$, the decoder will input a 0 before every $\bar{1}$. To achieve this, the value of Q_1 should appear at the output of FF_3 after the next clock pulse, i.e., D_3 should get the value of Q_1 when $C_2 = 1$. Similarly, $D_i = C_2.Q_{i-2}$, for all $i \geq 3$. Also, D_2 should be set to 0 when $C_2 = 1$.

Thus, considering both these cases of $Q_1Q_2 = \bar{1}1$ and $Q_1Q_2 = \bar{1}0$, we get,

$$\begin{aligned} D_i &= C_1Q_{i-3} + C_2Q_{i-2} + \bar{C}_1\bar{C}_2Q_{i-1} \\ &= C_1Q_{i-3} + C_2Q_{i-2} + \bar{X}_1Q_{i-1}, \forall i \geq 5, \end{aligned} \tag{4}$$

$$\begin{aligned} D_4 &= C_2Q_2 + \bar{C}_1\bar{C}_2Q_3 \\ &= C_2Q_2 + \bar{X}_1Q_3, \end{aligned} \tag{5}$$

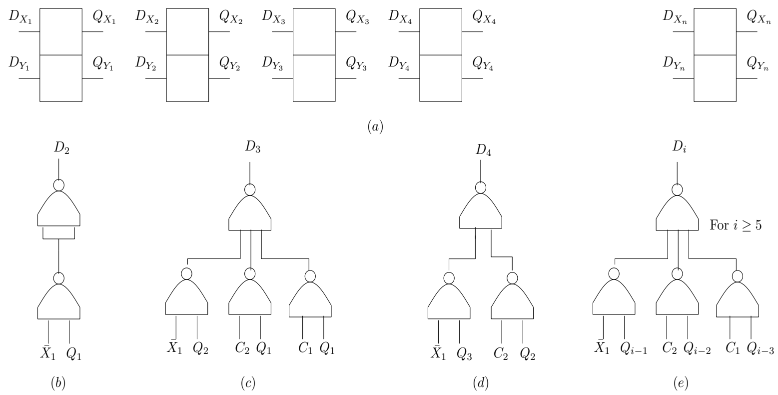

Fig. 3 Circuit Diagram of $MRBNS$ decoder

$$\begin{aligned} D_3 &= C_1Q_1 + C_2Q_1 + \bar{C}_1\bar{C}_2Q_2 \\ &= C_1Q_1 + C_2Q_1 + \bar{X}_1Q_2, \end{aligned} \tag{6}$$

$$\begin{aligned} D_2 &= \bar{C}_1\bar{C}_2Q_1 \\ &= \bar{X}_1Q_1 \end{aligned} \tag{7}$$

and

$$D_1 = \text{new input from } RBNS \text{ stream.} \tag{8}$$

In view of a very small number of logic gates and flip-flops required for the above encoding and decoding process, the total power consumption of the encoder and decoder will be insignificant, and may be neglected.

4.2.2 Transceiver Design

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 $\bar{1}$, respectively, and is switched off during the 0s. 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 [7, 22]. We use the same transceiver as presented in [7, 22] because we use the same type of coding system and it is easy to implement in hardware level with low manufacturing cost.

4.2.3 Synchronization Between The Receiver and The Transmitter

A necessary underlying requirement for the correct detection of silent symbols in the protocol is the presence of synchronization between the sender and the receiver for cognitive radio networks. In presence of the silent 0's, we adopt one of the three possible schemes for maintaining synchronization as described for $RBNSiZeComm$ [7].

4.2.4 Spectrum Sensing and 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 the neighboring nodes determine whether the channel is actually free for transmission or whether there is an ongoing transmission containing a run of 0s. An erroneous interpretation of the absence of any signal on air (carrier and/or baseband) may 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. We assume that the channel sensing, allocation and deallocation algorithms provided by the protocol used by Bhattacharya et.al. [23] based on *Sample Division Multiplexing* (SDM) are used by the CRN, so as to enable us to retain the channel even when silent 0's are received, until a specific deallocation message is transmitted by the sender.

5 Performance Analysis

In this section we to analyze our proposed $MRBNS$ scheme as follows.

5.1 Energy Savings for Ideal Channel

In [7] it is already described that after $reduction\ rule$ 2 for n number of bits the total number of 1's and $\bar{1}$'s in the $RBNS$ coded message is $(n+2).2^{n-2}$ and total number of bits for all possible combination is approximately $n.2^n$. Now in the $RBNS$ code the number of $\bar{1}$ is $n.2^{n-3}$ and the number of $\bar{1}01$ is $3.(n-3).2^{n-6}$. Using $reduction\ rule$ 3 and 4 for every $\bar{1}$ and $\bar{1}01$ we reduced one zero bit. Thus, the total number of bits in $MRBNS$ coding is $(53n+9).2^{n-6}$. Hence, the fraction of energy savings obtained at transmitter end by applying all $reduction\ rule$s is given by,

$$\eta_{te} = 1 - \left(\frac{16(n+2)}{53n+9} . \frac{53n+9}{64n} \right). \tag{9}$$

Typically, for $n = 1024$, η_{te} is nearly equal to 75% (approximately). Simultaneously savings at the receiver end due to reduction of bits is given by,

$$\eta_{re} = 1 - \frac{53n + 9}{64n}. \tag{10}$$

Typically, for $n = 1024$, η_{re} is nearly equal to 17.2%.

Theorem 1 *Using the $MRBNS$ communication strategy, theoretically it is possible to have an energy saving given by 75% at the transmitter for noiseless channels, while simultaneously generating a savings of 17.2% at the receiver, when compared to EbT schemes.*

5.2 Error Analysis

We consider a message frame containing n binary bits. Corresponding to each such frame, we consider the $MRBNS$ frame after converting the binary message to $MRBNS$ form containing three different types of symbols 0, 1 and $\bar{1}$. Instead of the conventional bit-error rate (BER) while receiving the transmitted message, we consider a frame error rate (FER) as used in [7] for both the original binary frame and the $MRBNS$ frame communicated through the non-coherent hybrid $FSK - ASK$ modulation scheme. This is because $MRBNS$ symbols have some interdependency due to the generation of $\bar{1}$. Thus, an erroneous reception of a $\bar{1}$ may affect a number of higher order bits in the decoded binary data. Hence, FER becomes a the appropriate performance metric for possible comparison between typical binary and $MRBNS$-based number systems.

In the hybrid $FSK - ASK$ modulation scheme, let α be the probability that a transmitted $MRBNS$ symbol was a 0 and it is also received correctly as a 0. Similarly, let β (or, δ) be the probabilities that a transmitted symbol was a 1 (or, $\bar{1}$) and the received symbol is also a 1 (or, $\bar{1}$). From symmetry, $\beta = \delta$. Note that

$$\alpha = P\{q_A = 0|0\}P\{q_B = 0|0\}, \tag{11}$$

where $P\{q_A = 0|0\}$ and $P\{q_B = 0|0\}$ are the probabilities of correctly receiving a 0 at q_A and q_B respectively, given that a 0 was transmitted. Hence,

$$\alpha = [P\{q_A = 0|0\}]^2 \tag{12}$$

(by symmetry).

Also, note that q_A for 0 transmission follows Rayleigh distribution. Hence, assuming a zero mean and standard deviation of σ for $AWGN$ channel, we can write,

$$P\{q_A = 0|0\} = \int_0^{e_{th}} \frac{e_A . e^{\frac{-e_A^2}{2\sigma^2}}}{\sigma^2} . de_A = 1 - e^{\frac{-e_{th}^2}{2\sigma^2}}. \tag{13}$$

Hence, we have

$$\alpha = \left(1 - e^{\frac{-e_{th}^2}{2\sigma^2}}\right)^2. \tag{14}$$

Next, we define β as,

$$\beta = P\{q = 1|1\}P\{e_A > e_B, \forall e_A|1\} = X_1.X_2 \tag{15}$$

(say), where $X_1 = P\{q = 1|1\}$ and $X_2 = P\{e_A > e_B|1, \forall e_A|1\}$.

From the transceiver system we can write,

$$X_1 = \int_0^\infty [1 - P\{q_A = 0|1\}Pq_B = 0|1]p_1(e_A).de_A, \tag{16}$$

where $P\{q_B = 0|1\}$ is Rayleigh distribution and $P\{q_A = 0|1\}$ is Rician distribution.

Thus,

$$P\{q_A = 0|1\} = \int_0^{e_{th}} \frac{e_A.e^{-\frac{e_A^2+s_A^2}{2\sigma^2}}}{\sigma^2}.I_0\left(\frac{s_A.e_A}{\sigma^2}\right).de_A \tag{17}$$

and

$$P\{q_B = 0|1\} = \int_0^{e_{th}} \frac{e_B.e^{\frac{-e_B^2}{2\sigma^2}}}{\sigma^2}.de_B = 1 - e^{\frac{-e_{th}^2}{2\sigma^2}}. \tag{18}$$

[7, 22]

So, finally we obtain,

$$X_1 = \int_0^\infty \left[1 - \left(1 - e^{\frac{-e_{th}^2}{2\sigma^2}}\right)\left(\int_0^{e_{th}} \frac{e_A.e^{-\frac{e_A^2+s_A^2}{2\sigma^2}}}{\sigma^2}.I_0\left(\frac{s_A.e_A}{\sigma^2}\right).de_A\right) \left(\frac{e_A.e^{-\frac{e_A^2+s_A^2}{2\sigma^2}}}{\sigma^2}.I_0\left(\frac{s_A.e_A}{\sigma^2}\right)\right)\right].de_A \tag{19}$$

and

$$X_2 = \int_0^\infty \left[1 - \left(1 - e^{\frac{-e_{th}^2}{2\sigma^2}}\right) \left(\frac{e_A.e^{-\frac{e_A^2+s_A^2}{2\sigma^2}}}{\sigma^2}.I_0\left(\frac{s_A.e_A}{\sigma^2}\right).u(e_A)\right)\right].de_A. \tag{20}$$

Let P_0, P_1 and $P_{\bar{1}}$ be the probabilities of occurrences of the symbols 0, 1 and $\bar{1}$ respectively in the transmitted $MRBNS$ message. Hence, the probability that the transmitted $MRBNS$ frame with n $MRBNS$ digits (approximately) will be received correctly by the above hybrid FSK/ASK scheme, can be expressed as *frame-correct rate* (FCR), given by

$$FCR = \alpha^{n.P_0}.\beta^{n.P_1}.\delta^{n.P_{\bar{1}}}. \tag{21}$$

Assuming that all possible binary strings with n bits are equally likely to appear in the message, we have already found in Section 5.1 that with the application of reduction rules, the average number of 0s in the $MRBNS$ frame will be asymptotically (for large n) 70% and those of all non-zero symbols, i.e., 1 and $\bar{1}$ taken together will be 30%. Thus, $P_0 = 0.7$ and $P_1 + P_{\bar{1}} = 0.3$. Hence, the probability that a message frame in $MRBNS$ will be received correctly (using the above hybrid $FSK-ASK$ modulation scheme), is given by,

$$FCR = \alpha^{0.7n}.\beta^{0.3n}. \tag{22}$$

Note that $\log(FCR) = n(0.7log\alpha + 0.3log\beta)$, from which we can easily evaluate FCR. Next we obtain the frame error rate (FER) for the $RBNS$ message as

$$FER_{MRBNS} = 1 - FCR. \tag{23}$$

On the other hand, let us consider the situation that we transmit the original binary message of n bits using non-coherent FSK with a BER of ρ. Then the probability that the whole frame will be received correctly is given by $(1-\rho)^n$. Thus, the FER for binary FSK will be given by,

$$FER_{bfsk} = 1 - (1-\rho)^n, \tag{24}$$

which may be approximated as $n\rho$, since ρ is usually very small. Hence, for a given frame size n, we can compare FER_{MRBNS} with FER_{bfsk} ($= n\rho$), or in other words, $\frac{FER_{MRBNS}}{n}$ with ρ. To compute $\frac{FER_{MRBNS}}{n}$, we set $s_A = 1$, i.e., signal power $= \frac{s_A^2}{2} = \frac{1}{2}$ and hence a signal-to-noise ratio $(SNR) = \frac{1}{2\sigma^2}$. The computations to find the optimum value of threshold voltage e_{th} that gives the minimum $\frac{FER_{MRBNS}}{n}$ for a given SNR value were implemented in Matlab. We get the required peak transmitter power with $MRBNS$ for a given value of FER_{MRBNS}.

The SNR values for binary FSK modulation are determined from the relation, $\rho = \frac{e^{\frac{\gamma}{2}}}{2}$, where SNR in $dB = 10\log_{10}\gamma$. For different values of frame size in the range $n = 1024$, the SNR values of our proposed hybrid modulation scheme with $MRBNS$ message and the corresponding SNR values for binary FSK to meet the same FER values are summarized in Table 2. From Table 2, we see that for the same FER, the required SNR values with the proposed $MRBNS$ is on an average 2.76dB higher than that with binary non-coherent FSK. However, in our proposed $MRBNS$ scheme, the transmitter will be in the transmit state only during the non-zero symbols (1 or $\bar{1}$ and in the idle state during the 0s), in the $MRBNS$ encoded message. Hence, the required average transmitter power for a given FER will be less than the value. Taking the percentage of non-zero symbols in the $MRBNS$ string as 30%, the required average transmitter power for our proposed scheme will be 0.30 times the values. This implies that the required average transmitter power for our proposed scheme will be reduced from the peak power

SNR for frame size 1024 bits			
$\rho = \frac{FER}{n}$	MRBNS	BFSK	QPSK
0.000460224	14.0	11.4555	5.5526
0.000110742	15.0	12.2609	6.8684
0.000014599	16.0	13.1979	8.7696
0.000001075	17.0	14.1664	11.2534
0.00000004	18.0	15.1423	14.4152

Table 2 SNR for $MRBNS$, $BFSK$ and $QPSK$

by $10\log_{10}(0.3)\text{dB} = 5.23\text{dB}$. A plot of the scaled transmitter power averaged is presented in Fig. 4 for $MRBNS$ as well as for binary FSK (with non-coherent detection).

From the plot in Fig. 4, we see that for a given $\rho = FER/n$ in the range 10^{-4} to 10^{-8}, $MRBNS$ needs approximately 2.47dB less average power than binary FSK. Let P_b and P_M be the required average transmitter power levels for binary FSK and our proposed $MRBNS$ scheme. Noting that $10^{-\frac{2.47}{10}} = 0.57$, we have $\frac{P_M}{P_b} = 0.57$.

5.3 Effect of Data Compression on Energy Savings

We now consider the effect of data compression on the overall transmitter energy. Let P_b and P_M be the transmitter power required for binary FSK and $MRBNS$ respectively. Also, let T_b, T_M be the transmission times for binary FSK and $MRBNS$, respectively. Since $MRBNS$ needs 0.83 time for transmission than binary FSK, $\frac{T_M}{T_b} = 0.83$. Noting that $10^{\frac{-2.47}{10}} = 0.57$, we have $\frac{P_M}{P_b} = 0.57$. Let E_b, E_M be the transmitter energy requirements for binary FSK and $MRBNS$, respectively. Hence we have, $\frac{E_M}{E_b} = \frac{P_M}{P_b}.\frac{T_M}{T_b} = 0.57\ .\ 0.83 = 0.473$, which translates to a savings of energy by an amount of 53% (approximately) transmitter energy on an average. It is quite interesting to note that using $RBNS$ [7], the average savings in transmitter energy over the conventional binary FSK (with non-coherent detection) was also 53%, although the percentage of non-zero symbols was different in the two cases.

Theorem 2 *Assuming an $AWGN$ channel, for equal probability of occurrence of the symbols* 1, 0 *and* $\bar{1}$ *$MRBNS$ saves approximately* 53% *energy as compared to binary FSK.*

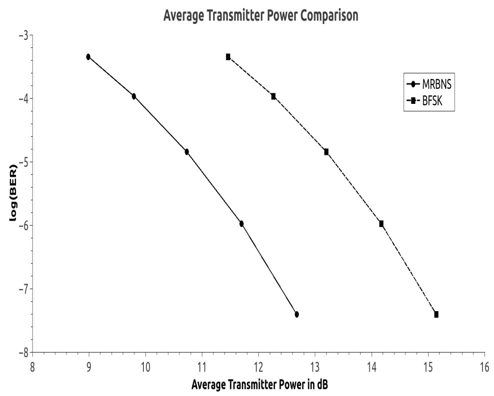

Fig. 4 Comparison of average transmitter power for given BER

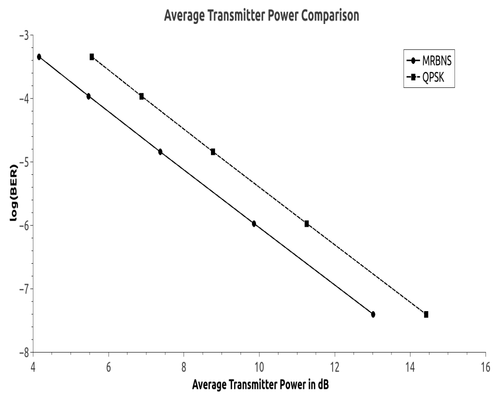

Fig. 5 Comparison of average transmitter power for given BER

5.4 Performance Comparison with QPSK

We now present a comparison with $QPSK$, using non-coherent receivers for the $MRBNS$ scheme. We compute the required SNR values with $QPSK$ for a given $\rho = \frac{FER}{n}$ from the relation,

$$\rho = Q.\sqrt{2.\gamma} \approx \frac{e^{-\gamma}}{2.\sqrt{\pi.\gamma}}. \tag{25}$$

From plot, as shown in Fig. 5, of the SNR values with the data from Table 2 against different values of ρ, we see that the peak transmitter power with $MRBNS$ employing non-coherent $FSK - ASK$ detection is about 6.63 dB more than that with $QPSK$ modulation. Noting that the average transmitter power with $MRBNS$ will be 5.23 dB less than the peak power, it appears that the average power requirement with the above implementation of $MRBNS$ is about 1.4 dB more than that with $QPSK$, which translates into $1.38 * 0.83$ times more energy i.e., about 11.46% approximately more energy than $QPSK$.

Theorem 3 *Assuming an $AWGN$ channel, for equal probability of occurrence of the symbols 1, 0 and $\bar{1}$ $MRBNS$ needs approximately 11.46% more energy as compared to $QPSK$.*

5.5 Performance Comparison with CtS and VarBaTaC

We now compare the performance of $MRBNS$ scheme with those of CtS [13] and $VarBaTac$ [21], which are also based on communication through silence. We first consider the transmission length duration. The transmission time in CtS is exponential in the number of bits to be sent. $VarBaTaC$ uses a variable coding base and controls the communication time by suitably tuning the base value. Suppose, without any loss of generality, we want to transmit a value M, where $0 \leq M < 2^k$, $k \geq 0$. Then the representation of M in base r will have $m = \lceil \frac{k}{logr} \rceil$ number of digits. Each of these m digits is then transmitted using CtS with a pulse separating each digit. Let t avg be the average number of time slots required in the $VarBaTaC$ scheme. We need to transmit $m+1$ pulses for the m digits to be transmitted. In addition, we need on an average, $\frac{m(r1)}{2}$ time slots for the digits (assuming equal likelihood for all possible values of the message). Hence, t_{avg} is given by,

$$\begin{aligned} t_{avg} &= (m+1) + \frac{m(r-1)}{2} \\ &= \frac{m(r+1)}{2} + 1. \end{aligned} \tag{26}$$

Let, $r = 2^p$. Hence, $m = \lceil \frac{k}{p} \rceil$. So, we have,

$$t_{avg} \begin{cases} \geq \frac{k}{p} \frac{2^p+1}{2} + 1 \\ < \frac{k+p}{p} \frac{2^p+1}{2} + 1 \end{cases} \tag{27}$$

Thus, for a given k, t_{avg} monotonically increases with p due to the function $\frac{2^p+1}{p}$.

p	Radix r	t_{avg}
2	4	81
3	8	100
4	16	137
5	32	215.5
6	64	357.5
7	128	646
8	256	1029
9	512	2053
10	1024	3588.5

Table 3 Number of slots for $VarBaTaC$ with radix as power of 2 and $k = 64$

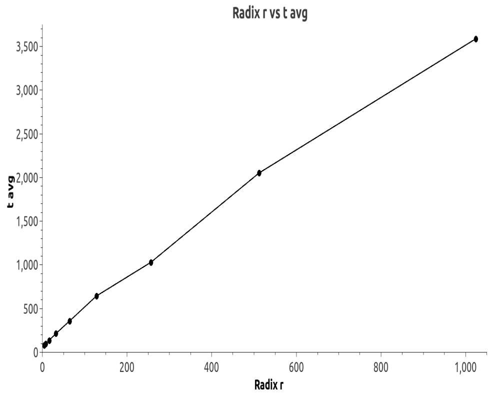

Fig. 6 Number of slots for $VarBaTaC$ with radix as power of 2 and $k = 64$

As we can see from the fig. 6 and the data from Table 3, on an average, $MRBNS$ will require fewer time slots than $VarBaTaC$. In general, the transmission time of the $MRBNS$ scheme will be less than that of both CtS and $VarBaTaC$, while generating significant savings in energy at both the transmitter and the receiver. It is to be noted here that neither CtS nor $VarBaTaC$ generates energy savings at the receiver [2, 7].

5.6 Effects 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. The penalty paid for this low power operational state is the switching time from the active to transmit state and vice versa. With chips having faster switching time, the data rate can be increased as described in [2, 7]. We now investigate the effect of the device characteristics on the energy saving aspect of our proposed protocol.

Let, V_{cc}, I_{high} and I_{low} denote the supply voltage, currents drawn in the transmit and idle states, respectively. Let, $I_0 = I_{high} - I_{low}$. We assume that the device moves from idle to transmit state in time t_{rise} and during this transient period, it draws a current I_{tran}. Also, let, t_p denote the duration of a symbol which is sufficiently larger than the switching time t_{rise}. Similarly, when the device moves from the transmit state to the idle state, it takes some finite amount of time, say, t_{fall}. Usually t_{fall} is very small. We, can neglect the energy consumed by the device during this t_{fall} time.

The total energy required to transmit an n-digit $MRBN$ data frame is

$$E_{MRBNS} = P_{base} + P_{1\bar{1}} + P_{rise}, \tag{28}$$

where, P_{base} is a base energy needed throughout the duration of the transmission, which is equal to the energy required when the device is in the active state. For an n-digit $MRBN$ data frame, considering all possible 2^n strings of length n each,

$$P_{base} = (53n + 9).2^{n-6}.t_p.I_{low}.V_{cc}. \tag{29}$$

$P_{1\bar{1}}$ is an extra energy in addition to the base energy required to transmit a 1 or $\bar{1}$ symbol in transmit state. For an n-digit $MRBN$ data frame, considering all possible strings, for $(n+2).2^{n-2}$ non-zero symbols (1 and $\bar{1}$ in the transmit state,

$$P_{1\bar{1}} = (n + 2).2^{n-2}.(t_p - t_{rise}).I_0.V_{cc}. \tag{30}$$

P_{rise} is an extra energy in addition to the base energy required during the edge transitions from a 0 to 1 or $\bar{1}$. This corresponds to switching from the active to transmit state and hence, the number of such transitions is equal to the number of non-zero symbols. Thus, we have,

$$P_{rise} = (n + 2).2^{n-2}.t_{rise}(I_{tran} - I_{low}).V_{cc}. \tag{31}$$

The total energy consumed by using an EbT transmission scheme for transmitting an n-bit binary data frame, is

$$E_{EbT} = n.2^n.t_p(I_{low} + I_0)V_{cc}. \tag{32}$$

Hence, considering the device characteristics, the fractional energy savings generated by the $MRBNS$ protocol over EbT transmission schemes is

$$\eta'_{te} = \frac{E_{EbT} - E_{MRBNS}}{E_{EbT}}. \tag{33}$$

So,

$$\eta'_{te} = \frac{11n - 9}{64n} + \frac{37n - 23}{64n}.\frac{I_0}{I_{high}} + \frac{n+2}{4n}.\frac{I_{high} - I_{tran}}{I_{high}}.\frac{t_{rise}}{t_p}. \tag{34}$$

The coherent detection scheme itself would require more complex electronics and consequently consume additional power. Thus, in typical applications where one would prefer to keep the circuit complexity and the cost low, it would be preferable to opt for non-coherent transmission supported by the $MRBNS$-based communication scheme. In non-coherent systems, $MRBNS$ scheme would indeed offer significant advantage (53% savings at transmitter and 17.2% savings at receiver) over the receiver implementation of $FSK - ASK$ modulation using envelope detectors.

5.7 Comparison of Performance

$MRBNS$ has the advantage of reducing receiver energy consumption, as the receiver receives all the symbol values in smaller time required to transmit the original binary message. Fig. 7 depicts the comparison among the transmitter and receiver energy savings generated by $MRBNS$, $RBNSiZeComm$ [7], CNS [2], TSS [22] and RZE [12] at the transmitter and receiver for equal likelihood of all possible binary strings of a given length, using non-coherent detection based receiver over $AWGN$ channels. Table 4 gives the numerical values of the energy savings generated by the various schemes at both the transmitter and the receiver, in comparison to a typical communication scheme utilizing binary FSK with non-coherent detection. From these results we see that $MRBNS$ outperforms the CNS, TSS and RZE techniques in saving energy at the transmitter side. The results also show that while the receiver energy savings by $MRBNS$ is less than that the CNS and TSS scheme, it definitely performs significantly better than these schemes in saving energy at the transmitter. As most CRNs tend to be multi-hop in nature, this fact makes $MRBNS$ more suitable than either $RBNSiZeComm$, RZE or TSS for use in low power CRNs.

The total transceiver energy savings in $MRBNS$ is 70.3% ($53\% + 17.2\%$) whereas, that in CNS is 80% ($30\% + 50\%$). However, $MRBNS$ needs only two frequencies, while CNS requires three frequencies for effecting the communication. Thus, CNS would require more bandwidth for communication as well as more cost for the transceivers. Hence, $MRBNS$ may be more appealing than CNS in different CR environments where bandwidth and cost are also considered to be equally important as energy savings.

Communication scheme	Energy savings at transmitter (%)	Energy savings at receiver (%)	Number of frequencies transmitted
$MRBNS$	53%	17.2%	2
$RBNSiZeComm$	53%	0%	2
CNS	30%	50%	3
RZE	35.2%	12.5%	2
TSS	20%	36.9%	2

Table 4 Comparison of transmitter and receiver energy savings among various energy-efficient communication schemes

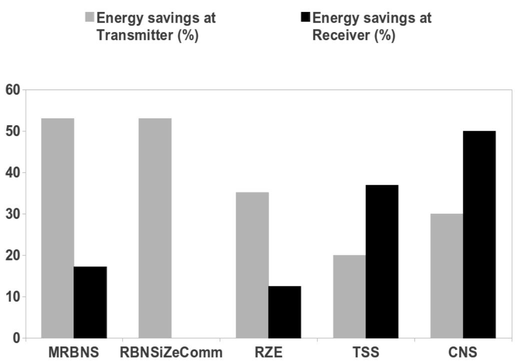

Fig. 7 Comparison of energy savings among various schemes

6 Conclusion

We have presented an energy-efficient communication scheme based on encoding the source data in *Modified Redundant Binary Number System* ($MRBNS$), coupled with the use of silent periods for communicating the 0s in the encoded message. A low cost and low complexity implementation scheme based on a hybrid modulation utilizing FSK and ASK has also been presented. We also investigate the performance evaluation for all these schemes and also design the corresponding protocols for transmission and reception of messages. Our results demonstrate that for *Additive White Gaussian Noise* ($AWGN$) noisy channels, compared to the conventional non-coherent transceivers using FSK, the transmitter energy is reduced by about 53% on an average with equal likelihood of all possible binary strings and the receiver energy is also reduced by 17.2% on an average. Taking into account the low cost/complexity of the proposed transceiver as well as total bandwidth for communication, these results clearly establish that our protocol is very suitable for cognitive radio networks using multi-hop communication.

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Ansuman Bhattacahrya obtained his B. Tech. degree in Electronics and Communication Engineering from West Bengal University of Technology, Kolkata in 2006 and M. Tech. degree with specialization in Radiophysics and Electronics from University of Calcutta, Kolkata in 2008. From October 2008 to January 2009, he joined Tech Mahindra as a Technical Associate. From March 2009 to July 2009, he worked as a Lecturer in Guru Nanak Institute of Technology. In July 2009, he joined the Indian Statistical Institute, Kolkata as a Project Linked Personnel and since April 2011, he has been working there in the Advanced Computing and Microelectronics Unit as a Senior Research Fellow. His research interests include channel allocation and routing in cognitive radio networks, secure wireless communication and energy-efficient communication. He is a Member of the IEEE.

Koushik Sinha received his PhD degree from Jadavpur University, Calcutta, India and his MS degree from Clemson University, South Carolina, USA. He joined Honeywell Technology Solutions, Bangalore in 2004 where he worked as a Lead Research Scientist in the Research and Technology (R&T) group. Then he joined HP Research Labs Bangalore as a Scientist in 2009. He received the "Indian Science Congress Young Scientist Award" for the year 2008-09 in the Information and Communication Science and Technology (including Computer Sciences) category. He holds several patents and has more than 40 publications in refereed international journals and conferences. He has served in TPCs and organizing committees of several international conferences such as IEEE PIMRC, IMSAA, IEEE Sarnoff and others. He has also served as a reviewer for the IEEE Transactions on Very Large Scale Integration Systems (TVLSI) and the Journal of Parallel and Distributed Computing (JPDC). His research areas include cellular networks, ad hoc and sensor networks, cognitive radios and high performance computing. He is a member of IEEE, ACM, IEEE Computer Society and IEEE Communications Society.

Debasish Datta received his BTech degree in 1973 from Institute of Radiophysics and Electronics, Calcutta University, and MTech and PhD degrees from IIT Kharagpur in 1976 and 1986, respectively. He has been serving in the faculty at IIT Kharagpur for the last thirty years. In the early phase of career, he also worked in electronics and telecom industry for about three years. At Kharagpur, he served as Head in the Department of E&ECE during 2007-2008 and, as Chairman in G.S. Sanyal School of Telecommunications during 1999-2002. From Kharagpur, he visited Stanford University during 1992-1993 to work on Coherent Optical Communications. Thereafter, he visited University of California, Davis, during 1997-1999 and Chonbuk National University, South Korea, during 2003-2004 to work on Optical Networking. He received the Sir J. C. Bose Award in 1985 from IERE, UK, for a paper on Optical Receiver in the Journal of IERE. He served as Guest Editor for IEEE JSAC for January-2002 Special Issue on WDM-based Network Architectures, and presently he serves as an Editor for the Elsevier Journal of Optical Switching and Networking. His current research interests include wavelength-routed optical backbones, WDM-PONs and wireless communication systems and networks.

Bhabani P. Sinha joined the faculty of Electronics Unit of the Indian Statistical Institute, Calcutta in 1976, where he became a Professor in 1987. From 1993 to 2010, he served as the Head of the Advanced Computing and Microelectronics Unit of the Indian Statistical Institute, Calcutta. He was an *Indian Space Research Organization (ISRO) Chair Professor* during 2000 in the Indian Institute of Technology Kharagpur, India. He has published more than 145 research papers in various international journals and refereed conference proceedings in the area of computer architectures, algorithms, parallel and distributed computing, mobile computing and wireless communication. His recent research interests include parallel and distributed computing, mobile computing, wireless networks and algorithms. He served as an Editor of the IEEE Transactions on VLSI Systems and as a subject area editor of the Journal of Parallel and Distributed Computing. He is a Fellow of the IEEE, USA.

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