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Abstract

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Image Transmission over IEEE 802.15.4 and ZigBee Networks

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***Index Terms*— ZigBee, IEEE 802.15.4, JPEG, JPEG-2000, multi-hop, sensor network.**

I. INTRODUCTION

Until recently most wireless communication standards focused on high speed and long range and have been applied successfully for cellular and local area data networks. The ZigBee Alliance (www.zigbee.org) is a consortium of over 90 companies that is developing a wireless network standard for commercial and residential control and automation applications. The Alliance has recently released its specifications for a low data rate wireless network. The design goals for the network have been driven by the need for machine-to-machine communication of small simple control packet and sensor data and a desire to keep the cost of wireless transceivers to a minimum. Additionally, the network possesses self-organizing capability so that little or no network setup is required. Ideally, individual nodes should be battery powered with a long lifetime and should cost very little. The applications for such networks are numerous and include: Inventory management, product quality monitoring, factory process monitoring, disaster area monitoring, biometrics monitoring, and surveillance.

ZigBee networks are similar to Ad-hoc networks in the sense that the networks borrows heavily on the self-organizing and routing technologies developed by the ad-hoc research community. However, a major design objective for ZigBee networks is reducing the cost of each node. For many of the above applications the desired cost for a wirelessly enable device is less than one dollar.

While it is not a stated goal of the Alliance to support the transfer of images over the network, it is clearly a desirable capability especially for surveillance systems. Additionally, with the publication of the ZigBee standards it is expected that compliant transceivers will become readily available. This paper examines the use of ZigBee networks for image transmission. The paper is organized as follows: Section II gives a brief overview of the key features of ZigBee. Section III discusses some issues specific to image transmission over ZigBee networks. Section IV describes an experimental system built at MERL for the purpose of testing applications over ZigBee networks and modifications required to support image transmission. Section V discusses the results of the image transmission test and reports performance metrics such as delay, and throughput. We conclude the paper with observations and suggestions for future versions of ZigBee standards.

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II. OVERVIEW OF ZIGBEE

ZigBee is best described by referring to the 7-layer OSI model for layered communication systems. The Alliance specifies the bottom three layers (Physical, Data Link, and Network), as well an Application Programming Interface (API) that allows end developers the ability to design custom applications that use the services provided by the lower layers. Figure-1 shows the layered protocol architecture adopted by the alliance. It should be noted that the ZigBee Alliance chose to use an already existing data link and physical layers specification. These are the recently published IEEE 802.15.4 standards for low-rate personal area networks. We describe the key features of each layer in the following. Complete descriptions of the protocols used in ZigBee can be found in [3],[4], [5].

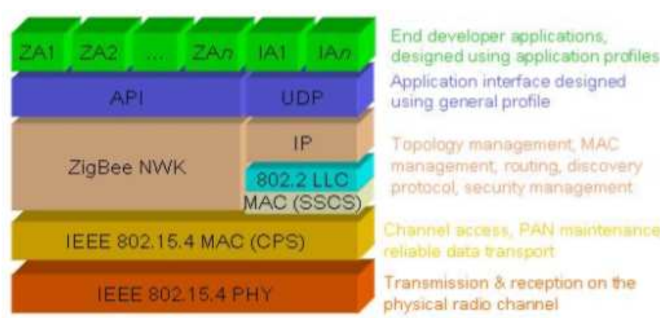

Fig. 1. Illustration of ZigBee stack

A. PHY Layer Features

The IEEE 802.15.4 standard [3]defines three frequency bands of operation: 868MHz, 916MHz and the 2.4GHZ bands. We will focus on the 2.4GHz bands as these are the most commonly available products at the moment and in addition this band offers the highest achievable data rate of 250Kbps at the physical layer. The 2450 MHz PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK). Essentially, this modulation format can be thought of as coded O-QPSK and is typically implemented with a table look-up for generating channel symbols which reduces transceiver cost.

Typical transmission distances have been reported and are within the range from 30 meters in an indoor non-line of sight environment to over 80 meters in a line of sight environment. We note here that clearly the bit rate is a limiting factor if applications require the transfer of large amounts of data among network devices.

B. Data Link Layer Features

The IEEE 802.15.4 is a light weight simple protocol that is based on CSMA (Channel Sense Multiple Access). Its responsibilities may also include transmitting beacon frames, synchronization and providing a reliable transmission mechanism. A key aspect of the data link layer is that individual packets are each acknowledged thus providing link level delivery guarantees. However, there are no quality of service guarantees or support for priority levels of network traffic. Essentially, ZigBee offers only best effort end-to-end delivery of individual packets.

C. Network Layer Features

The majority of the new technology development that has occurred within the ZigBee Alliance has been in the creation of the network layer. The responsibilities of the ZigBee network layer includes mechanisms used to join and leave a network, and to route frames to their intended destinations. The routing of course may involve using multiple intermediate relay devices within the network. In addition, the discovery and maintenance of routes between devices devolve to the network layer. Also the discovery of one-hop neighbors and the storing of pertinent neighbor information are done at the network layer.

III. Image Transmission over ZigBee

With the rapidly growing market for short range wireless communication systems, image based sensor networks is becoming important to support security, surveillance and inspection related applications. However, to design an efficient image communication system in wireless sensor networks, there still exist many challenges. Some are caused by resource limitations, such as power supply and processing capability, and some by adverse wireless channel conditions and the error resilience capability of image compression schemes.

Due to path loss, small and large fading, co-channel interference, and noise disturbances, the capacity of wireless channels is much lower than wired channels, and the bit error rate (BER) is much higher [1]. Furthermore, the throughput may fluctuate due to time varying characteristics of the wireless channels.

In this section, we adress inherent limitations of ZigBee technology for image transmission. We consider two image types: JPEG and JPEG-2000. Pros and cons of each image format over ZigBee networks are discussed.

A. Limitations of ZigBee

The 2.4GHz band provides the highest bit rate of 250Kbps in IEEE 802.15.4 PHY specs. The physical layer supports transfer of only small sized packets limited to 127 bytes. Due to overhead at the network, MAC and physical layers, each packet may contain no more than 89 bytes for application data. This leads to fragmentation of bit streams larger than 89 bytes. The networking layer does not perform fragmentation. Therefore, the fragmentation and reassembly should be handled at the application layer. A flow control mechanism is also needed to acknowledge and request retransmission of missing fragments above the network layer.

B. JPEG vs JPEG-2000

JPEG and JPEG-2000 differ in various aspects from compression efficiency and complexity to scalability. JPEG-2000 is a dyadic multi-resolution subband (wavelet) transform based still image compression standard and uses embedded arithmetic block coding with an optimized truncation algorithm [2], while JPEG is DCT based and uses Huffman coding. JPEG-2000 has higher source coding complexity, but its compression efficiency is better and it provides resolution and quality scalable bitstream. Figure 2 illustrates the hierarchical organization of quality layers, packets and code blocks within a JPEG-2000 image bitstream. The wavelet transform decom-

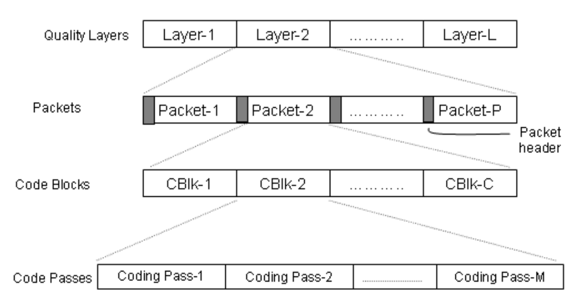

Fig. 2. Illustration of the quality layer progressive bit stream structure of JPEG-2000 encoded images

poses each image component into several resolution levels, each containing a series of subbands. After quantization, the coefficients in each subband are partitioned into regular arrays of code blocks for entropy coding. Each code block is entropy-coded independently using context adaptive arithmetic coding. Each bit-plane is coded with three passes, and each pass generates an embedded bitstream, called a coding pass, to provide a variable quality contribution to the reconstructed image. The selected coding passes are packetized into data packets, which are then assembled into final coding stream. Each packet consists of packet header and packet body. Figure

3 illustrates a subjective comparison of the two for an image at compression ratio of 1:128 with the original image size of 900KB. At low bit rates, JPEG-2000 can provide a better subjective image quality.

Simplicity of JPEG source coding makes it preferable in highly distributed sensor network applications in which every node is required to capture shots and send images to a central controller. On the other hand, if computational complexity of source coding is not a concern, tolerance to bit errors and packet losses may favor JPEG-2000. This is applicable to networks in which only a source and destination end nodes are required to encode and decode images, and intermediate nodes are only to relay. Ship inspection is a typical example.

Fig. 3. Illustration of the subjective quality comparison of JPEG-2000 (left) and JPEG (right) images. Original size of the image is 900KB, and the compression ratio is 1:128

IV. Experimental Setup

Our experimental testbed setup consists of 4 Zigbee compliant devices that have been developed according the current version of the standard specifications. In other words, implementations of the NWK, datalink and physical layers have been completed. In order to support image transfer, additional features have been added to the application that enables the fragmentation and reassembly of the compressed image files. One ZigBee device is connected to a general purpose PC via an RS-232 connection and acts as a gateway into the wireless portions of the testbed. The gateway allows the collection of various data from the network such as network topology, neighbor tables and route information. A simple application runs on the PC and issues requests for an image transfer from one of the devices in the network. In this system, images have been prestored on devices so that no actual image compression is needed at imaging sensors. The route that the packets traverse is also available to the gateway/PC data sink.

V. Results

We specify two performance metrics: number of bytes received in error per image and PSNR (Peak Signal to Noise Ratio) of received images. The first directly corresponds to the link status and link layer adversaries, and the latter is dependent on image compression efficiency and scalability. Assume that the pixel value of a transmitted image at location *(i,j)* is denoted as *T(i,j)*, and of the received image as *R(i,j)*. The mean square error of the received image with respect to the transmitted would be

$$e_{ms} = \frac{1}{MN} \sum_{i}^{N-1} \sum_{j}^{M-1} (T(i,j) - R(i,j))^2 \tag{1}$$

where M and N are the pixel dimensions of the image. Then, the PSNR of the received image is computes as

$$PSNR = 10log_{10}(\frac{255^2}{e_{ms}}) \tag{2}$$

Between two images exposed to the same number of byte errors, the one with scalable coding would be more error tolerant. We tested transmissions of JPEG and JPEG-2000 images over 1-hop and 2-hop routes. The JPEG-2000 test images encoded into 4 quality layers. In the 2-hop case, the distance per hop is kept the same as in the 1-hop case, and the at the intermediate node no image reconstruction or error correction is performed. Therefore, Each image bit stream, which is 4KB, is partitioned into 80-Byte payloads. Each payload is then inserted in a ZigBee packet. Reassembly of the received packets are performed at the server, which is connected to the ZigBee coordinator over an RS232 link. Figure 5 gives the histograms of the number of bytes received in error for each of 100 JPEG and JPEG-2000 image transmissions in 1-hop and 2-hop scenarios. A 2-hop scenario for JPEG-2000 images could not be completed due to adverse affect of uncontrolled environment to transmissions. In 1-hop JPEG image transmissions, 73 images received in error-free and 2 images were undecodable; while in the 2-hop case, 54 JPEG images received with no byte error, but 14 images were unrecoverable. Such images are considered to be fully in error. In testing of JPEG-2000 images, eight nine 2-quality layer encoded images were received without any byte-error, while seventy five 4-quality layer encoded images arrived without no byte-error. The differences in byte error performance of 2-layer and 4-later transmissions can be ascribed to the interference from other uncontrollable IEEE 802.15.4 and IEEE 802.11 devices near the test environment. The comparison of the byte error histograms of 1-hop JPEG and JPEG-2000 transmissions indicate that the link layer characteristics were similar during testing. Therefore, PSNR comparisons can be considered to be fair.

Figure 6 a-b give the histograms of the PSNRs of the received JPEG images. Since in the 2-hop case the intermediate node does not perform any error correction or image reconstruction on received images prior to relaying , more end-to-end byte errors occur. Hence, expectedly the PSNR performance gets worse. On the other hand, the received JPEG-

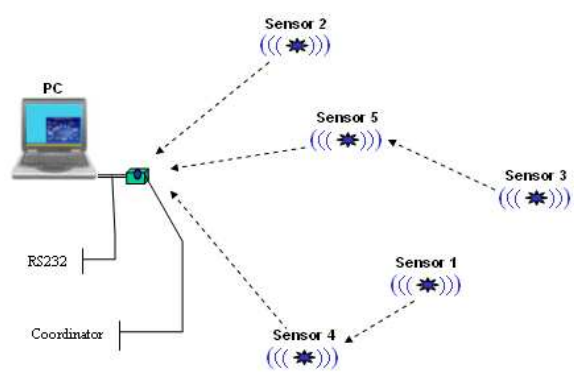

Fig. 4. Illustration of the experimental test-bed

2000 images display better PSNR performance as illustrated in Figure 6c-d, due to JPEG-2000 images being encoded into multiple quality layer streams.

VI. Conclusion

Wireless transmission of 100 JPEG and 100 JPEG-2000 images over ZigBee networks is tested. It is shown that JPEG-2000 images encoded into multiple quality layers are more error-resilient, and high PSNR is maintained. Therefore, it is a more suitable image compression format in low rate image sensor network applications. Multi-hop transmission of JPEG-2000 images were unfortunately not completed due to adverse environment with interference from uncontrolled IEEE 802.15.4 and IEEE 802.11 wireless devices.

Acknowledgment

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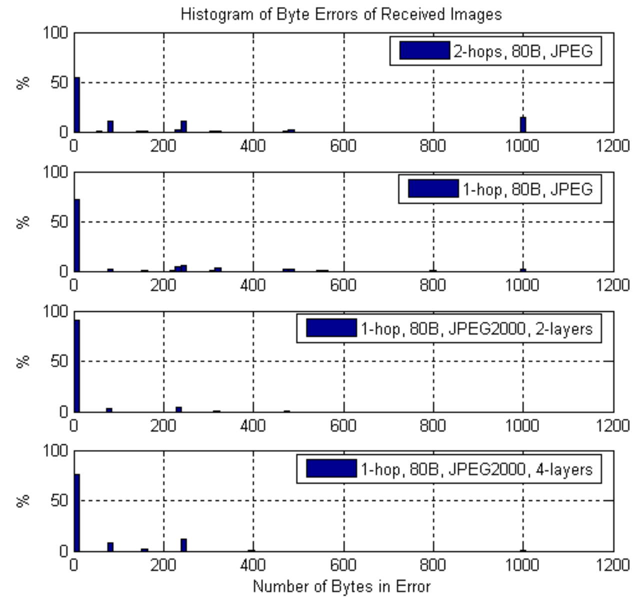

Fig. 5. Byte error histograms in two different routing cases with 80 byte application payload sizes. a) JPEG 2-hop transmission, b)JPEG 1-hop transmission, c) 2 quality layer JPEG 2000 1-hop transmission d) 4 quality layer JPEG2000 1-hop

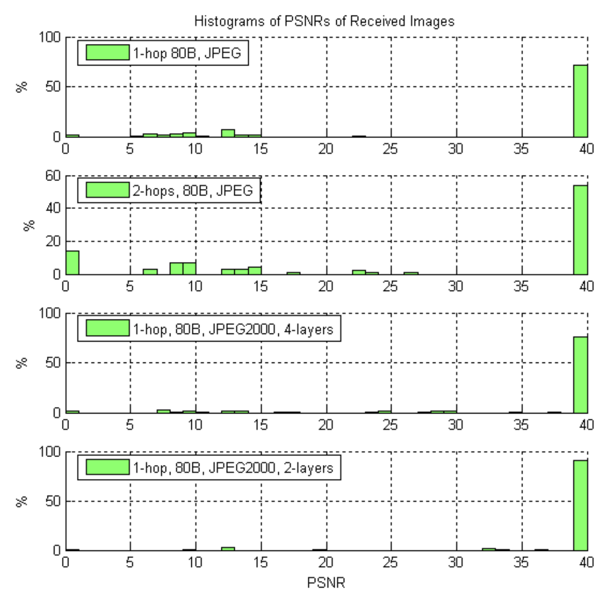

Fig. 6. The PSNR distribution of received images a) JPEG 1-hop transmission, b)JPEG 2-hop transmission, c) 4 quality layer JPEG 2000 1-hop transmission d) 2 quality layer JPEG2000 1-hop