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Energy-Efficient Architecture for Wireless Sensor Networks in Healthcare Applications

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ABSTRACT The need to deploy wireless sensor networks (WSNs) for real-world applications, such as mobile multimedia for healthcare organizations, is increasing spectacularly. However, the energy problem remains one of the core barriers preventing an increase in investment in this technology. In this paper, we propose a new technique to resolve the problems due to limited energy sources. Using a quaternary transceiver (in the architecture on a sensor node), instead of a binary one, which will use the amplitude/phase, modulator/demodulator units to increase the number of bits transmitted per symbol. The system will reduce the consumption of energy in the transmission phase due to the increased bits transmitted per symbol. Moreover, neural network static random access memory (NN-SRAM) implementation in a clustering-based system for energy-constrained WSNs is proposed. The scheme reduces the total amount of energy consumption in storage and transmissions during the data dissemination process. Through simulation results based on MATLAB and Spice software tools, it is shown that the neural network static random access memory implementation in a clustering-based system reduces the energy consumption of the entire system by about 76.99%.

INDEX TERMS Wireless sensor networks, mobile healthcare, multimedia, multi valued logic, neural networks, NN-SRAM.

I. INTRODUCTION

The importance of wireless sensor network (WSN) systems comes from the variety of its practical applications. WSNs are systems that play a significant role in civil (Figure 1) and medical applications (Figure 2), [1]–[3]. An example of a medical application is the multimedia for mobile healthcare applications, where the WSN can be used to remotely monitor the patient's activity in order to direct the emergency units.

In healthcare applications, a real-time system is needed to monitor the patient's activities by placing sensors directly on the patient's body [4] as shown in Figure 2. In addition, it is used to identify emergency cases like sudden falls, heart attacks, low oxygen level, and/or temperature by transmitting secured signals, images and/or videos to the designated trustworthy unit, [5], [6]. Few extra seconds might be sufficient to save lives.

Therefore, providing real-time monitoring requires an energy source for data collection, processing, transmission and reception [2]. In Addition, all devices in WSNs are operating by batteries; therefore, power challenge is present in almost every application of wireless sensor networks [3].

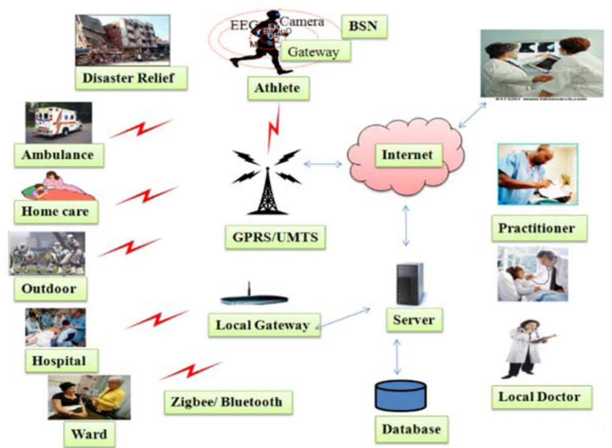

FIGURE 1. Typical applications of WSNs [1].

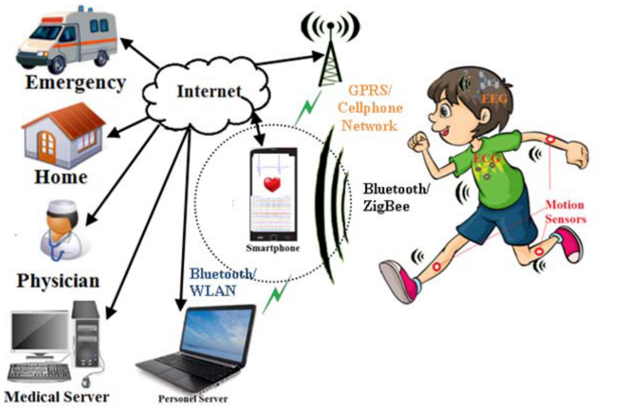

FIGURE 2. Mobile healthcare application of WSNs.

The reduction of sensor node energy consumption minimizes the total energy consumption of the entire network and thus prolongs the lifetime of the whole network. One common approach to achieve this is called compressive sensing [7]–[10], which compresses data (signals, images or video) before transmission and decompresses it upon reception. Another important approach is clustering [11], [12], where the WSN is divided into a group of clusters with each having a Cluster Head (CH). CHs then communicate with each other to transmit the collected data, from the patient sensors, to a Base Station (BS), which in turn communicates with the server. However, all communication protocols presented are based on a binary transmission scheme [12]–[15].

Adopting a quaternary transmission scheme instead of a binary scheme will definitely result in using energy more efficiently. In other words, we will be presenting an energy-efficient architecture for a wireless sensor network system that uses multi-valued logic instead of a binary logic.

We have to modify the design of sensor networks (SNs) so that each SN is able to manipulate four symbols (quaternary) instead of two (binary). In the transmission phase, any two bits will be modulated as one symbol, and at the receiving end, the symbol will be demodulated producing the original two bits.

The main contributions of this paper are as follows:

- We propose a quaternary interconnect architecture that can modify the transmission of data in a WSN for mobile multimedia and healthcare applications from binary symbols to quaternary ones. The proposed scheme will make energy use more efficient.
- We present a novel architecture of Neural Network Static RAM (NN-SRAM) for the collected and saved data. The NN-SRAM stores binary data and remains valid as long as power is supplied. Since the NN-SRAM reduces energy consumption, it is used in WSNs for extending the lifetime of the system. The power consumption in neural network static random access memory with clustering based energy efficient systems (NN-SRAM-CBEES) for WSNs will be reduced by the reduction of the storage cost due to the use of neural networks and the reduction of the transmission/reception cost between the SNs and their CHs.

The remainder of this paper is organized as follows: Section II summarizes some state of the art related work. The multi-valued logic (MVL) technique is explained in section III. In section IV, the proposed scheme for converting a binary network to a quaternary system and vice-versa are explained. The performance of a quaternary system is described in detail in section V. The usage of neural network storage SRAM unit (NN-SRAM) to store the SN information is highlighted in section VI. In section VII, NN-SRAM-CBEES routing protocol used is illustrated. Finally, performance and simulation results of the proposed technique are presented in section VIII, followed by a brief conclusion.

II. RELATED WORKS

Nowadays, the energy consumption is one of the most important factors when designing a wireless sensor network (WSN) for mobile multimedia and healthcare applications. Many techniques are used in wireless sensor network to reduce the energy consumption [16]–[18]. Jelicic *et al.* [16] proposed a wake-up radio in multimodal sensing that automates sensor nodes and reduces response latency to manage and reduce the energy consumption of WSN. They applied this methodology for high-energy consuming sensors in a two-tier WSN for camera/video surveillance applications with low-energy consuming infrared sensor nodes.

Mekonnen *et al.* [17] proposed a heterogeneous multi-tier wireless multimedia sensor network (WMSN) prototype which consists of low-power hardware systems. This prototype uses a network architecture that includes three operational modes: wake-up mode, a shut down mode, and a sleep mode.

In [18], the authors presented a big health application system, based on the health Internet of Things (IoT) and big data. They proposed the cloud to end fusion big health application system architecture. This system consists of many layers such as perception, transport and big health cloud layer. One of the main challenges among these layers is the energy consumption, especially in the short-range wireless communication.

In WSN, the data transmission and reception lead for the most part of the energy consumption [16]. The above approaches do not consider the power consumption of the transceiver nor of the memory, which are critical in wireless sensor networks used in healthcare applications. Moreover, our proposed architectures will reduce the consumption of energy in the transmission phase and the memory phase.

III. MULTI-VALUED LOGIC

Multi-valued logic (MVL) can execute arithmetic operations faster than binary logic while using fewer interconnections [19], [20]. In addition, MVL data transmission consumes less power because there will be fewer coded words. It can be of base three, base four, or any other numbering system. Using a ternary numbering system is complex and it needs more calculations due to difference in the base, thus requiring more computations and energy consumption [21], [22].

Using an octal numbering system means that there will be eight levels of voltages. As example, dividing the 6 volts (0 logically is a voltage between 0 V and 3 V, while 1 logically is a voltage between 3.5 V and 6 V, thus the available max voltage is 6 V) that is dividing available voltage into eight levels means that the levels will be in approximate values and as a result will lead to more errors. Therefore, a quaternary numbering system fits best.

Quaternary quadrature-amplitude modulation (QAM) uses two bits instead of one, where one bit represents phase shift keying (PSK) and the second represents amplitude shift keying (ASK). Thus, we will have a lower number of amplitudes and thus the probability of error will be minimized.

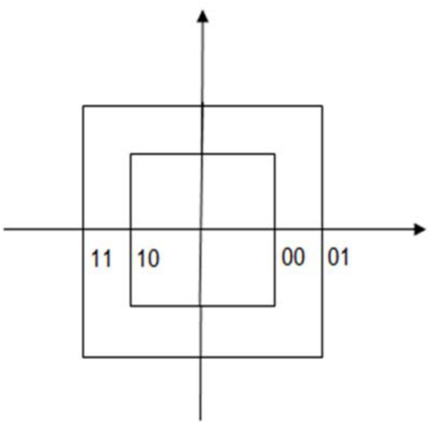

FIGURE 3. Quaternary constellation diagram.

Figure 3 shows the quaternary constellation diagram, where each frame represents a state (amplitude) and each axis represents two states (positive values are assigned to one state and negative values to the other one). Table 1 represents the truth table of the Quaternary quadrature amplitude modulation.

TABLE 1. 4-QAM truth table.

PSK	*ASK*	*Overall*
0	0	presented in Figure 3
	1	presented in Figure 3
1	0	presented in Figure 3
	1	presented in Figure 3

IV. PROPOSED SCHEME

Available solutions that convert a binary interconnecting link into a quaternary one are composed of two main modules: a binary-to-quaternary modulator and a quaternary-to-binary demodulator. The conversion scheme of the link is illustrated in Figure 4 and the WSN architecture (that can be used for mobile healthcare applications) is shown in Figure 5 [23].

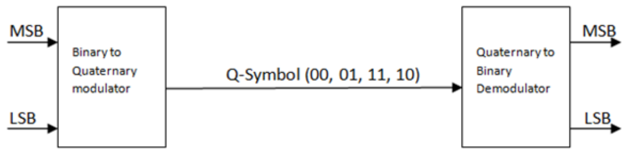

FIGURE 4. Structure of proposed link.

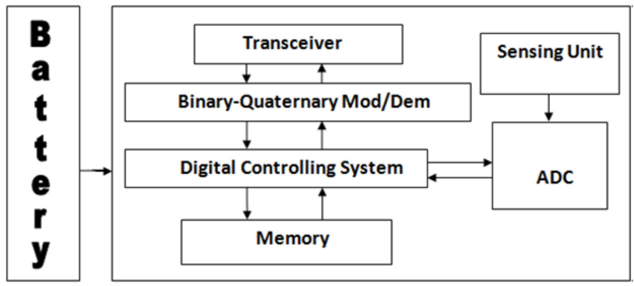

FIGURE 5. Wireless sensor network architecture with the quaternary transceiver.

The design of the modulator used in the scheme is shown in Figure 6. This circuit converts a two-bit binary symbol to a quaternary symbol. The outputs of a SN are the binary inputs to the modulator, where each modulator has two input bits (least significant (LSB) and most significant (MSB)) in addition to one output named Q0, which is the quaternary symbol to be transmitted over the network between SNs, from a SN to a BS, then from the BS to the server.

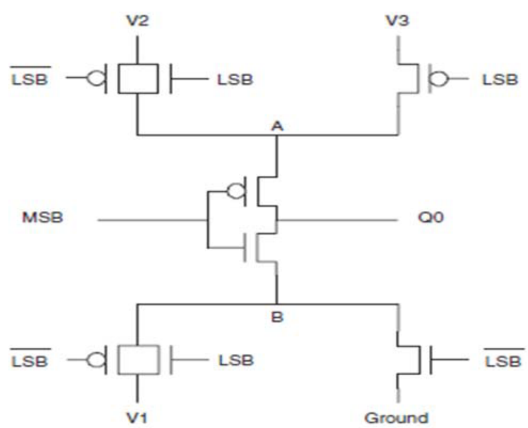

FIGURE 6. Binary to quaternary modulator design [19].

TABLE 2. Binary to quaternary modulating.

MSB	*LSB*	*Q0*
0	0	3 (V3)
0	1	2 (V2)
1	1	1 (V1)
1	0	Ground

The coding scheme is presented in Table 2, where 0, 1, 2 and 3 (Ground, v1, v2, v3) are considered to be the four logic levels to be transmitted using the proposed quaternary link.

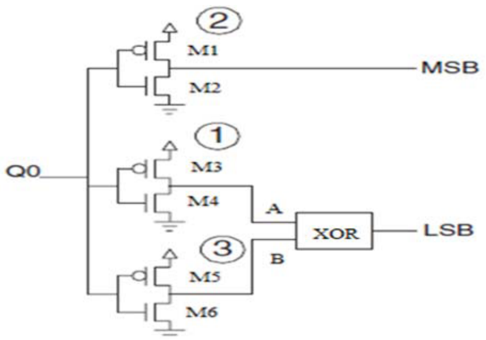

FIGURE 7. Quaternary to binary demodulator design [19].

The quaternary symbol transmitted from the source SN (generated by modulator) to the destination is received by the demodulator. The outputs of the demodulator are the inputs of the BS.

Figure 7 represents the quaternary to binary demodulator used in our design. It is composed of three modified inverters whose inputs are the quaternary symbols. The quaternary to binary demodulator is composed of 12 transistors using the same power supply as the modulator [22].

Q0 quaternary signals drive the inverters, which in turn permits the isolation of the four quaternary digits used to reconstruct the binary symbol originally sent by the source SN.

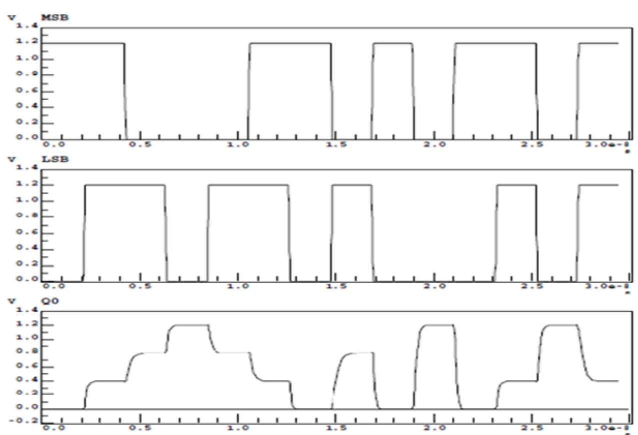

FIGURE 8. Binary to quaternary modulator simulation.

V. PERFORMANCE OF QUATERNARY TRANSMISSION

The feasibility of the proposed architecture is assessed through simulation using the SPICE simulator for the hardware parts. Simulation results of the binary to quaternary modulator of Figure 6 are presented in Figure 8, and the quaternary to binary demodulator of figure 7 are shown in Figure 9. Furthermore, the Matlab simulation results of the proposed quaternary architecture are illustrated in Figure 10. It clearly demonstrates the reduction in power consumption of a SN by approximately 41% compared to the binary systems.

A comparison of the proposed quaternary link scheme with the binary ones (bits are chosen randomly) to measure the

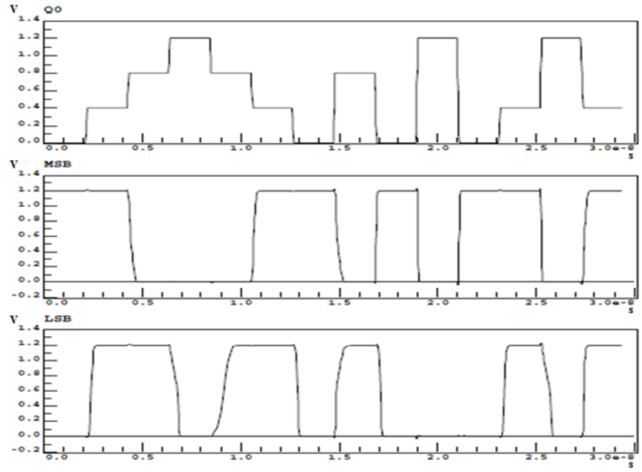

FIGURE 9. Quaternary to binary demodulator simulation.

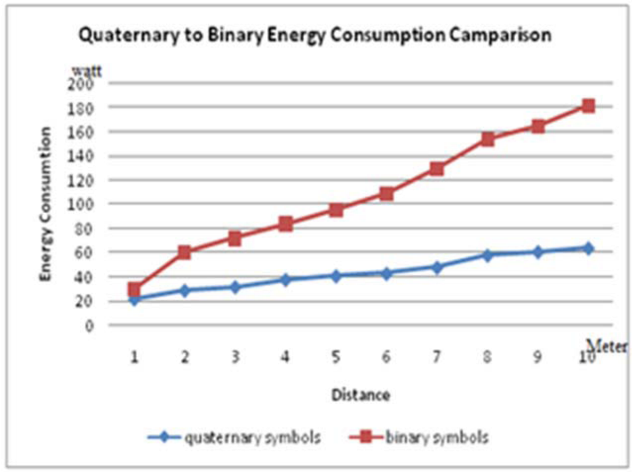

FIGURE 10. Energy consumption comparison between binary and quaternary transmitted symbols.

energy consumption led to the result that the link is saving 41%. Moreover, probability of error is less in quaternary systems than in binary systems due to the use of both amplitude and phase shifting modulation.

VI. NEURAL NETWORK SRAM

The temporary storage of information in an SN is a main source of power consumption in a WSN system. Neural network storage units (NN-SRAM) instead of conventional temporary storage in an SN will lower the power consumption and expand its life span.

The basic structure of a NN-SRAM cell is presented in Figure 11, where a binary data storage neural network can be constructed using the basic artificial neuron [24], [25]. Three nodes are used in the design of the NN-SRAM cell where each node can be implemented by a transistor. Thus, NN-SRAM cells can be implemented using three transistors, whereas the conventional SRAM is implemented using 4 to 6 transistors.

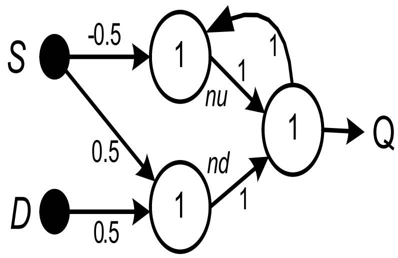

FIGURE 11. Basic structure of NN-SRAM cell.

Since there are two artificial neural network nodes that can work in parallel in NN-SRAM, the response time is less than that of conventional SRAM, making it faster. The inputs of NN-SRAM are enabled by a select control signal (S). If select equals 0, the stored content is held, and if select equals 1, the stored content is determined by the values of D (Data Input).

TABLE 3. Truth table for NN-SRAM.

Q	*S*	*D*	*nd*	*nu*	*Next Q*	*Action*
0	0	0	0	0	Hold	N.C.
1	0	0	0	1	Hold	N.C.
0	0	1	0	0	Hold	N.C.
1	0	1	0	1	Hold	N.C.
0	1	0	0	0	D to Q	Reset
1	1	0	0	0	D to Q	Reset
0	1	1	1	0	D to Q	Set
1	1	1	1	0	D to Q	Set

The overall operations are summarized in Table 3. D is sampled if S = 1. If D is 1, then Q output will be 1, putting the NN-SRAM in the set state. If D is 0, then Q will be 0, putting the NN-SRAM in the reset state. NN-SRAM latch has the ability to hold data as a storage unit.

The binary information present at the data input D is transmitted to the Q output when the control input S is enabled. Output Q follows changes in the data input, as long as the select control input is enabled.

If the select (S) is disabled, the binary information that is present in input D cannot be latched and Q output will retain its value until the select control input is enabled again.

Figure 12 shows the logic model of the NN-SRAM cell with the associated network to control the operations (Select, Read/Write, and Input/output). The latch inputs are enabled by a select signal (S). For S=0, the stored content is held. For S=1, the stored content is determined by R'/W (Read/Write).

The 4 × 4 NN-SRAM presented in Figure 13 consists of 4 rows and 4 columns, thus forming a matrix of 16 cells in which each NN-SRAM cell is the main storage element in the internal structure of an m × n NN-SRAM chip (m and n are the dimensions of the storage unit in rows and columns).

The loading of the NN-SRAM is controlled by a Row select input RSi (Figure 13).

If RSi = 0, the cell latch contents remain unchanged.

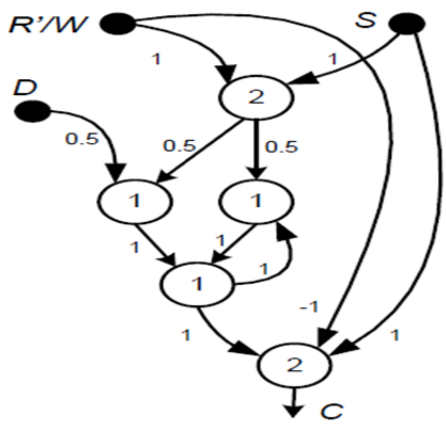

FIGURE 12. Logic model of the NN-SRAM cell with the associated circuitry.

If RSi = 1, the values to be loaded into the latches are controlled by data input D. To change the stored value, the read/write signal R'/W must be 1 and the selected RSi must be 1.

If data in D is 1, the latch is set to 1, and if D is 0, the latch is reset to 0, completing the write operation. In a read operation, R'/W must be 0 and RSi must be 1. If the stored value is 1, then the output C is set to 1. If the stored value is 0, then the output C is reset to 0, completing the read operation.

TABLE 4. Operation for controlled m × n NN-SRAM cell.

S	R'/W	Memory	Operation
0	0	N.C	hold
0	1	N.C	hold
1	0	read	Q to C
1	1	write	D to Q

Table 4 summarizes the operation for a controlled m × n NN-SRAM cell. Figure 14 presents the simulation results of an NN-SRAM cell and Figure 15 shows the final architecture of the sensor node.

VII. NN-SRAM-CBEES ROUTING PROTOCOL

Low Energy Adaptive Clustering Hierarchy (LEACH) is a protocol that was proposed to reduce the power consumption of a WSN [26], [27]. The transmitted data in a LEACH protocol contains only meaningful data. The clustering approach used in the LEACH protocol divides the entire WSN into a group of clusters, with each cluster having a CH [24]. CHs then communicate with each other and transfer the available data to a BS which communicates with the server. Such a protocol reduces the amount of transmitted data because each CH checks the data for duplication before it is received. If the data was received before, the CH eliminates it. Otherwise, it will be accepted.

For the CH to check if data was received, it needs a temporary storage, which consumes a high percentage of the available power. Neural networks are characterized by fault tolerance, because they are able to hold incomplete and

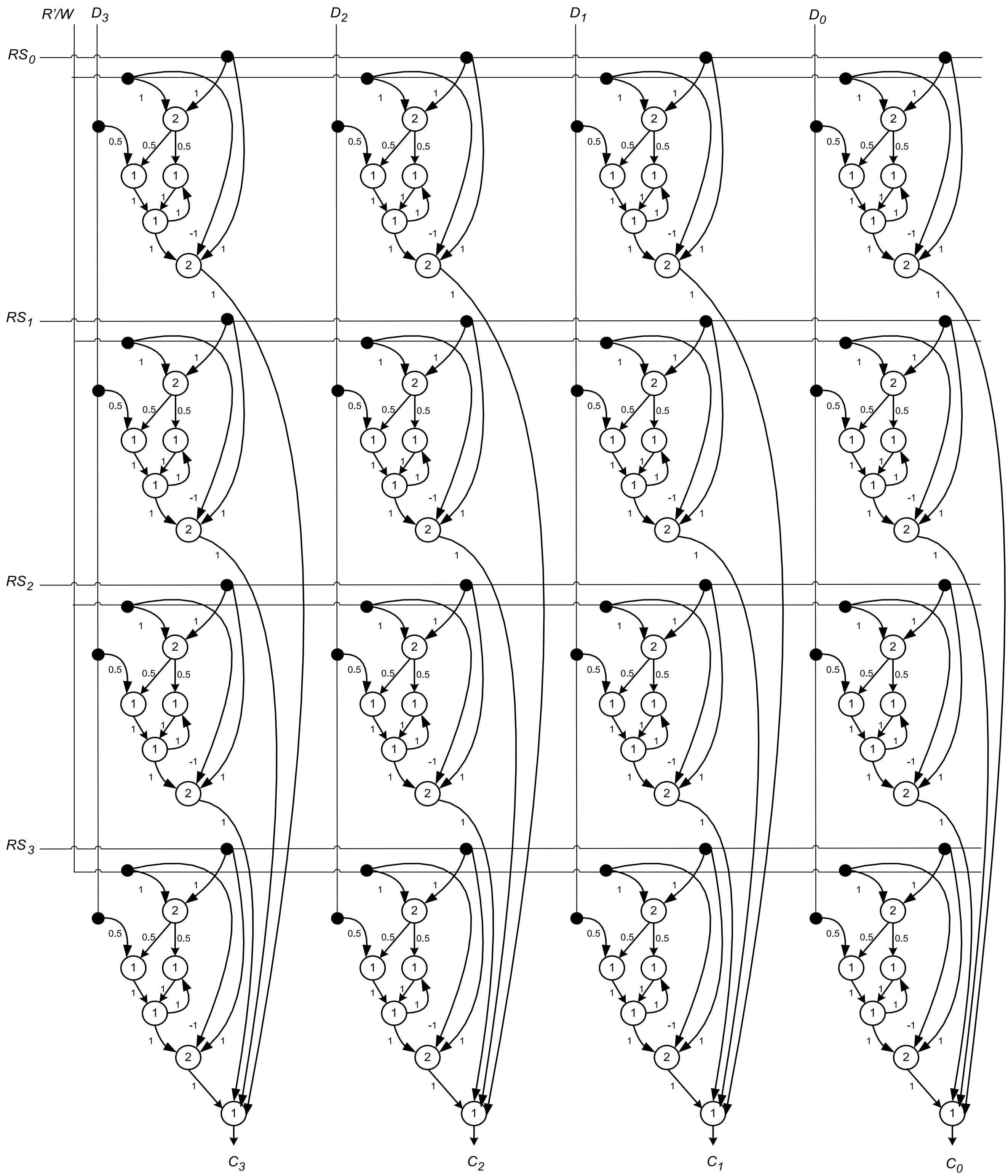

FIGURE 13. **A state diagram of a 4 × 4 NN-SRAM.**

noisy data [23], in addition to their ability to solve non-linear problems and, once trained, to perform prediction at high speed. Consequently, NN-SRAM has proven to be less power consuming than conventional RAMs.

Errors reported in these models are well within the acceptable limits. This suggests that artificial neural networks can be used for modeling in areas concerned with decreasing energy consumption.

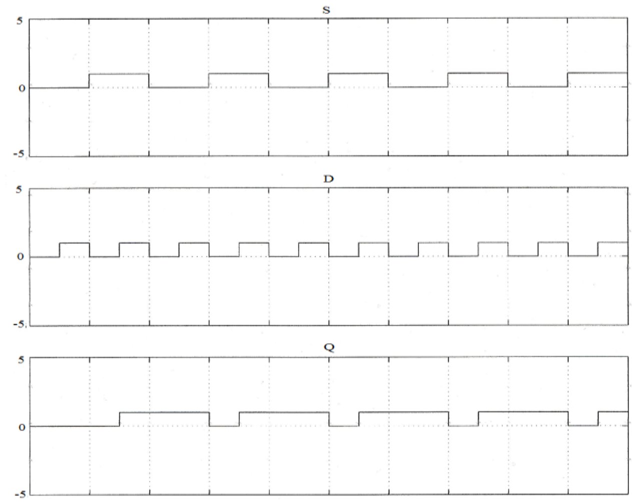

FIGURE 14. Simulation result of the NN-SRAM cell.

The key tasks performed by the NN-SRAM Clustering-Based Energy efficient system (NN-SRAM-CBEES) for WSNs are [28]–[31]:

- An NN-SRAM is used instead of conventional RAM in all SNs,
- Randomized rotation of CHs inside the corresponding clusters of each one,
- Localization, operation and control of each cluster during setup phase,
- Low power consuming MAC,
- The applications specified for data processing.

CHs are chosen stochastically [32]–[34] in the NN-SRAM-CBEES system, where the overall functioning state is divided into rounds, each of which consists of two main phases:

a) A setup state consisting of:
   - Division of the overall WSN into clusters,
   - Choice of CHs and their announcements,
   - Transmission/reception schedules formation.

b) A steady state consisting of:
   - Aggregation of data at the CH,
   - Compression of data,
   - Transmission to the BS.

The power consumption in neural network static random access memory with clustering based energy efficient systems for WSNs will be reduced by the reduction of the storage cost due to the use of neural networks and the reduction of the transmission/reception cost between the SNs and their CHs. The non-CH SNs must be turned off as much as possible.

VIII. PERFORMANCE AND SIMULATIONS

We use a WSN size of 200 m $\times$ 200 m, by taking 200 nodes, while the BS is located outside the network. This size can represent a hospital, a rehabilitation center or a fitness center where the WSN are distributed randomly. The processing delay is 82 μs, and the radio speed is 1 Mbps.

Three systems were simulated using Matlab software tool running on a Core i5 platform (Figure 16). The first system

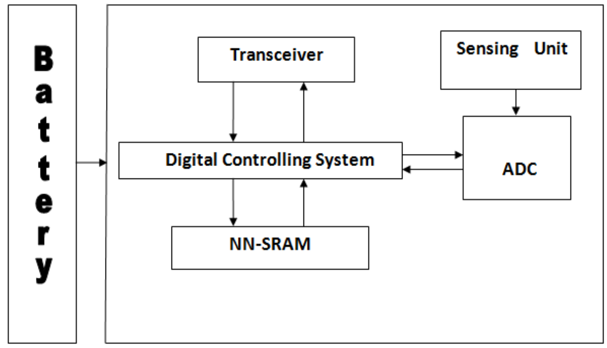

FIGURE 15. Final Sensor node architecture.

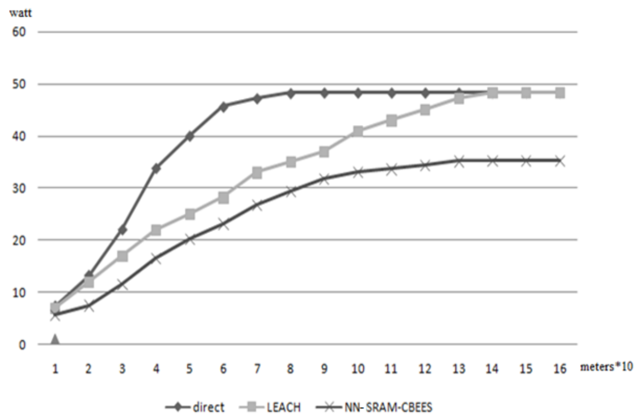

FIGURE 16. Energy consumption comparisons.

direct communication, the second system uses LEACH protocol, and the third uses NN-SRAM-CBEES. NN-SRAM-CBEES proved to be consuming 76.99% of the power consumed by LEACH and 64.2% of that used by direct communication.

IX. CONCLUSION

Two advanced energy-efficient architecture systems were proposed to prolong the lifetime of a wireless sensor network used in mobile healthcare applications. A new quaternary interconnect scheme was presented. The scheme modifies the transmission of data in a WSN from binary symbols to quaternary ones. Upon transmission, each two bits are modulated as one symbol, and upon reception the symbol will be demodulated producing the original binary bits. This scheme has been simulated with SPICE, and the simulation results have shown that it can increase the life span of a WSN. The increase in life span is due to the decrease in the symbol rate for the same transmission rate. The savings in power consumption has been found to be 41% compared to binary transmission signaling schemes, thus consuming 59% of the original binary scheme.

Moreover, the energy consumption in NN-SRAM-CBEES for WSNs is reduced by the reduction of the storage costs due to neural networks and the reduction of the transmission/reception costs between the SNs and their CHs.

A novel Neural Network Static RAM (NN-SRAM) that consists of internal latches to store the binary information was proposed. The NN-SRAM stores binary data and remains valid as long as power is supplied. Since the NN-SRAM reduces energy consumption, it is used in WSNs for extending its lifetime. Simulation results (using Matlab) shows that for wireless sensor network systems using neural network static random access memory instead of conventional temporary memory decreases the amount of power to 76.99% of the conventional one.

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