Performance Analysis of Hybrid Multiple Radio IoT Architecture for Ubiquitous Connectivity

Y. SivaKrishna, P. Rajalakshmi, Jagadish Bandaru, Ajay Kumar, M. P. R. Sai Kiran, M. A. Zubair, U. B. Desai
Department of Electrical Engineering, Indian Institute of Technology Hyderabad, India
Email: ee14resch11008, raji, ee15resch02010, ee15resch02002, ee12m1021, ee14mtech01003, ubdesai@iith.ac.in

Abstract—In this study, we propose a novel physical layer architecture which is a hybrid of IEEE 802.15.4 and IEEE 802.11b for providing ubiquitous connectivity in IoT remote sensing platforms. The proposed architecture multiplexes the commonly available functional units of IEEE 802.15.4 and IEEE 802.11b, thereby achieving significant area and power savings. In order to achieve this, we modified the existing PHY layer to incorporate QPSK and RC pulse shaping for both the radios during the process of modulation. Performance analysis shows that the proposed architecture resulted in an area savings of 17.2% and power savings of 17.8% compared to traditional architecture without any performance degradation. In addition the CMOS transistors count is reduced by 6592, which is a significant reduction in complexity when compared to traditional independent radio’s architectures.

I. INTRODUCTION

Over the past few years, Internet of Things (IoT) system architectures have experienced a rapid development. Primary expectation of any IoT application includes ubiquitous data aggregation which is not feasible with a single radio. Single radio architectures are constrained by multiple factors such as low range, high power consumption, low data rate etc. which can be avoided intelligently with the proposed hybrid architecture. The proposed hybrid architecture primarily aims in delivering the functionality of multiple radios (IEEE 802.15.4 and IEEE 802.11b in this case) with minimal power consumption and low form factor by multiplexing the commonly available functional units at the PHY layer.

For the proof of concept in this study, we selected two radios IEEE 802.15.4 (ZigBee) and IEEE 802.11b (Wi-Fi). ZigBee supports low data rate and low power while Wi-Fi supports high data rate and long range communication that aids for ubiquitous connectivity. Consider a scenario where in a remote patient monitoring application, a patient is dynamically changing his position with respect to time. In such scenarios, the probability of user crossing the range is definitely non zero. Ubiquitous connectivity in such scenarios can be achieved by communicating using Wi-Fi when user is out of ZigBee network’s range. Primary reason behind the selection of IEEE 802.15.4 and IEEE 802.11b is the presence of functional similarities between IEEE 802.15.4 and IEEE 802.11b such as carrier frequency, spreading mechanism, single carrier modulation and pulse shaping techniques. An on-chip controller is also present in the proposed architecture to intelligently control the usage among these multiple radios. The controller aids in context aware switching between the two radios based on the Received Signal Strength Indicator (RSSI) values. For the performance evaluation of the proposed architecture Bit Error Rate (BER), Error Vector Magnitude (EVM) and hardware complexity are considered as primary metrics. The proposed architecture delivered better EVM and acceptable BER values when compared to independent traditional architectures. In addition the area of SoC and power consumption are also reduced significantly.

The rest of the manuscript is arranged as follows. In section II we have briefly described the related work regarding multiple radio architectures. Section III discusses the functionality of IEEE 802.15.4 and IEEE 802.11b radios along with EVM and BER performances with different modulation techniques. The proposed multiplexed on-chip multiple radio architecture is presented in section IV. Section V describes the performance analysis of proposed architecture in comparison with traditional architectures. Finally, Section VI concludes the paper by summarizing the work.

II. RELATED WORK

IEEE 802.15.4 and IEEE 802.11b merely serve contrary applications in terms of their range and data rate support. IEEE 802.15.4 targets low range and low data rate communications with low power consumption and has found wide applications in Wireless Sensor Networks (WSNs) and Body Area Networks (BANs) [1]-[3]. Although IEEE 802.11b supports high range and high data rate, it consumes high power which makes it a non feasible solution on battery powered devices. For detailed description on IEEE 802.11b and IEEE 802.15.4 one can refer to [1] and [4] respectively. The interest in selecting these two radios are

- ZigBee supports low range with low power consumption whereas Wi-Fi supports high range with high power consumption. Hence if the user is in range of ZigBee network, the communication can occur at low cost and at the same time if user crosses the range, the connectivity can be guaranteed.
- Depending on the network traffic density, appropriate radio can be selected.

In addition to the above mentioned advantages, due to the same channel being used by the aforementioned radios there may be possible interference. This problem of interference is a well investigated subject in the literature and many solutions...
are also proposed. In [5] authors discussed an interference avoidance algorithm between Zigbee and Wi-Fi which can detect interference and switch nodes to safe channel. In [6], authors have proposed Wi-fi and Zigbee combined gateway for a smart home applications.

In recent years many researchers have tried to achieve ubiquitous connectivity by integrating multiple radios on a single system on chip (SoC). There are some commercially available products which have multiple radios on a single chip. RS 9117 is one such product in which IEEE 802.11n and Bluetooth LE radios are resided on a single chip [7]. The IEEE Standard 1905.1-2013 [8] defines an abstraction layer without architectural optimization of different radios at physical and MAC layers. In all the above mentioned technologies, design doesn’t involve any architectural optimization at the PHY layer.

III. FUNCTIONALITY AND PERFORMANCE ANALYSIS OF IEEE 802.15.4 AND IEEE 802.11b

In this section, we briefly describe the functionality and performance of Zigbee and Wi-Fi architectures. The BER and EVM performances of both architectures are analysed with QPSK, OQPSK and DQPSK modulation schemes.

A. IEEE 802.15.4-PHY Architecture

The physical layer architecture of IEEE 802.15.4 involves modulation of the digital message signal along with performance enhancement techniques. The DSSS spreading and Half Sine (HS) pulse shaping are used to enhance the performance of data transmission. Zigbee’s power consumption primarily depends on the duty cycle with which it operates which makes Zigbee a widely used device in the field of WSNs and BANs. Fig. 1 shows the traditional architecture of IEEE 802.15.4-PHY with HS pulse shaping and OQPSK modulation. Every four bits are mapped as one symbol before spreading the data. The performance of spreading technique depends on the randomness of the generated sequences. The Zigbee standard uses predefined chip sequences for spreading the data. The Zigbee is well researched standard and the detailed explanation is presented in [9].

1) Performance Analysis: The performance of IEEE 802.15.4-PHY is analyzed in combination of three different modulation techniques (QPSK, OQPSK and DQPSK) and two pulse shaping techniques (HS and RC). The parameters like BER and EVM are considered as key performance metrics.

Both BER and EVM values are affected by type of modulation and pulse shaping employed in the architecture. The BER performance comparison of IEEE 802.15.4 with different modulation and pulse shaping techniques are presented in Fig. 2. The simulation results shown in Fig. 2 shows that, the performance of OQPSK modulation is dominating the performance of other two modulation techniques. The performance with DQPSK modulation is 3 dB less than that of QPSK. But the advantage of DQPSK modulation is, it avoids carrier synchronization at receiver. The EVM performances are compared and presented in Fig. 3. The procedure for calculation of EVM is discussed in detail in following sections. From Fig.3, QPSK modulation with RC pulse shaping is having minimum value of EVM for all SNRs. Zigbee standard suggests a minimum value of 30% EVM, which is obtained at SNR 4 dB with QPSK modulation which means a minimum SNR of 4 dB has to be maintained for quality operation. From Fig. 2 and Fig. 3, QPSK modulation with RC pulse shaping has less EVM and acceptable BER values.

B. IEEE 802.11b-PHY Architecture

IEEE 802.11b is the most popular wireless networking standard operating in 2.4GHz ISM band which makes use of DQPSK modulation along with CCK spreading at a data rate of 11 Mbps. Fig. 4 shows the physical layer architecture of IEEE 802.11b. Each of the eight bits are mapped as one symbol before spreading the message. The 11 bit Barker
sequence spreading used in previous standards is incapable of proving data rates greater than 2Mbps. To get higher data rates, equation (1) shown below is used to generate 64 eight bit spreading sequences which have unique mathematical properties and supports data rate up to 11 Mbps.

\[
CW = \{e^{j(\phi_1+\phi_2+\phi_3+\phi_4)} e^{j(\phi_3+\phi_3+\phi_4)} \} - e^{j(\phi_1+\phi_4)} e^{j(\phi_1+\phi_2+\phi_3)} e^{j(\phi_3+\phi_1)} - e^{j(\phi_1+\phi_2)} e^{j(\phi_1)}
\]

where CW is code word and the parameters $\phi_1 - \phi_4$ determine the phase values of complex code set from data bits being spread. The advantage of using RC pulse shaping is to provide data transmission over band limited channels. For better spectral efficiency, a filter of order 64 with roll off factor 0.3 is considered in this paper. For further information on IEEE 802.11b one can refer to [4].

1) **Performance Analysis:** The performance of Wi-Fi is analyzed with three different modulation techniques with RC pulse shaping. Fig. 5 shows the BER performance with QPSK, OQPSK and DQPSK modulation techniques. From Fig. 5, it is clear that OQPSK modulation is dominating the performances compared to other two modulation techniques. But, the performance of QPSK is almost same as that of OQPSK at lower values of SNRs and there is slight degradation at high values of SNRs. The EVM performances are presented in Fig. 6. For IEEE 802.11b, the suggested minimum required EVM is 35% and in order to achieve that a minimum SNR of 15 dB has to be maintained for quality performance. From comparisons of BER and EVM values QPSK modulation has least EVM values along with better BER performance.

IV. PROPOSED HYBRID ON-chip MULTIPLE RADIO ARCHITECTURE

Aiming at ubiquitous connectivity with small form factor, authors in [10] proposed an on-chip seamless handoff mechanism which aids for ubiquitous connectivity using multiple radios targeting remote health monitoring applications. The proposed on-chip controller does intelligently select the radio depending on the context. As the performance of the on-chip controller is out of scope of this study, for more information readers are suggested to refer [10]. The architecture proposed in this study considers IEEE 802.15.4-PHY and IEEE 802.11b-PHY but not limited to and can be applied to any scenario where the similar functional units are available. Due to presence of functional similarities such as direct sequence spreading, single carrier modulation and pulse shaping, we selected ZigBee and Wi-Fi for our study. In addition IEEE 802.15.4 and IEEE 802.11b can definitely aid in achieving ubiquitous connectivity. Fig. 7 shows the proposed on-chip multiple radio architecture for ubiquitous connectivity. The type of modulation and pulse shaping technique to be used in proposed architecture is decided from the performance analysis presented in the previous section. From the performance analysis of IEEE 802.15.4 and IEEE 802.11b provided in earlier section, QPSK modulation with RC pulse shaping can suffice better performance in terms of EVM and BER for both. The BER performance of OQPSK is better than QPSK but, the EVM values of OQPSK are very high compared to QPSK. So, QPSK modulation along with RC pulse shaping is selected for proposed hybrid architecture.

Proposed architecture also aims at reducing hardware complexity by multiplexing common hardware functional units present in both radios. In Fig. 8, the Spartan 3E FPGA based hardware prototype developed in IIT Hyderabad for complexity analysis is provided. The detailed complexity analysis of individual radios along with reduced complexity in proposed hybrid architecture is explained in section V.

V. PERFORMANCE AND HARDWARE COMPLEXITY ANALYSIS OF PROPOSED HYBRID ARCHITECTURE

In this section we analyze the BER and EVM performances of proposed hybrid on-chip multiple radio architecture with QPSK modulation and RC pulse shaping followed by hardware complexity analysis. The amount of area and power
V is normalized error vector magnitude over N samples and where I and Q samples. The steps involved in EVM calculation by finding the normalized error vector magnitude for received I and Q samples calculated over N number of samples respectively.

A. EVM performance analysis

From the EVM performance analysis of individual radio architectures shown in Fig. 3 and Fig. 6, it is clear that QPSK modulation has better performance in both radios compared to other two modulation techniques. The EVM is calculated by finding the normalized error vector magnitude for received I and Q samples. The steps involved in EVM calculation for N samples are shown in following equations (2)-(5).

\[ I_{\text{mean}} = \frac{\sum_{n=0}^{N-1} I(n)}{N} \]
\[ Q_{\text{mean}} = \frac{\sum_{n=0}^{N-1} Q(n)}{N} \]
\[ I_{\text{dc}}(n) = I(n) - I_{\text{mean}} \]
\[ Q_{\text{dc}}(n) = Q(n) - Q_{\text{mean}} \]
\[ I_{\text{mag}} = \sum_{n=0}^{N-1} | I_{\text{dc}}(n) | / N \]
\[ Q_{\text{mag}} = \sum_{n=0}^{N-1} | Q_{\text{dc}}(n) | / N \]
\[ V_{\text{err}}(n) = \frac{1}{2} \times (\{ | I_{\text{dc}}(n) | - I_{\text{mag}} \}^2 + \{ | Q_{\text{dc}}(n) | - Q_{\text{mag}} \}^2) - V_{\text{corrected}} \]

Where \( I_{\text{mean}}, Q_{\text{mean}}, I_{\text{dc}}, Q_{\text{dc}} \) are mean and DC values of I, Q samples calculated over N number of samples respectively. \( I_{\text{mag}}, Q_{\text{mag}} \) are error magnitudes of I and Q samples. \( V_{\text{err}} \) is normalized error vector magnitude over N samples and \( V_{\text{corrected}} \) is the error induced by the reference receiver signal. The EVM performance comparison of hybrid architecture with traditional IEEE 802.15.4 and IEEE 802.11b architectures are presented in Fig. 9 and Fig. 10. From the analysis, multiplexed architecture is having less values of EVM in both radios. The performance improvement is very high in case of IEEE 802.15.4 and comparatively a significant improvement is also present in IEEE 802.11b.

B. BER performance analysis

From the performance analysis of individual radio architectures shown in Fig. 2 and Fig. 5, OQPSK and RC pulse shaping has better performance than other two modulation techniques whereas QPSK modulation also has very near performance to OQPSK and also it has very low values of EVM. Hence, QPSK is employed in proposed architecture and corresponding BER performances are compared with traditional IEEE 802.15.4 and IEEE 802.11b radios as shown in Fig. 11 and Fig. 12 respectively. It is observed that, there is around 3 dB improvement in BER at high values of SNRs for IEEE 802.11b but, for IEEE 802.15.4 there is 1 dB performance loss compared to traditional architecture which is negligible as there is a significant EVM improvement in this case.

C. Hardware Complexity Analysis

Hardware complexity is calculated by transforming the entire architecture to logic gates. Authors in [11]-[14] presented specific ways to analyse the hardware complexity by calculating the number of logic gates and transistors required for physical implementation of each building block present in the architecture.
1) IEEE 802.15.4 and IEEE 802.11b: The hardware architecture of IEEE 802.15.4-PHY is shown in Fig. 13 and requires two parallel to serial converters (32 bit and 2 bit), two serial to parallel converters (32 bit and 2 bit), two 4 bit shift registers and chip to symbol mapping. The two shift registers are used to convert serial binary data into a 4 bit symbol and vice versa. Each symbol is mapped onto 16 in phase and 16 quadrature phase parallel chip sequences using symbol to chip mapping. Then 32 bit parallel to serial converter (PSC) is used to serialize chip sequences from which in phase and quadrature phase samples (I and Q samples) are separated by a 2 bit serial to parallel converter (SPC). These I and Q samples are received at receiver and the respective demodulation followed by decoding is performed using corresponding functional units. TABLE I shows the total number of logic gates and CMOS transistors required to implement IEEE 802.15.4-PHY. From the analysis it is observed that Zigbee is low complex in terms of logic gates and CMOS transistors. The reduced complexity is due to single modulation and pulse shaping for both Zigbee and Wi-Fi which avoids use of DQPSK and HS pulse shaping techniques presented in traditional architectures.

Fig. 13: Hardware architecture of IEEE 802.15.4-PHY

### TABLE I: Hardware complexity of IEEE 802.15.4-PHY in number of logic gates

<table>
<thead>
<tr>
<th>Type of Gate/Block</th>
<th>NAND</th>
<th>AND</th>
<th>OR</th>
<th>XOR</th>
<th>NOT</th>
<th>XNOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three SPC(2, 8, 32 bit)</td>
<td>822</td>
<td>66</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>CCK implementation</td>
<td>576</td>
<td>100</td>
<td>12</td>
<td>40</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Three PSC(2, 8, 32 bit)</td>
<td>442</td>
<td>226</td>
<td>42</td>
<td>0</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>RC pulse shaping</td>
<td>0</td>
<td>24848</td>
<td>8264</td>
<td>16528</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total gates count</td>
<td>1840</td>
<td>25240</td>
<td>8318</td>
<td>16568</td>
<td>26</td>
<td>44</td>
</tr>
<tr>
<td>No of CMOS Transistors</td>
<td>7360</td>
<td>151440</td>
<td>49908</td>
<td>99408</td>
<td>52</td>
<td>352</td>
</tr>
</tbody>
</table>
TABLE III: Reduced hardware complexity in multiplexed architecture

<table>
<thead>
<tr>
<th>Type of logic gate</th>
<th>No. of logic gates</th>
<th>No. of CMOS Transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAND</td>
<td>1200</td>
<td>4000</td>
</tr>
<tr>
<td>AND</td>
<td>224</td>
<td>1344</td>
</tr>
<tr>
<td>OR</td>
<td>32</td>
<td>192</td>
</tr>
<tr>
<td>XOR</td>
<td>32</td>
<td>256</td>
</tr>
</tbody>
</table>

TABLE IV: Comparison of Power consumption and Area of different radio architectures

<table>
<thead>
<tr>
<th>Name of Architecture</th>
<th>Power Consumption ($\mu$W)</th>
<th>Area ($\mu$m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigbee</td>
<td>99.44</td>
<td>41218.5998</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>105.8</td>
<td>13390.2399</td>
</tr>
<tr>
<td>Multiple Radio Architecture</td>
<td>205.24</td>
<td>55148.7997</td>
</tr>
<tr>
<td>Proposed Multiplexed Architecture</td>
<td>168.64</td>
<td>45623.0397</td>
</tr>
</tbody>
</table>

Fig. 15: Hardware architecture of proposed multiplexed architecture

VI. CONCLUSION

In this paper, we proposed a novel hybrid on-chip multiple radio architecture which reduces the size of node and amount of power consumption. For performance analysis we considered IEEE 802.15.4 and IEEE 802.11b for multiplexed architecture. The BER and EVM performances of individual ZigBee and Wi-Fi with three different modulation techniques (QPSK, DQPSK and OQPSK) are analyzed and compared with standard results. The QPSK modulation with RC pulse shaping has less EVM values and acceptable BER values in both radios compared to other two modulation techniques. The BER and EVM performances of proposed architecture with QPSK modulation and RC pulse shaping are compared with traditional architectures. The hardware complexity analysis proves that a reduction of 6592 CMOS transistors is achieved due to the proposed architecture. The amount of power and area required are also computed by using Synopsys Design Compiler. From this analysis, proposed architecture achieved 17.2% of area savings and 17.8% of power savings by multiplexing the common functional units. We believe that our work can have a significant impact in realization of ubiquitous connectivity and convergence of networks.

REFERENCES