A Review of ZigBee-UMTS Hybrid Networks

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***Abstract*—A ZigBee Network is a low-cost and low-power wireless network based on the IEEE 802.15.4 standard, which allows wireless connectivity with limited power and relaxed throughput requirements. On the other hand, the Universal Mobile Telecommunications System (UMTS) is a third-generation cellular network that provides high-speed wireless traffic transfer to the Internet. This paper presents the design and implemen-tation of a novel integrated ZigBee and UMTS hybrid network in the Network Simulator (ns-2). In this hybrid network, we design a new Mobile Gateway to interconnect these two different sub-networks. With the hierarchical addressing and some special UMTS network discovering mechanisms, routing in the hybrid network, from the ZigBee network via the UMTS network to the wired network, is achieved. We also design a simulation platform to make it easier for protocol designers to design and evaluate new protocols in such a hybrid network.**

***Index Terms*—UMTS, ZigBee, simulation platform, ns-2.**

I. INTRODUCTION

ZIGBEE [1] is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard. The goal of the ZigBee network approach is to maximize the application market through standardization and low cost. Universal Mobile Telecommunication System (UMTS) [2] is one of the third generation (3G) mobile communication systems. The main purpose for UMTS is to offer a universal infrastructure that is able to support both existing and future services. The Network Simulator (*ns*-2) [3] is a discrete event simulator targeting at networking research. The simulator can help people test the performance of a network. It is a convenient way for protocol designers to evaluate their new network protocols using *ns*-2. In the literature, several versions of UMTS have been implemented in *ns*-2. In [4], the authors proposed to integrate the IEEE 802.11 ad hoc network and the UMTS network, and designed the integrated network modules in *ns*-2. However, some research areas, such as industrial control and medical monitoring, need low-power wireless network connectivity. And it is preferred to choose the ZigBee rather than the IEEE 802.11 ad hoc network as the intra wireless communication mechanism. We found that the integrated ZigBee and UMTS network modules have not been provided in *ns*-2, which makes it extremely hard to simulate a ZigBee-UMTS hybrid network.

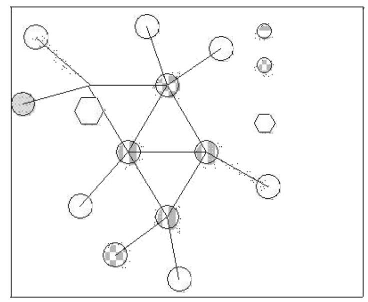

Fig. 1. ZigBee network topology.

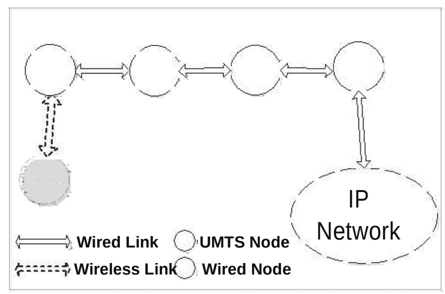

Fig. 2. UMTS network topology.

In this paper, we design a new Mobile Gateway to interconnect the ZigBee and UMTS networks. We also redesign the addressing and routing mechanisms to make it possible that the two nodes respectively in ZigBee and UMTS sub-networks can communicate with each other. To the best of our knowledge, we are the first to address this problem. Besides implementing a novel integrated ZigBee and UMTS network module in *ns*-2, we also design a simulation platform to make it easier for protocol designers to design and evaluate new protocols.

II. HYBRID NETWORK ARCHITECTURE

A ZigBee-UMTS hybrid network consists of two parts: a ZigBee network and a UMTS network.

Fig. 1 depicts a ZigBee network, which typically includes three types of nodes: Coordinator, Router, and End Devices. If two devices are out of the communication range, a routing protocol must be used in a ZigBee network, e.g., Ad hoc On Demand Distance Vector (AODV) [5] Routing Protocol or other ZigBee Routing Protocols [6]. Fig. 2 depicts a UMTS network topology structure. The UMTS network includes five components: User Equipment (UE), Base Station (BS), Radio Network Controller (RNC), Serving GPRS Support Node (SGSN), and Gateway GPRS Support Node (GGSN).

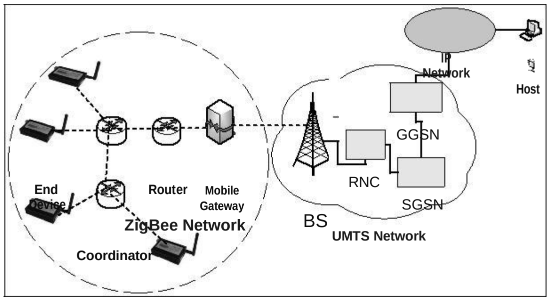

Fig. 3. The ZigBee-UMTS hybrid network architecture.

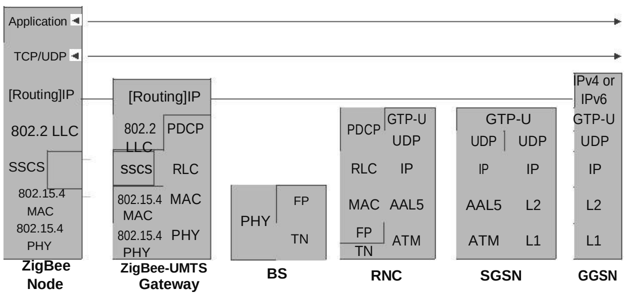

Fig. 4. The ZigBee-UMTS hybrid network protocol architecture.

Now we design a ZigBee-UMTS hybrid network. Fig. 3 depicts its architecture. A hybrid device named as *Mobile Gateway* is used to interconnect the UMTS network and the ZigBee network. The hybrid network uses the IEEE 802.15.4 protocol stack in the ZigBee sub-network and uses the UMTS protocol stack in the UMTS sub-network. Fig. 4 depicts the protocol architecture of a ZigBee-UMTS hybrid network. The Mobile Gateway has two different network interfaces and protocol stacks that belong to ZigBee and UMTS, respectively. The "[Routing] IP" in a ZigBee node or the gateway means the routing protocol used in ZigBee.

III. The Simulation Model for Hybrid Networks

We implement the integrated ZigBee and UMTS network modules in the Network Simulator (*ns*-2).The problem is how to integrate those two modules, so that nodes in the ZigBee network can communicate with the nodes in the UMTS network. Therefore, we rewrite the ZigBee protocol stack and the UMTS protocol stack. We implement a new node, *Mobile Gateway*, which has two different network interfaces and supports two different protocol stacks, as shown in Fig. 3 and 4.

A. ZigBee and UMTS Simulation Model

ns-2 provides the IEEE 802.15.4 Media Access Control (MAC) and several physical models in the "wpan" pack-age [7], [8]. The network and application layers are left to the applications developers [9]. An intermediate sub-layer called the Service Specific Convergence Sublayer (SSCS) has been provided in the ZigBee protocol stack as an interface to the higher layers. The function of SSCS in the ZigBee modules is to provide commands that are used to start a node as a coordinator or as a device and define some characteristics.

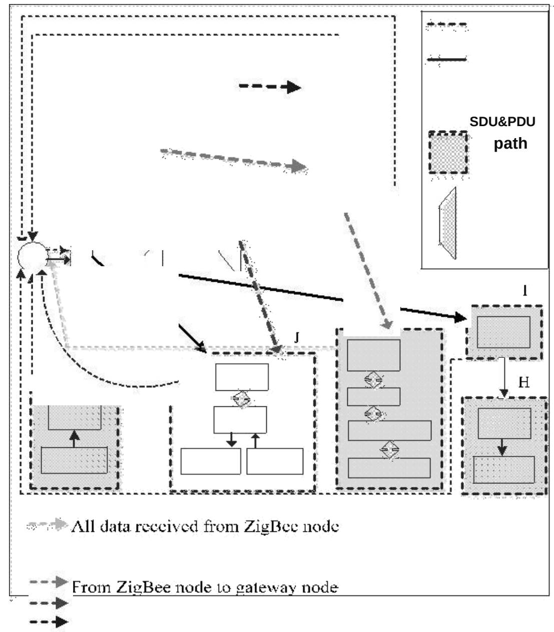

Fig. 5. Mobile gateway architecture.

EURANE [10] has been developed to provide the UMTS modules in *ns*-2. The UMTS simulation model [10] includes three components: a Radio Link Control (RLC) protocol, a MAC layer protocol, and a physical layer protocol. Each RLC instance is configured by the Radio Resource Control (RRC) protocol to operate in one of the three modes [11]: Transparent Mode (TM), Unacknowledged Mode (UM) or Acknowledged Mode (AM). AM is chosen in our hybrid networks.

B. Mobile Gateway

Because of the differences in the architectures between ZigBee and UMTS, the hybrid network requires a Mobile Gateway to connect the two sub-networks.

The Mobile Gateway is designed based on a UMTS UE node. It contains all of the UE's functional blocks. Besides, the ZigBee network interface and a routing agent are added to the Mobile Gateway model. Some modifications on these modules are necessary to ensure a correct packet flow direction. All of the implementations enable the Mobile Gateway to intercon-nect the ZigBee sub-network and the UMTS sub-network. The main modules of the Mobile Gateway are illustrated in Fig. 5.

The gateway has an "entry" point (A) to a series of classifiers. The Service Data Units (SDUs) and the Protocol Data Units (PDUs) have different paths to go through the gateway. Classifier B de-multiplexes RLC, PDUs, and SDUs (IP layer packets) and sends them in different directions. The functionalities of Classifiers C, D, and E are the same as the functionalities of the corresponding classifiers in a normal wired node in *ns*-2, except for a small modification on the address classifier (C) to make it link to three other modules. If the received SDU is sent to the gateway, it will be forwarded to D; if it is sent to a UMTS node, it will be forwarded to E (default target); if it is sent to a ZigBee node, it will be forwarded to the Routing Agent. Classifier F, named as Network Interface (NIF) Classifier, forwards PDUs to the corresponding RLC entities according to the packet network interface values.

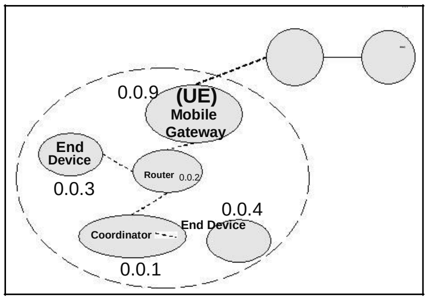

Fig. 6. Addressing in hybrid networks.

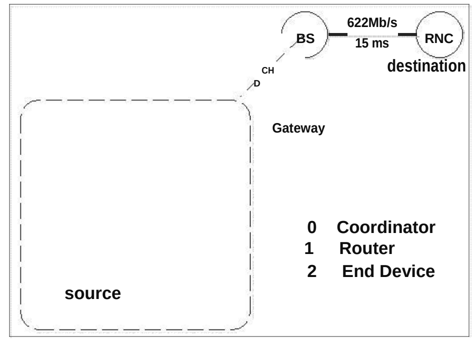

Fig. 7. Hybrid network simulation model.

Different packets are received or sent by different NIFs. In the Mobile Gateway simulation model, the common channels (G, H), the dedicated channel (J) and the ZigBee network interface (K) are added. Each of them has an interface value. The modifications on ZigBee modules have also been made in the Mobile Gateway.

C. Addressing and Routing

We create the Mobile Gateway to interconnect the two sub-networks and ensure that data flows can find the right directions when going through the gateway. However, the hybrid network still requires a uniform addressing and routing solution in order to provide end-to-end communication paths between the nodes in different sub-networks.

Different routing protocols are used in ZigBee networks and UMTS networks. AODV or other ZigBee Routing protocols is used in ZigBee networks. A UMTS node is designed by modifying an *ns*-2 wired node, and it has a different structure from a normal wired node. So, UMTS has its own routing solution, which is achieved by using OTCL commands to make network-level flows routed over the correct transport channels between the UE and RNC [12].

ns-2 supports two addressing modes: flat addressing and hierarchical addressing. The UMTS simulation model only supports the flat addressing mode, while both of them are allowed in the ZigBee model. We choose the hierarchical addressing mode as the solution for individual network modules with different routing schemes in the hybrid network. The reason is that a node does not necessarily know the routing information of the nodes in other sub-networks when using hierarchical addressing. We make the following modifications to let the UMTS nodes support hierarchical addressing: transferring the hierarchical address (as a function parameter) to the function that creates UMTS nodes in the UMTS simulation modules; adding the hierarchical address classifier to the UMTS nodes. UMTS nodes now support hierarchical addressing as shown in Fig. 6. Each address contains three components: sub-network ID, cluster ID, and node ID.

ZigBee and UMTS networks are in different sub-domains. So, the Mobile Gateway should support a mechanism to notice the ZigBee nodes that the gateway can provide connectivity to the external IP network. The details are as follows. Once the Mobile Gateway receives a routing request from a ZigBee node to an external IP network node, the gateway replies to the ZigBee node a message containing the routing information to the external IP network node. After this, a routing path could be established. We modify the routing protocols to support this mechanism in the ZigBee sub-network. For example, the new "Reply" mechanism is added in the AODV routing protocol.

IV. Routing Setup and Simulation Results

In this section, we create a ZigBee-UMTS hybrid network routing scenario. By simulating this routing scenario and analyzing the results, we can test the effectiveness of the integrated network models implemented in *ns*-2.

A. Routing Setup

Fig. 7 shows the network topology. There are 21 nodes in the ZigBee network, including 1 Coordinator, 9 Routers, and 11 End Devices. The other nodes are the Mobile Gateway, UMTS BS node, and UMTS RNC node. The nodes used to connect IP network have not been included since the main purpose of the simulation is to test the Mobile Gateway.

The hybrid network is divided into two sub-networks. One includes the ZigBee nodes and the Mobile Gateway; the other one includes a UMTS BS node and a UMTS RNC node. The BS node and RNC node are connected to the ZigBee nodes via the Mobile Gateway. The link between BS and RNC is labeled with its transmission rate and delay. The channel between the Mobile Gateway and the BS is the dedicated channel (DCH).

The source node is an end device in the ZigBee sub-network as shown in Fig. 7, and the destination is the RNC node in the UMTS sub-network. The AODV routing protocol is chosen for the ZigBee sub-network.

B. Simulation Results and Analysis

We trace all packets through the hybrid network and use a trace file to collect the simulation raw data. Then, we analyze the raw data to get simulation results including real-time throughput, average throughput, end-to-end delay, jitter, and packet loss rate. In order to test the ability of route rebuilding of the Mobile Gateway, we randomly disconnect the routing path between the source and destination nodes.

Fig. 8 depicts the real-time throughput at the destination. The throughput is defined as the amount of received data in bits per second. The traffic generator generates the first data packet at the 10th second and the data generation rate is 1 kbps. The routing path between the source and the destination is broken after some packets have been transferred, which results in low throughput values. Fig. 9 illustrates the average

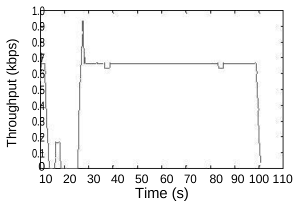

Fig. 8. Throughput.

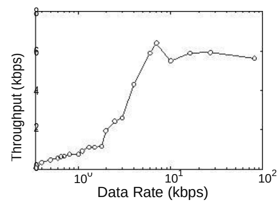

Fig. 9. Average throughput.

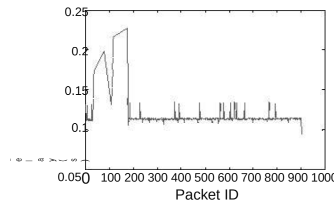

Fig. 10. End-to-end delay.

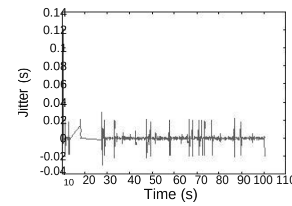

Fig. 11. Jitter.

throughput when setting different data generation rates. First, the throughput increases as the data rate increases. Then, it keeps stable at about 6 kbps since the data transmission rate of the link between the Mobile Gateway and BS is only 6.4 kbps and the data transmission rate of the links between ZigBee nodes is 20 kbps.

The end-to-end delay of a packet is defined as the time that a packet spends on traveling from the source to the destination. As shown in Fig. 10, initially the delay is stable. Then, the delay increases tremendously from the packet with ID 20 to the packet with ID 180. After that, the delay is back to the normal small value. The reason is that the routing path is broken, which causes the tremendous increment of the delay. Once the routing path is re-established, the delay is back to the normal small value.

Jitter measures the packet delay variation. It is defined as the difference in the end-to-end delay between the two adjacent packets with any lost packets being ignored. As shown in Fig. 11, small jitter value indicates that the hybrid network is in a good transmission condition.

The packet loss rate is defined as the ratio between the number of lost packets and the number of generated packets. It is 0.134 in the simulation. Most of packet losses occur when the routing path is broken.

With the above analysis, the simulation results confirm that the designed ZigBee-UMTS hybrid network (including the Mobile Gateway) works correctly.

V. Simulation Platform

We design a simulation platform so that protocol designers can easily design and evaluate new protocols on the new *ns*-2 modules. The platform adopts a C/S structure. The client provides an interface (shown in Fig. 12) for users to input and modify the simulation parameters, uploads the parameter information to the server, receives the simulation results from the server, and finally shows the simulation results to users. The server receives simulation parameters from the client, converts them into TCL commands, runs the *ns*-2 software with the integrated ZigBee-UMTS hybrid network modules, and returns the simulation results which include detailed data and pictures of the analytical results to the client. The platform can be downloaded at [13].

VI. Conclusion

This paper presented the design and implementation of the novel integrated ZigBee and UMTS network modules in *ns*-2. We designed a new Mobile Gateway to interconnect these two different sub-networks. We also redesigned the addressing and routing mechanisms to make it possible that the two nodes

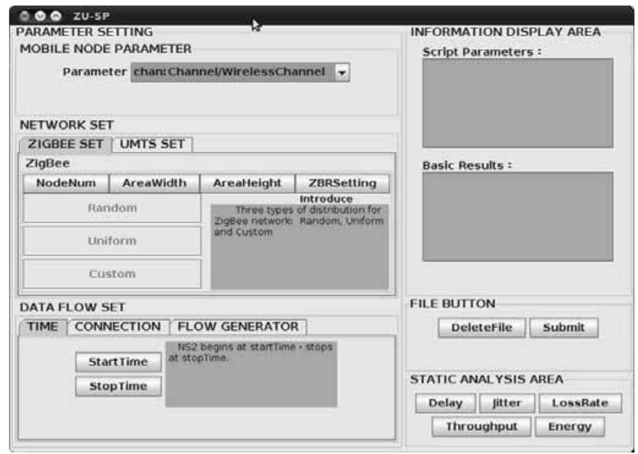

Fig. 12. Simulation platform client interface.

respectively in ZigBee and UMTS sub-networks communicate with each other. Based on the simulation results, it can be concluded that the designed ZigBee-UMTS hybrid network works correctly in *ns*-2. This paper also presented the design of a simulation platform, which lets protocol designers easily design and evaluate new protocols on the new *ns*-2 modules.

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