An Enhanced Version of IEEE 802.15.4 Standard Compliant Transceiver Supporting Variable Data Rate

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***Abstract*—In Industrial Wireless Sensor Networks (IWSN), standard compliant state-of-the-art devices typically provide fixed data rate (for instance, IEEE 802.15.4 based devices has a 250kbps with fixed Bandwidth (BW) of 2MHz in 2.4GHz.). The fixed BW restricts these devices from presenting their optimal performance in a continuously varying radio spectrum environment, i.e., narrow-band modes fit best in a crowded spectrum, whereas wide-band modes perform better for low latency scenario). The flexible feature of a Software Defined Radio (SDR) allows us to propose a communication system capable of operating in both standard BW and non-standard BW modes with the same hardware accelerator. In this work, IEEE 802.15.4 compliant SDR transceiver is introduced, where flexible Medium Access Control (MAC) and Physical (PHY) layers are implemented in Time-Annotated Instruction Set Computer (TAISC) and FPGA, respectively. This unique introduction of flexibility at both layers enables our solution to operate in multiple modes which can be categorized into the three subtypes depending on the signal bandwidth, i.e. Narrow-Band (NB), standard compliant, and Wide-Band (WB). The multi-band feature enables the solution to work efficiently in a diverse radio spectrum environment. Experimental results unveil that our transceiver provides receiver sensitivity of -107dBm, -98dBm, and -90dBm when it is configured in NB, standard and, WB modes respectively.**

Keywords—SDR; IEEE 802.15.4; Flexible Data Rate; Configurable Bandwidth; Low Latency Communication

I. INTRODUCTION AND MOTIVATION

Wireless Sensor Networks (WSN) has been increasingly used in a wide range of applications, including health care monitoring, area monitoring, home automation, and water quality monitoring. General requirements of a WSN include small form factor, low cost, power efficiency, self-healing, scalability, and robustness. Industrial WSN (IWSN) is an industrial application of WSN which requires additional requirements of link reliability, deterministic latency, and resistance to noise. Zigbee, WirelessHART, and ISA 100.11a protocols, which are specially designed for IWSN applications, are based on IEEE 802.15.4 standard [1]. The standard defines Media Access Control (MAC) and Physical (PHY) layers specifications, which imply that all these protocols have the same MAC and PHY layers. In contrast to the upper layers, MAC and PHY layers are generally implemented in hardware which limits the flexibility, adversely affecting the performance of a communication system. For instance, the fixed data rate (i.e., 250kbps with a Bandwidth (BW) of 2MHz) of IEEE standard in 2.4GHz band prevents a wireless device from obtaining desired performance (e.g., link reliability) in a continuously changing Radio Frequency (RF) environment. This is because 2.4 GHz ISM band is generally heavily occupied, fixed BW limits the capability for a device to take advantage of leftover spectrum or time gap in real time communication.

Software Defined Radio (SDR) is a newly introduced technology that enhances the flexibility of a communication system by implementing the MAC and PHY layers in software. Flexible characteristic of an SDR motivates us to implement an enhanced version of IEEE 802.15.4 standard that has flexible data rate and respective BW. Data rate refers to throughput in PHY layer, while BW refers to the signal's bandwidth in RF channel. This flexible data rate feature together with a channel sensing mechanism drives our solution to seamlessly change its BW according to spectrum availability, thus providing deterministic latency and reliability in a dynamic RF environment.

II. RELATED WORKS

There are many IEEE 802.15.4 based SDR solutions reported in the literature [2-4]. T. Schmid et al. has implemented the first SDR architecture for the Physical (PHY) layer of this standard, including dedicated Transmit (TX) and Receive (RX) chains [2]. This work has permitted researchers, for the first time, to access and explore the physical layer features of IEEE 802.15.4 standard. In [3], a communication stack from PHY up to network layer is implemented on GNU Radio and USRP N210. Although both of the above-mentioned SDR-based transceivers introduce considerable flexibility in the design, they provide fixed data rate i.e. 250 kbps. The authors in [4] go one-step further and propose an efficient system that incorporates three different data rates which are 20 kbps, 40 kbps, and 250 kbps. Though the design only allows the data rate to be configured according to its operating frequency band, for example, 250kbps data rate only works in 2.4GHz band. Another disadvantage of this architecture is that each data rate implementation requires a dedicated hardware implementation, consuming more FPGA resources.

In our work, we support not only variable data rates, but also utilize the same hardware for various data rate implementation; we do not have restrictions of data rate in different frequency bands.

III. Our Proposed Solution

Our IEEE 802.15.4 based transceiver is capable of runtime switching between standard compliant (i.e. 250 kbps) and non-standard modes (i.e. higher or lower than 250 kbps). The block diagram of the transceiver is represented in Fig. 1. The transceiver mainly consists of flexible MAC and PHY layers.

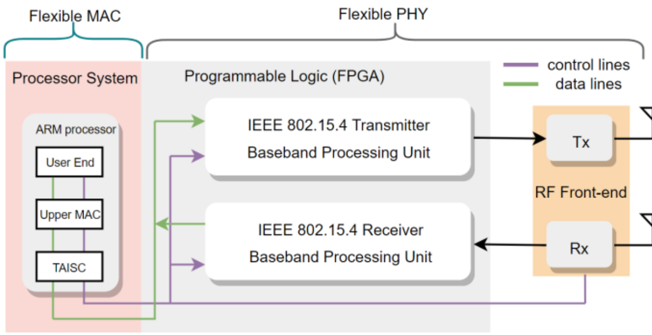

Fig. 1. Block Diagram of our Proposed Transceiver

A. *The Flexible PHY layer implementation*

Our PHY layer implementation contains independent TX and RX chains, with each chain consists of a flexible Baseband Processing Unit (BBP) and a configurable analog part. The SDR platform used in our setup is composed of Zynq-7000 All Programmable System on Chip (AP SoC) [5] and FMCOMMS2 board [6]. Zynq 7000 AP SoC is further comprised of Programmable Logic (PL) and Processor System (PS). Both BBPs are implemented in PL part, while FMCOMMS2 board is used as analog RF Frontend.

B. *Flexible MAC layer implementation*

The Time-Annotated Instruction Set Computer (TAISC) was developed, which is a cross-platform MAC protocol compiler and execution engine [7]. It divides the MAC layer into two distinct sub-layers: the lower and upper-MAC. The sub-processes running in lower-MAC are mostly hardware-dependent and time-critical (e.g. back-off time execution in CSMA, etc.). On the other hand, the upper-MAC is hardware-independent and less time-critical (e.g. scheduling of the super-frame in TDMA). TAISC introduces time-annotated radio instructions which the compiler utilizes to generate precise timing information. The execution engine later uses this timing information to schedule instructions. In this way, the engine ensures deterministic behavior of the lower-MAC. Full flexibility is offered by exposing a set of at runtime configurable parameters per MAC protocol. TAISC along with a complete network stack is running on ARM processor embedded in PS part of ZYNQ 7000.

IV. Experimental Results and Discussion

We claim that our PHY and MAC layers are flexible, which is achieved by exposing a rich set functions in radio drivers to upper layers. For example, a new radio function, namely set_data_rate(), is capable of changing the data rate on the fly.

Data rate directly influences the performance of our transceiver. Therefore, we have experimentally measured system performance under different data rates (see Table I). The performance metrics considered in our experimental setup are latency, coverage, and sensitivity.

TABLE I. Measured performance of our Transceiver in terms of coverage range, sensitivity and RTT

Parameters	**Standard Mode**	**Non Standard Mode**	
	Standard BW	***Narrowest BW***	***Widest BW***
Data Rate (kbps)	250	31.25	≈2000
Bandwidth (MHz)	2	0.25	≈16
BB Sampling Frequency (MHz)	8	1	61.44
Round Trip Time (RTT) (ms)	1.39	14.08	0.213
Sensitivity (dBm)	-98	-107	-90
Calculated Coverage Range (m)	123	347	49

V. Conclusive Remarks

We introduce an SDR based transceiver that can be configured in IEEE 802.15.4 compliant mode and non-standard modes (i.e., wider BW or Narrower BW) depending on the spectrum occupancy. Flexible feature of an SDR enables our transceiver to achieve the run-time data rate adaptation without utilization of any extra hardware. Narrow-BW mode of our transceiver outperforms the standard mode in terms of reliability in heavily occupied radio spectrum environment , or offers a better coverage range with a given transmit power, whereas wide-BW mode may provide relatively low latency communication link and higher throughput when more radio spectrum is available.

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