Splitting a PAN into Frequency&Location-Transparent Segments using Virtual ZigBee Router

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***Abstract*—This paper proposes a ZigBee MAC protocol tunneling method for splitting a PAN into partial multi-frequency segments as well as extending a PAN domain over geographically wide area. The method bridges two ZigBee routers across the tunnel to virtually compose one "virtual ZigBee router." The bridge is effective for both point-to-point access and global IP connection. The MAC layer tunneling achieves the transparency for the application layer transactions such as service discovery and firmware delivery for wireless nodes existing in segments that may be operating on different locations or multiple frequency channels. We demonstrate a model implementation using only a combination of publicly available free ZigBee protocol stack software and commercial embedded computers. For performance evaluation of the method, the authors experiment how the virtual ZigBee router resolves the radio congestion when deployed to split a PAN into partial double-channel segments. The result shows the 36% throughput improvement, from 17.5kBps to 23.8kBps (kilo Byte per second). Since the method can take any given two regular ZigBee routers to compose a virtual router that can split a PAN to form multi-channel segments, the method allows for more adaptive multi-channel segmentation of a PAN as compared to the existing multi-channel networks.**

I. Introduction

Attaching wireless sensor nodes to things and their surrounding environments enables the measurement of real physical space data. Those data can be retrieved via many local sensor networks and then transmitted to the existing information networks, thus effectively establishing a wide area sensor network. Within the entire process however there are two major problems posed by multi-hop wireless sensor networks: radio congestion and geographical constraints of extending a network domain.

1) Radio Congestion : Multi-hop wireless sensor networks often suffer severe data-delivery latency and potential data loss due to radio traffic congestion. Multi-channel and multi-hop network has been extensively studied using a multi-channel WiFi access point[1]-[3]. Those existing studies reveal that we can avoid adjacent channel interference by securing sufficient separation distance among transceivers or by optimally adjusting the antenna pattern[4]. Application of multi-channel WiFi network to ZigBee is not straightforward because ZigBee has a whole set of networking and application protocols for network association and service discovery as we later explain in Section II. A multi-channel ZigBee router would be required to transfer and process received packets in accordance with the MAC frame type and the destination address. The process needs to be synchronized with the other routers and its PAN coordinator.

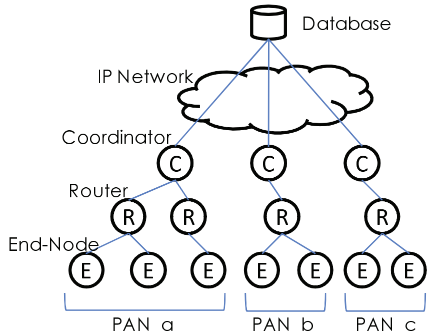

Fig. 1. Integration of Multiple ZigBee PANs

2) Geographical Constraints for Extending a PAN domain: ZigBee is a promising WSN technology with multi-hop and low-power features and abundant product choice. Its advantages include the standardized mechanism of service discovery. For instance, ZigBee-enabled appliances can discover their communication peers by broadcasting service names such as "smart energy." When extending ZigBee-enabled appliance network(PAN) in main office to remote branch offices, the usual practice is to combine independent PANs in different locations above the ZigBee layer (Fig.1). However, such practice allows appliances to discover and subscribe to service only under their corresponding PAN domain, thus requiring additional means of inter-PAN service discovery and subscription through the IP layer. For another example, wireless firmware delivery for nodes is an efficient native ZigBee feature. However, to utilize the feature in a wide area network made of multiple PANs all combined above the ZigBee layer, we need to implement IP multicast service for delivering firmware data to the coordinator of each PAN.

There are a few examples of cross-protocol architecture for wide area sensor network. DLMS over ZigBee[5] using advanced wireless metering device aims at a unified meter-monitoring infrastructure. The ZigBee Bridge Device(ZBD)[6] adds a new "Bridge Routing Layer" to the existing protocol stack with special interface to map ZigBee network layer into UDP/IP network. 6LoWPAN[7] implements network-association and service-discovery functions over the 6LoWPAN protocol. Frequency agility is a feature of ZigBee Pro, which migrate frequency channel upon detecting interference with, for example, WiFi[8]. This does not contribute to the congestion mitigation inside a PAN.

Even though the methods in these existing research integrate

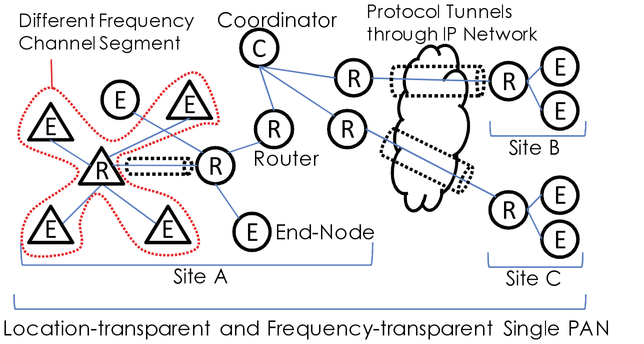

Fig. 2. Extending a PAN Domain over Multiple Frequency Channels and Different Locations with Protocol Tunneling

local sensor networks and achieve a wide area sensor network in effect, they require new special hardware and/or new protocols, adding changes to the existing stack architecture.

Solution proposal and the scope of the paper: The authors propose in this paper the "Virtual ZigBee Router" method with ZigBee protocol tunneling to enable frequency-transparent and location-transparent segmentation of a single PAN. A virtual ZigBee router can split a PAN into partial multi-channel segments (Fig.2 Left). In this case a virtual ZigBee router is realized by interchangeably connecting UART interfaces of two ZigBee routers. Also, a virtual ZigBee router can extend a single PAN domain over a geographically wide area (Fig.2 Right). In this case, virtual ZigBee routers are realized by establishing ZigBee-over-IP tunnels. The method empowers all ZigBee nodes to appreciate all ZigBee native features, including firmware delivery and communication with other appliances and services, transparently and ubiquitously over different geographical locations and multiple frequency channels. Although the virtual ZigBee router is designed to solve both of the two aforementioned problems in wireless sensor networks, for the purpose of this paper, the authors specifically tackle the former topic, i.e., radio traffic congestion. We use virtual ZigBee router to adaptively change frequency channels of PAN segments. It should be noted that we advocate in this paper the advantage of the method to provide a mechanism to change frequency channels while preserving all the native ZigBee features. The frequency allocation algorithm is out of scope of this paper.

The remainder of this paper is organized as follows. Section II explains the virtual ZigBee router method in depth and demonstrates a model implementation with its functional verification test. Section III describes the application of the proposed method for splitting a PAN into partial multi-channel segments to mitigate congestion. Section III also gives quantitative analysis of throughput improvement performance achieved by the implemented system. Section IV concludes the paper.

II. Virtual ZigBee Router

This section introduces the fundamental principles of the virtual ZigBee router and its requirements. We present a model implementation and its functional verification test.

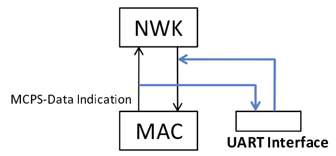

Fig. 3. Extraction/Insertion of Data Frames with MCPS Data Indication

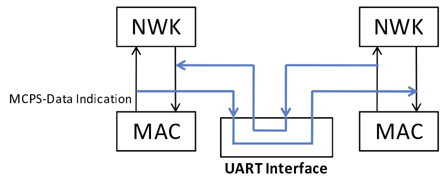

Fig. 4. Perpetual Exchange of MAC Frames between Two Nodes

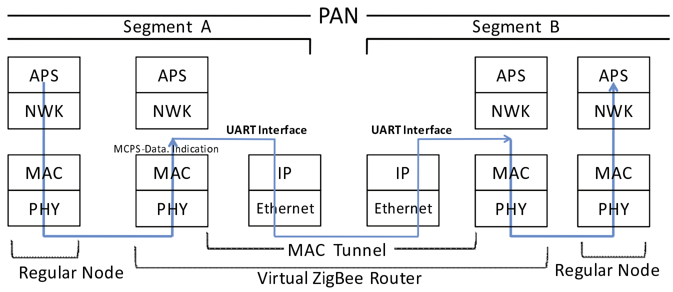

Fig. 5. Routing Packets through a MAC Tunnel between Segments

A. *Virtual ZigBee Router - Principles and Requirements -*

We bridge two ZigBee routers across the tunnel to virtually compose one "virtual ZigBee router." The protocol tunneling is possible through either of four key layers of the ZigBee protocol stack: PHY, MAC, NWK and APS (Application Sub-Layer).

To ensure nodes to be able to appreciate native ZigBee application features(e.g. service discovery) transparently across different segments, we need to conduct the protocol tunneling below the APS layer. The PHY layer tunneling examples include propagating radio frequency band via optical fiber[9], and sampling and extending radio space over broadband networks[10]. However, transferring the PHY layer communication to different network segments confines all connected segments into one radio space, incurring congestion of bandwidth. Also, ZigBee uses a wide frequency bandwidth, and thus the PHY layer tunneling will require large scale complex equipments. The NWK layer tunneling neglects IEEE802.15.4 frames employed in network association process as well as other transactions within a PAN, e.g., data request. Also, neglecting MAC frames will not provide accurate measurement of network throughput for performance analysis. Therefore the authors adopt the MAC layer tunneling.

The IEEE802.15.4 standard requires an MAC common part sublayer(MCPS) data indication to ascend through the protocol stack every time a node receives data. We may use MCPS data indication as a trigger to output/input all MAC frames from/to a ZigBee node. The UART interface can be used for such an operation (Fig.3). The interface may be used to bridge two nodes and automatically exchange MAC

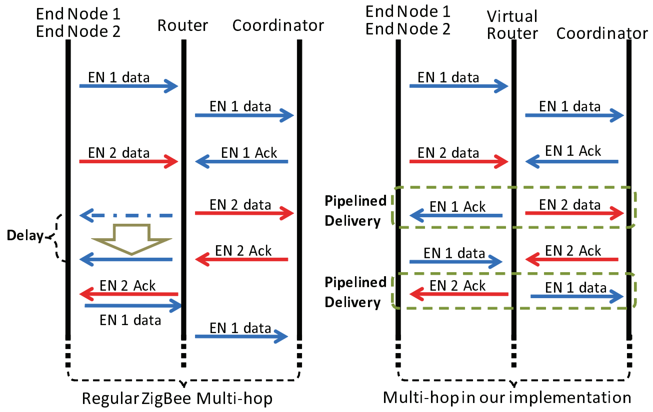

Fig. 6. Pipelined Data Multi-Hop by Virtual ZigBee Router

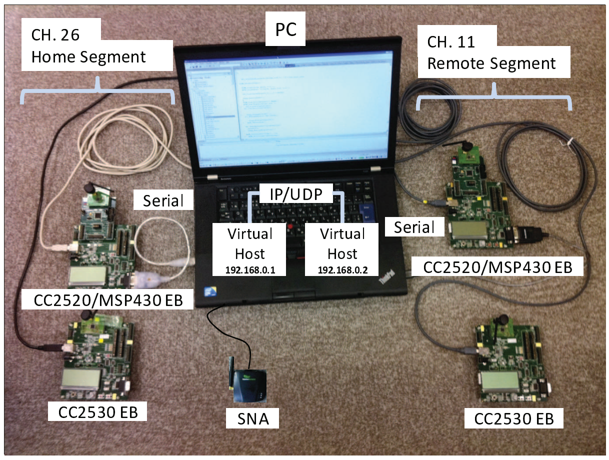

Fig. 7. Logical Structure of Implemented System

frames (Fig.4). Furthermore, connecting the interface to an IP-capable device such as PC will create a ZigBee-IP gateway. The tunnel extends over the global IP network to bridge two geographically separate nodes. ZigBee frames can be encapsulated into UDP/IP datagrams and sent over the tunnel that functions as a perpetual static route between the bridged nodes. Figure 5 shows the routing of an APS packet between two normal ZigBee nodes over separate segments. In addition, virtual ZigBee router exploits its trait of having two physical routers to pipelined-processing of packets, unlike a regular router which processes packets sequentially (Fig.6).

B. Consideration on Implementation

Implementation Design Choices: There are two major options for configuring two routers into a virtual ZigBee router. The first option is to make two ZigBee routers the identical twin routers. The second option is to make two routers independent. The first option is superior in the contexts of both network association and packet routing. Making a twin router requires only simple copying of NWK address and PAN ID. Also, because twin routers share the same address, they never have to alter the source/destination MAC addresses of data frames every time they exchange MAC frames over the protocol tunnel. Thus we chose the first option.

C. Realization of Virtual ZigBee Router

Mere interconnection of two ZigBee devices does not suffice to establish a virtual ZigBee router. The home-segment router and the remote-segment router need the following configuration procedure; After the home-segment router joins the PAN by regular ZigBee join-process, the router indefinitely awaits the join-request from the remote-segment router. Upon the request arrival, the home-segment router returns its network address, its parent node ID, and the PAN ID. The remote-segment router then instigates its configuration as a full functional ZigBee router. Specifically, we use functions of ZigBee device object(ZDO), network layer management entity(NLME), operation system abstraction layer(OSAL) to register attributes in both MAC PAN information base(PIB) and the network information base(NIB). For selection of frequency channel, we can predefine particular channels to target devices before stack recompilation or we can store channel bit-mask into non-volatile memory, which can be committed with a reset command. These modifications make two routers identical to each other. As a result, each router handles packets exclusively but they act virtually as one network node. The exchange of MAC frames between the two routers is done by for UART communication. In this process, we need to enable MAC "promiscuous mode" in the node settings, so that all MAC frames can be captured and exchanged regardless of frames' destination address. Note that ZDO-layer packets such as request/response for service discovery can be transferred transparently from remote-segment nodes to the coordinator in the home segment with virtual ZigBee router.

Consideration for Industrial Deployment: For industrial deployment of virtual ZigBee router with IP tunnel scenario, we must consider the practicality of the method against possible IP network delay involved in the protocol tunnel. For example, when the router in a branch office initiates its Beacon Request to the router in the main office, the congestion suffered in the IP network may delay the response. This can potentially be a fatal problem because the IEEE802.15.4 standard officially stipulates that response must come within a predefined period which is set 492 msec by default. Any response time exceeding the time range will lead to the association failure of the branch office router. The analysis of such aspect of the method is not the scope of this paper because the author's focus here is on splitting a PAN in one location into partial multi-frequency segments for throughput improvement, not the viability of the method for connecting geographically remote segments with IP tunnel.

D. Functional Verification

Based on the above consideration, we implemented a model virtual ZigBee router using a representative ZigBee protocol stack, Z-Stack, by Texas Instruments (TI). ZStack provides C source code for major components of the stack architecture. For ZigBee nodes, we have used CC2520+MSP430 and CC2530 SoC by TI. We made a PAN with a coordinator in the home segment, an end node in the remote segment, and a virtual ZigBee router bridging both segments. An end

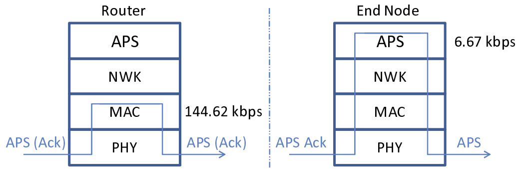

Fig. 8. Hardware Limit for APS and MAC Transaction

node which joins the PAN in the remote segment sends out a test packet with a constant time interval (150msec) to the coordinator. We used a sensor network analyzer(SNA) by Daintree Networks and confirmed the coordinator in the home segment successfully receives the test packets (Fig.7)*. We also confirm that a service discovery feature of ZigBee (ZDO match description) can be transparently exchanged between the remote-segment end node and the home-segment coordinator.

III. Performance Evaluation

This section presents an experiment we conducted to investigate how the proposed virtual ZigBee router can improve network throughput when deployed to split a PAN into multi-channel partial segments by pipelining the transmission as shown in Fig.6. We expect to achieve some degree of traffic load distribution over different frequency channels because of the out-band-emission. The authors predict that this "multi-channel PAN-segmentation" will prove effective especially for a multi-hop wireless sensor network where packet relaying multiplies the pressure on the traffic. Note that all the channel assignment algorithms for a multi-channel system can be applied compatibly to the virtual ZigBee router since we can specify the frequency channel for each segment even from a remote location through the IP network. This allows the operator to adaptively configure segmentation and channel assignments when segmenting a PAN.

Precondition: Serial Bus Throughput Limitation on CC2530

One hardware-bottleneck exists in the embedded computer chip of CC2530 as a critical precondition to the network throughput experiment. The serial bus connecting the micro-controller and the transceiver is able to process successive data transmission orders with the minimum interval of 150 msec for each packet. The maximum size for a single packet is 125 bytes, consisting of 27 bytes of header information and 98 bytes of payload. This determines the theoretical maximum amount of APS packets that can be transmitted by an end node per second to be 6.67kbps (Fig.8 Right). The hardware limitation for routing packets(MAC-layer transaction) is significantly higher. CC2530, by design, takes approx. 0.4 to 0.9 msec per packet, amounting to 144.62kbps (Fig.8 Left).

Experiment

With one end of a virtual ZigBee router joining the coordinator in the home segment, we added routers and end nodes

*we have a PC in the implementation because we intend to provide a virtual ZigBee router that can bridge remote segments over IP, as well as realizing multi-channel segments. For the latter purpose only, interconnecting two routers by their UART interfaces would suffice.

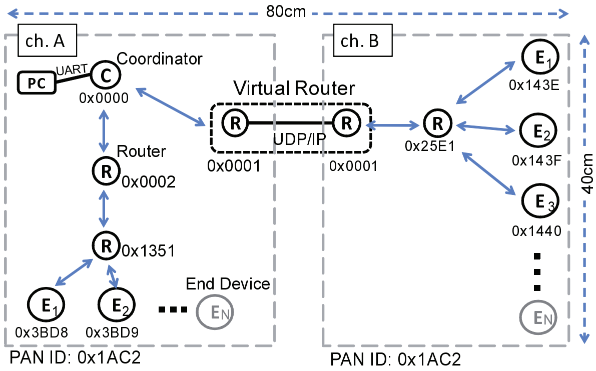

Fig. 9. Logical Structure of the Experiment

in both segments (Fig.9). The frequency channel of the home segment is fixed to 11ch(2405MHz). The frequency channel of the remote segment is set to either 11ch, 12ch(2410MHz), 13ch(2415MHz) or 26ch(2480MHz) and bridged by the virtual ZigBee router. Each end node is transmitting APS packets of 6.67kbps with some added overhead. For retransmission control, we use the APS acknowledgement. In this experiment, all the transmitted data from end nodes are collected by a PC connected to the coordinator via the UART interface. Then, the PC yields network throughput which is the aggregated throughput of data stream from all the end nodes. We also measure the average data transmission interval of each end node. Since the designated transmission interval is 150 msec, an interval exceeding 150 msec indicates the ZigBee network congestion. We measure the PAN throughput as we split the single-channel PAN into two segments and assigned a combination of different frequency channels.

Note on adjacent/alternate channel interference: The IEEE802.15.4 standard regulates 5MHz of bandwidth for each channel in the 2.4GHz band operation. For interference avoidance, the standard mandates power spectral density(PSD) limits for output signal. Specifically, with the frequency offset of $\pm$3.5MHz, the relative PSD limit is -20dB, and the absolute PSD limit is -30dBm. However, the authors presume the sum of spurious emission spreading over adjacent channels will be greater than the carrier-sensing level (=-75dBm), and thus splitting a PAN into two adjacent-channel segments may not help increase the throughput. Figure 10 shows the frequency spectrum over these channels from the experiment. With measured values of RSSI(dBm), the sum of spurious emission(SE) over a certain frequency range n to m can be calculated by the following†;

$$SE = 10\log_{10}\left[\sum_{i=n}^{m} 10^{\frac{1}{10}D_i}\right] \quad (1)$$

where D_i denotes the measured dBm value at frequency i. According to the calculation, when nodes are transmitting in the channel 11, the sum of spurious emission over the channel 12 accumulates to -33.8dBm, exceeding the carrier-sensing level(=-75dBm). The ample separation distance d for

†Depending on the resolution band width used by spectrum analyzer, some additional calibration may be required.

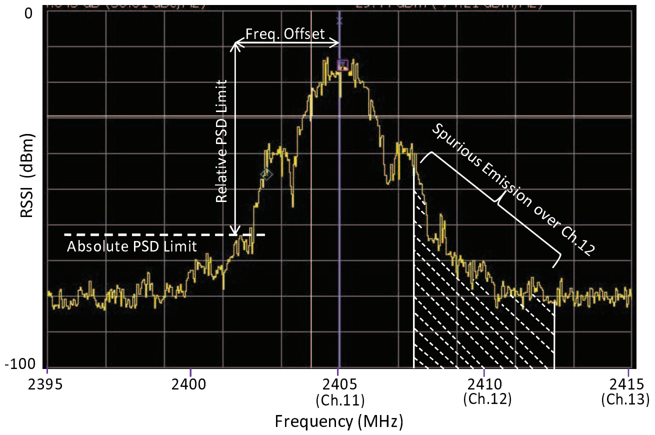

Fig. 10. Spurious Emission over Adjacent Channel (Center Ch. = 11)

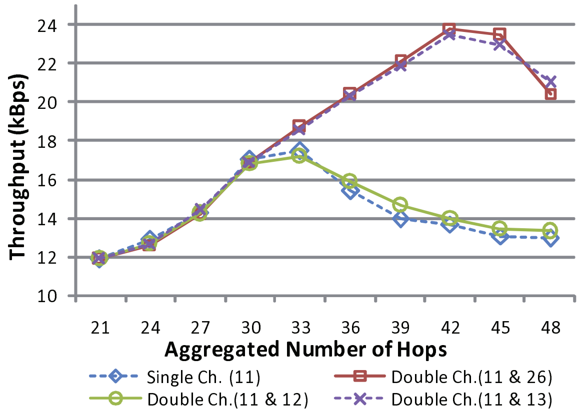

Fig. 11. Throughput Improvement of Splitting a Single-channel PAN into Double-channel Segments

not triggering the carrier-sensing level can be computed by solving the following free space pathloss equation (expressed in terms of dB) for d;

$$Pathloss = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (2)$$

$$d = \frac{\lambda}{4\pi}10^{\frac{Pathloss}{20}} \quad (3)$$

where

$Pathloss$; the target pathloss in this case is -75-(-33.8) = 41.2

λ; the wave length lambda in this case is (299×2405) so that d is expressed in meters.

The resulting d is 1.14 meters. The result indicates that when splitting a PAN into multi-channel segments in physical proximity, one has to avoid adjacent channels.

Result

Figure 11 shows the result of the experiment. The single-channel PAN reaches its congestion point with the aggregated hop count of 33, whereas that of the double-channel PAN is 42 except in the case where the remote segment channel is 12ch. The network throughput increases in accordance with the number of aggregated hops in a linear proportion until the ZigBee network starts to get congested. The maximum throughput of the single-channel PAN is approx. 17.5kBps while that of the double-channel segmented PAN is 23.8kBps, translating to roughly 36% improvement. For the case of adjacent channel segmentation (11 and 12), the throughput did not improve. The experimental result agrees well to the analysis. Although the efficient channel assignment algorithm is not the scope of this paper, examining the effect of adjacent/alternate channel interference in the experiment casts insight into the future phase of the research where we might use virtual ZigBee router to split a PAN into, not just two, but several partial segments for further throughput leverage. Also, because we can take any given two regular ZigBee routers to compose a virtual router, the method allows for more adaptive multi-channel segmentation of a PAN as compared to the existing multi-channel networks.

IV. Conclusion

Virtual ZigBee router is effective in solving two fundamental problems in wide area sensor networks; radio congestion and geographical constraints of a PAN domain. Virtual ZigBee router demonstrates two functional advantages over the existing multi-channel routers;(1) Facilitating network association between nodes operating on different frequency channels, and (2) Leveraging the segmentation scope to global IP network. Our implementation uses only software adjustment on commercial nodes whereas the existing methods use new hardware or change the ZigBee stack architecture. Experiment shows that virtual ZigBee router, by splitting a single-channel PAN into multi-channel segments, can improve network throughput. Future work from this paper could include a more complex yet effective throughput optimization by adopting several virtual ZigBee routers in a multi-hop-intensive network.‡

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