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A Multi-link Mechanism for Heterogeneous Radio Networks

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Abstract Nowadays, smart mobile devices drive the mobile traffic growth rapidly. Most smart mobile devices are equipped with multiple radio network interfaces, such as High Speed Packet Access (HSPA), Long Term Evolution (LTE), and Wi-Fi. Therefore, integration of multiple networks is a viable solution to fulfill traffic offloading and the Quality-of-Service (QoS) requirement of data usage for mobile users. In this paper, we propose a multi-link mechanism to handle the radio network selection and switching between LTE and Wi-Fi networks. A Multi-Link Adaptor (MLA) and a Multi-Connection Manager (MCM) are proposed for the User Equipment (UE) and the core network, respectively, to handle the multi-link mechanism. The applications executed in the UEs do not need to be modified under the proposed approach. The MLA maintains a QoS class table and a routing table for the network selection procedure and uses the GPRS Tunneling Protocol-Control plane (GTP-C) control messages to execute network switching. In the future, we will measure the throughput of the multi-link network and the switch delay between the heterogeneous radio networks.

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1 Introduction

In the recent years, mobile devices (e.g., smartphones and tablets) drive mobile traffic growth rapidly. As forecasted by Cisco [1], Global mobile data traffic grew 70 % in 2012, and will grow at a Compound Annual Growth Rate (CAGR) of 66 % from 2012 to 2017. Overall mobile data traffic is expected to grow to 11.2 exabytes per month by 2017, a 13-fold increase over 2012. To deal with the traffic explosion, heterogeneous radio network integration is a cost-effective solution for mobile operators to reduce network congestion.

Currently, most smartphones or tablets are equipped with both cellular and Wi-Fi radio interfaces. Compared with the cellular technology, Wi-Fi utilizes non-licensed spectrum with a relatively low cost. It makes a viable solution by taking advantage of Wi-Fi technology for mobile operations to fulfill users' data usage. Many mobile operators have deployed Wi-Fi hotspots integrated with mobile networks. In addition, several Wi-Fi offloading mechanisms were proposed to switch the cellular connections to the Wi-Fi connections. For example, Taiwan's Chunghwa Telecom has proposed an auto switch mechanism [2] to switch the network access from cellular to Wi-Fi for Apple iOS and Google Android platforms. However, this mechanism does not support seamless session mobility. Therefore, the application sessions are broken when the device switches the connection from Cellular to Wi-Fi.

The 3GPP and the IETF proposed two network protocols, GPRS Tunneling Protocol (GTP) [3,4] and Proxy Mobile IP (PMIP) [5] to support IP mobility. Both GTP and PMIP based approaches rely on an all-IP core network to enable session mobility. One of the PMIP solutions was presented in [6], but it lacked the services classification method and the network selection mechanism. In [7], the heterogeneous network interworking issues (e.g., bandwidth aggregation) of the application, transport, network, and link layers had been surveyed. In this paper, we propose a GTP-based approach for cellular (i.e., LTE) and Wi-Fi interworking. In our approach, User Equipment (UE) is required to install a Multi-Link Adaptor (MLA) to manage both the LTE and Wi-Fi network interfaces. The MLA provides a unified radio network interface to host applications, such that the application connections are not affected when the radio link is switched (e.g., from LTE to Wi-Fi). In addition, this paper proposes a network selection mechanism for MLA to select a suitable radio network interface based on the characteristics of an application. The network selection mechanism first collects some transmission packets of an application, analyzes the traffic pattern for the application, and finally selects an appropriate radio interface for the application. Multiple connections of a UE are allowed to deliver through different radio networks concurrently. A Multi-Connection Manager (MCM) is deployed in the mobile core network to coordinate the multi-link connections. In our approach, the applications need not to be modified.

The paper is organized as follows. Section 2 describes the network architecture and the GTP Protocol. Section 3 introduces the software architectures of Multi-Link Adaptor and Multi-Connection Manager. Section 4 proposes the network selection procedure. Section 5 presents the network switching procedure. Conclusions are given in Sect. 6.

2 Network Architecture, GPRS Tunneling Protocol, and QoS Classes

This section first discusses the Wi-Fi and LTE integrated network architecture. Then we introduce the GPRS Tunneling Protocol used in the integrated network. Finally we describe

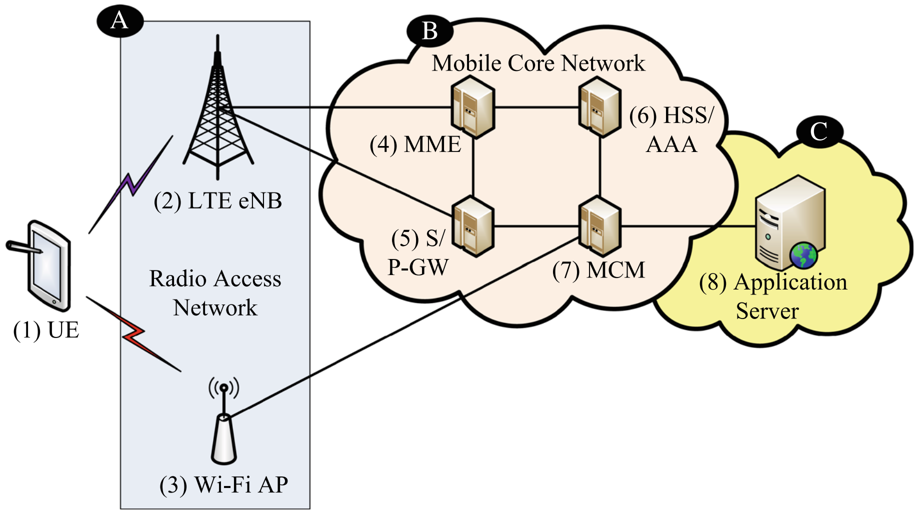

Fig. 1 Wi-Fi and LTE integrated network architecture

the Quality-of-Service (QoS) classes of the applications that will be used in the network selection scheme to switch the GTP tunnels.

2.1 Wi-Fi and LTE Integrated Network Architecture

Figure 1 depicts the integrated network architecture for multiple radio access networks (e.g., the Wi-Fi and LTE in this example) through the Multi-Connection Manager [MCM; see Fig. 1(7)] and Multi-Link Adaptor [MLA in UE; see Fig. 1(1)]. The UE equipped with MLA has both LTE and Wi-Fi network access interfaces. The UE connects to the mobile core network [see Fig. 1(B)] through either LTE base stations [eNBs; see Fig. 1(2)] or Wi-Fi Access Points [APs; see Fig. 1(3)] in the radio access network [see Fig. 1(A)]. The MLA in the UE helps to schedule, reschedule, and balance the packet flows of the UE.

To accommodate the Wi-Fi traffic, the MCM is introduced to the LTE core network that consists of the Mobility Management Entity [MME, see Fig. 1(4)], Serving Gateway/Packet data network Gateway [S/P-GW, see Fig. 1(5)], Home Subscriber Server/Authentication, Authorization, and Accounting server [HSS/AAA, see Fig. 1(6)].

The MME hosts the UE mobility related functions, such as authentication, location tracking and management, connection management, and interworking with the S/P-GW and the HSS/AAA [8]. The S-GW is responsible for data delivery between the LTE core network and the radio access network. The P-GW is responsible for managing connectivity between the LTE core network and the external data network [see Fig. 1(C)]; specifically, it provides the connection between the UE and an application server [see Fig. 1(8)].

The HSS is a database for storing information related to the users. It also supports the user authentication and the network access authorization [9]. The 3GPP AAA server authenticates Wi-Fi users based on Universal Subscriber Identity Module (USIM) credentials, and interacts with the HSS to retrieve the non-3GPP access authorization information for the 3GPP subscribers [10,11].

The MCM interworks with the MLA in the UE to manage the multiple radio access links for the UE. To manage these links, the MCM exchanges the control messages with the MLA to maintain data transmission tunnels between the MCM and the MLA. Based on the request of the MLA, the MCM transmits data through different radio connections. In our multi-link approach, the GPRS Tunneling Protocol is used to control the LTE and Wi-Fi link switch and transport the data packets between the UE and the MCM server.

2.2 GPRS Tunneling Protocol

GPRS Tunneling Protocol is an IP-based communications protocol that maintains GTP tunnels to carry user data in the GPRS, the UMTS or the LTE core networks. The GTP protocol is first proposed for GPRS to tunnel user plane packets between GPRS Support Nodes (GSNs) in the GPRS backbone network, and it is therefore called the GPRS tunneling protocol.

GTP is composed of the GPRS Tunneling Protocol-Control plane (GTP-C) protocol [3] and the GPRS Tunneling Protocol-User plane (GTP-U) protocol [4]. A GTP-C flow is logically associated with one or more GTP-U tunnels, while the GTP-U protocol realizes the GTP tunnels that carry the encapsulated user plane data between the tunnel endpoints (e.g., P-GW or MCM in Fig. 1). A GTP tunnel is a one-direction tunnel. Multiple GTP tunnels can be established between each set of endpoints. At each tunneling node, a GTP tunnel is identified by a Tunnel Endpoint Identifier (TEID), an Internet Protocol (IP) address, and a User Datagram Protocol (UDP) port number. The TEID is a locally unique number assigned by the receiving endpoint of a GTP tunnel. The identity is present in the GTP header to indicate which tunnel a particular user data packet belongs to.

Our approach extends the GTP protocols to implement data bearers between the UE and the MCM. The GTP-C is used for maintaining the tunnels between the UE and the MCM, while the GTP-U is used for carrying user data between the UE and the MCM through the GTP tunnels. The GTP-U packet consists of a GTP-U header and a GTP-U payload. The GTP-U header is composed of a source UDP port, a source IP [i.e., IP of the network interface of UE (MCM)] and a destination IP [e.g., IP of the corresponding network interface of MCM (UE)]. The GTP-U payload is the carried user data packet.

With the LTE and the Wi-Fi technologies, our approach manages multiple radio access links between the UE and the MCM by different GTP tunnel sets. Our mechanism allows the MLA to activate a multi-link session, to deactivate the multi-link session, to adjust, update, and switch the access link of a session. The MLA uses the following GTP-C control messages to manipulate the multi-link session.

- **Create Session Request/Response:** this message pair establishes the tunnels as the first bearer to carry the user plane data between the UE and the MCM.
- **Modify Bearer Request/Response**: this message pair modifies the parameter settings for a user plane bearer between the UE and the MCM.
- **Delete Session Request/Response:** this message pair removes the existed user plane bearer between the UE and the MCM.

The MLA uses a network selection scheme (to be elaborates in Sect. 4) that switches the GTP tunnels based on the QoS requirements of the applications. The QoS class is described in the next subsection.

2.3 Quality-of-Service Classes

Following the Universal Mobile Telecommunications System (UMTS) specification [12], we classify the applications into four Quality-of-Service classes:

Table 1 The characteristics of the QoS classes

Packet size	Packet interval	QoS class
Small	Periodical	Conversation
Medium to large	Periodical	Live streaming
High variance	High variance	Interactive
Large	Dense arrival	Background

- Conversation: the traffic of conversational service typically carries small-sized packets (e.g., 40–500 bytes), where the transmission data are compressed. The application information is sampled by a fixed rate, and the packets are periodically transmitted by a fixed period (e.g., 15–40 ms). A representative service is Voice over Internet Protocol (VoIP).
- Live Streaming: the live streaming service typically carries medium to large-sized packets (e.g., 500–1,600 bytes), where the application packets are transmitted periodically by a fixed period (e.g., 15–100 ms). A representative service is video streaming.
- Interactive: the traffic pattern of interactive service depends on the relationship of the request and response messages. The variance of packet sizes and transmission intervals are high (e.g., the packet size may range from 40 to 1,600 bytes). A representative service is web browsing.
- Background: the traffic typically carries large-sized packets (e.g., 1,000–1,600 bytes), where the size of the source data is fixed, and the applications do their best to fill up the packets. The packet transmission interval is short (e.g., 0.02–0.08 ms) to finish transmission as early as possible. A representative service is File Transfer Protocol (FTP).

The characteristics of each QoS class are summarized in Table 1.

3 Multi-link Adaptor and Multi-connection Manager

This section describes the software architectures of the Multi-Link Adaptor (MLA) and the Multi-Connection Manager (MCM). Figure 2 shows the MLA software architecture, which is a client-side software module installed at the multi-network-module UE (e.g., the UE equipped with both LTE and Wi-Fi network modules). The MLA consists of the virtual network interface [see Fig. 2(2)], and the GTP tunnel client [see Fig. 2(3)]. The virtual network interface provides a unified network interface for applications [see Fig. 2(1)], where an IP address is allocated to the virtual network interface as the *IP_UE*. All applications in the UE use the *IP_UE* to access Internet services, and the *IP_UE* will not be changed when the physical network link (i.e., LTE or Wi-Fi link) is switched.

The GTP tunnel client is responsible for the creation, modification, deletion of the GTP tunnel (i.e., maintenance of the GTP tunnel) between the MLA and the MCM by exchanging the GTP-C messages [see Fig. 2(4)]. It also handles data packet routing between the virtual network interface and physical network interfaces (e.g., LTE or Wi-Fi) by using the GTP-U protocol.

Initially, a default radio network is selected by the GTP tunnel client. When the virtual network interface receives IP packets from an application, it first sends to the GTP tunnel client. The GTP tunnel client encapsulates the received packet into GTP-U packet [see Fig. 2(4)]. The GTP-U packet is implemented by the UDP protocol [see Fig. 2(5)] and is sent by the network adaptor [e.g., LTE or Wi-Fi, see Fig. 2(6), (7)] to the corresponding network module [Fig. 2 (8), (9)). We note that the sending network could be modified by the GTP tunnel client

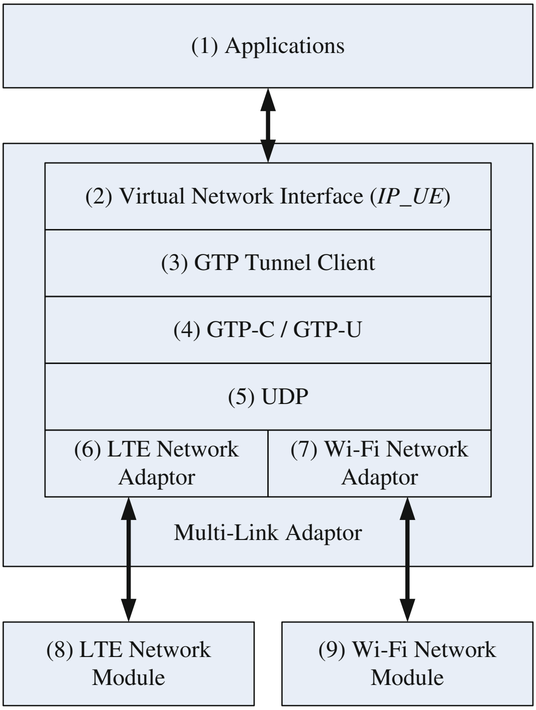

Fig. 2 MLA software architecture

when it finds that the other network is more suitable for the application than the default one (the details are described in the next section).

In addition, if the GTP tunnel client receives a GTP-U packet from the network module, it first removes the GTP-U header and sends the user data packet (i.e., the payload of the GTP-U packet) to the virtual network interface. Then the virtual network interface routes the user data packet to the application.

Figure 3 shows the MCM software architecture, which consists of the IP management [see Fig. 3(1)] and the GTP tunnel server [see Fig. 3(2)]. The IP management module is responsible for IP address allocation to the virtual network interface of the MLA for a UE. The IP address is allocated by the Dynamic Host Configuration Protocol (DHCP) function.

The GTP tunnel server is responsible for GTP tunnel management for a UE. It stores the IP addresses of the interfaces of UE and the current UE-established GTP tunnel ID (i.e., TEID) to identify the UE. It also interworks with the GTP tunnel client of the MLA to maintain the GTP connections through the GTP-C [see Fig. 3(3)] messages for network switching.

When the GTP tunnel server receives a packet from the external networks [Fig. 3(9)], the GTP tunnel server checks the destination IP of the packet and finds the corresponding TEID. Then it uses the GTP-U [see Fig. 3(3)] to forward the packet to the destination UE. The GTP-U packet is sent by UDP [see Fig. 3(4)] and IP [IP of intranet; see Fig. 3(5)] through the internal network interface [see Fig. 3(8)].

When the GTP tunnel server receives data from a UE through internal network interface, the GTP tunnel server checks the destination IP of the data and finds the corresponding routing path. Then the GTP tunnel server removes the GTP-U header and sends the IP packet (which includes the TCP/UDP and IP headers; see Fig. 3(6), (7)] through the external network interface [see Fig. 3(9)] to the corresponding destination Internet server.

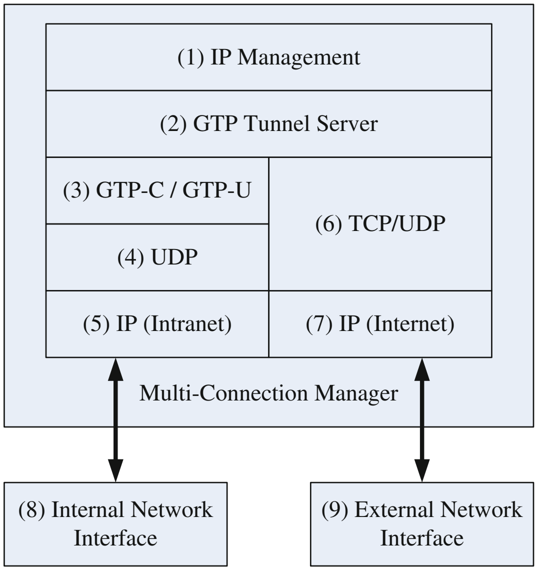

Fig. 3 MCM software architecture

Table 2 The characteristics and the QoS requirements of the QoS classes

Packet size	Packet interval	Guaranteed bit rate	Maximum transfer delay (ms)	QoS class
Small	Periodical	Yes	100	Conversation
Medium to large	Periodical	Yes	300	Live streaming
High variance	High variance	No (best effort)	N/A	Interactive
Large	Dense arrival	No (best effort)	N/A	Background

4 The Network Selection Procedure

To exercise the network selection procedure, the MLA (i.e., the GTP tunnel client of MLA) maintains two tables: the QoS class table and the routing table, where the details of QoS class table are described in Sect. 2. Since the QoS class table follows the UMTS specification [12], each class can map to corresponding QoS requirements of the UMTS specification [13]. The QoS requirements include the support of Guaranteed Bit Rate (GBR, e.g, guarantee 500 Kbps) and the maximum transfer delay (e.g., 100 ms from the MLA to the MCM). Table 2 extends Table 1 with the QoS requirements for each QoS class.

The routing table is utilized for packet routing. This table contains two entries, which are serving port number (port number of the virtual network interface of MLA for an application) and the serving network module (network module for transmitting the application packets). In general, a service flow utilizes only one serving port. Thus we use the serving port to uniquely identify a service flow. Table 3 indicates an example of the routing table.

Figure 4 illustrates the network selection procedure, the execution steps are described as follows.

Step 1. An application (e.g., FTP) initiates a new service flow, and the virtual network interface of MLA receives the first packet from the application.

Table 3 An example of the routing table

Serving port number	Serving network module
1234	LTE
5678	Wi-Fi

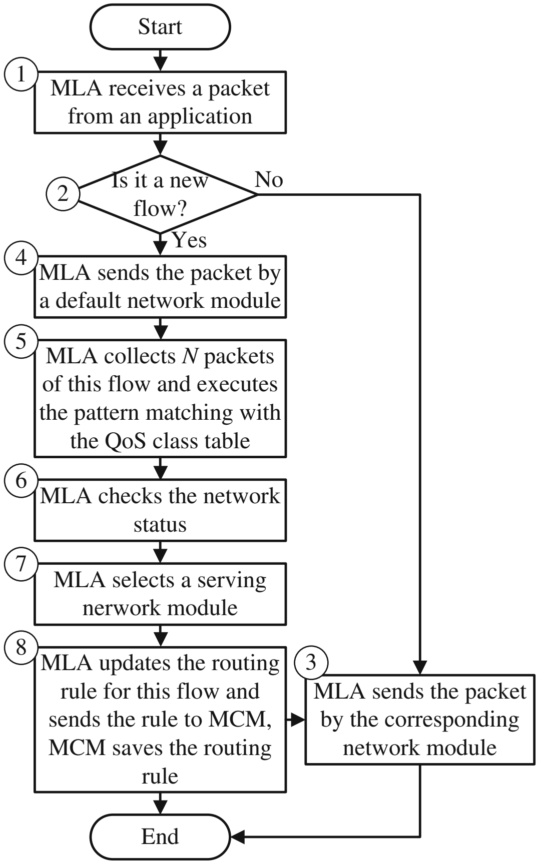

Fig. 4 The network selection procedure

Step 2. The GTP tunnel client of MLA checks the routing table with the source port (i.e., the serving port) of the packet header to see if the routing rule of the source port exists in the table. If so, the MLA executes **Step 3**, otherwise goes to **Step 4**.
Step 3. The MLA retrieves the serving network module from the routing table and delivers the packet by the corresponding network module. The procedure exits.
Step 4. The MLA sends the packet through a default network module (e.g., LTE). The MLA then creates a temporary routing rule in the routing table with the serving port and the default serving network module for handling the packets of this service flow.
Step 5. The MLA collects N packets of this service flow and compares the size of the collected packets with the packet size range of each QoS class (except for the interactive service). If most collected packets (e.g., more than 90 %) match one or more QoS classes, the MLA then compares the interval of the collected packets with the packet interval range

of each QoS class. The traffic pattern of the collected packets should at most match one QoS class (i.e., conversation, live streaming, or background). If none of the above classes is matched, the service flow is identified as an interactive class service.

Step 6. The MLA checks the network status (e.g., the GBR or the available network bandwidth and the transfer delay) to select a serving network module. The required bit rate of the services which belongs to the first two QoS classes could be estimated by counting the total packet sizes of data in a period of time. The LTE network guarantees the bit rate by the establishment of dedicated bearer [14]. As for the available network bandwidth, we assume that the MCM monitors the available bandwidths of LTE eNBs and Wi-Fi APs (e.g., by the performance management protocols defined in [15,16]). Then the MLA sends a query to the MCM for retrieving the available bandwidth information of the networks that the UE currently uses. The transfer delay between the MLA and the MCM is measured by the ping command of the Internet Control Message Protocol (ICMP) [17].

Step 7. After retrieving the status of the networks, the MLA selects a suitable radio network interface according to the QoS requirements of the QoS class that fits the service flow. The MLA sequentially checks the QoS requirements (i.e., GBR or available network bandwidth and transfer delay) to see if each network matches the requirements of the QoS class. If more than one or none of the networks matches the requirements, the MLA selects the network having the better performance (e.g., higher available network bandwidth or lower transfer delay).

Step 8. The MLA updates the routing rule according to the network selection result in **Step 7** to replace the old one created in **Step 4**. Then the MLA sends the updated routing rule to the MCM (i.e., the GTP tunnel server), and the MCM saves this routing rule in the table, and then executes **Step 3**.

In the routing table, every rule is associated with an expiration timer T_e when it is created in **Step 4** of Fig. 4. When T_e is expired, the flow is considered inactive, and the GTP client/server will remove the corresponding rule from the routing table.

5 The Network Switching Procedure

This section describes the GTP tunnel creation and the network switching procedures between the MLA and the MCM. Figure 5 shows the message flow with the following steps.

Step 1. Initially the GTP Tunnel Client of the MLA sends a GTP Create Session Request message to the MCM to create the multi-link tunnel for the UE after the UE attachment. This message carries the UE's identity (e.g., International Mobile Subscriber Identity, or *IMSI* in this example), the UE's LTE and Wi-Fi addresses (i.e., the *IP_LTE* and the *IP_Wi-Fi*) as tunneling transport addresses, and the MLA's receiving TEIDs of the LTE and the Wi-Fi networks (i.e., the *TEID_MLA_LTE* and the *TEID_MLA_Wi-Fi*). After this message is received by the MCM, the new downlink tunnels are established from the MCM to the MLA through the LTE and the Wi-Fi networks, and the UE can receive the downlink packets from the MLA through both the LTE and Wi-Fi networks. The default downlink radio tunnel is set to LTE.

Step 2. The MCM assigns an IP address for the UE (i.e., the *IP_UE*) by the IP management module. Then the MCM responses with the Create Session Response message to the MLA with the parameters *IP_UE*, the MCM tunneling address (i.e., the *IP_MCM*), and the receiving TEIDs in the MCM (i.e., the *TEID_MCM_LTE* and the *TEID_MCM_Wi-*

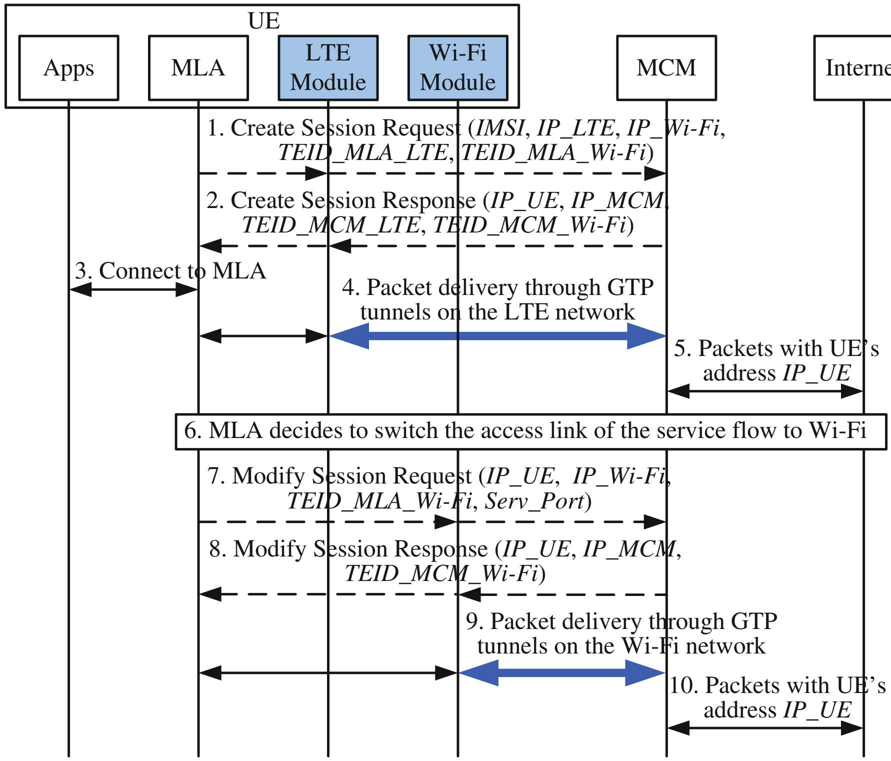

Fig. 5 Message flow for network switching procedure

Fi). After receiving this message, the uplink tunnels are established from the MLA to the MCM through both the LTE and the Wi-Fi networks. The default uplink radio tunnel is set to LTE.

Step 3. The UE application connects to the MLA for packet delivery.

Step 4. All user packets are transmitted between the UE and the MCM through the MLA and the LTE network. The MLA encapsulated the packets and sent them to the MCM through the GTP tunnel with the uplink TEID (e.g., the LTE TEID *TEID_MCM_LTE*). The packets are delivered and received through the GTP tunnels on the LTE network between the MLA and the MCM.

Step 5. The MCM acts as the tunnel endpoint by processing the user plane data based on the packet directions. For an uplink packet from the UE, the MCM decapsulates the tunneled packet (e.g., with the uplink LTE TEID *TEID_MCM_LTE*) and forwards it to the Internet with the *IP_UE* as the source packet address. For a downlink packet to the UE (destined for the *IP_UE* address), the MCM checks its destination port in the routing table and the MCM encapsulated the packet and sent it to the UE through the GTP tunnel with the downlink TEID (e.g., the LTE TEID *TEID_MLA_LTE*).

Step 6. Through the traffic pattern analysis in Fig. 4, the GTP tunnel client of the MLA decides to switch the access link of the service flow from LTE to Wi-Fi.

Step 7. The GTP tunnel client of the MLA sends a GTP Modify Session Request message to the MCM through the UE's Wi-Fi module with the *IP_UE* as the UE's identity, the *IP_Wi-Fi* as the tunneling transport address, its receiving TEID (i.e., *TEID_MLA_Wi-Fi*), and the serving port number (i.e., *Serv_Port*) of the flow. After this message is received by the MCM, the MCM creates the corresponding routing rule for this flow (see **Step 8** of the network selection procedure), and the downlink packets of the flow are transmitted from the MCM to the MLA through the Wi-Fi network.

Step 8. The MCM responses with the Modify Session Response message to the MLA with the parameters *IP_UE*, the *IP_MCM* and the receiving TEID in the MCM (i.e., *TEID_MCM_Wi-Fi*). After receiving this message, the uplink packets of the flow are transmitted from the MLA to the MCM through the Wi-Fi network.

Step 9. The service flow of the UE application then accesses the Internet through the MLA and the Wi-Fi network module. The packets are delivered and received through the GTP tunnels on the Wi-Fi network between the MLA and the MCM.

Step 10. The MCM decapsulates the uplink tunneled packet from the UE (with the uplink Wi-Fi TEID *TEID_MCM_Wi-Fi*) and forwards it to the Internet. For a downlink packet to the UE (destined for the *IP_UE* address), the MCM encapsulated the packet and sent it to the UE through the GTP tunnel with the downlink Wi-Fi TEID (i.e., *TEID_MLA_Wi-Fi*).

The above example illustrates how our approach switches the radio link of a service flow for the user application. In this example, we use GTP tunnels as the data bearer to carry the user packets transmitted either through the LTE network or the Wi-Fi network. Our approach adapts the modified GTP-C protocols for session management, and the maintenance between the MCM and the MLA is also based on the GTP-C protocol, which is utilized by the LTE core network to carry the user data between the S-GW and P-GW. Our multi-link switching approach is similar to the handover procedure with S-GW relocation in LTE. In this case, the MCM acts as a P-GW to switch the data path between LTE and Wi-Fi without establishing extra tunneling between the MCM and the MLA, and thus mitigates the tunneling overhead.

6 Concluding Remarks

This paper presented a multi-link mechanism to deal with selection and switching between LTE and Wi-Fi networks. The Multi-Link Adaptor (MLA) and the Multi-Connection Manager (MCM) are proposed respectively for the UE and the core network to handle the multi-link mechanism. The applications executed in the UE do not need to be modified under the proposed approach. The MLA maintains the QoS class table and the routing table for the network selection procedure and uses the GTP-C control messages to execute the network switching procedure. In the future, we will measure the throughput of the multi-link network and the switch delay between the heterogeneous radio networks for evaluating the performance of the multi-link mechanism.

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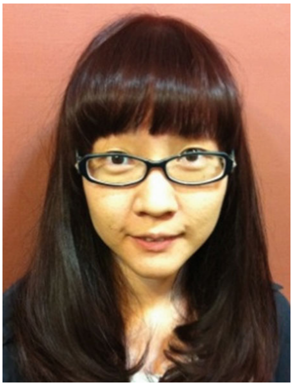

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