Distribution of UMTS protocols for ad-hoc extensions with direct signaling

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***Abstract*—Ad-hoc extensions of cellular networks help reducing intra-cell interference and hence increasing the capacity of cellular systems. This paper proposes an appropriate distribution of UMTS protocols between end terminals and intermediate relaying devices aiming at increasing capacity in UMTS while following two main principles: improving robustness by using a direct cellular connection for signaling and maintaining end-to-end data privacy between the end terminal and the network.**

I. INTRODUCTION

IN recent years, an active research area in the field of mobile communication networks has been the integration of cellular and ad-hoc networks. Its purpose is twofold: on the one hand, network operators can take profit of ad-hoc extensions to improve the coverage and capacity of their cellular networks; on the other hand, ad-hoc users can access services provided by the cellular network.

Network operators will be mainly interested in extending their cellular systems by means of ad-hoc networks. In such scenarios, end terminals are connected via their ad-hoc interface to an intermediate relaying device, which in turn provides access to the cellular network. In the following, the terms Mobile Client (MC) and Mobile Relay (MR) will be used to refer to the end terminal and the intermediate relaying device, respectively. The MC can connect to the MR, through the ad-hoc interface, either directly or via a multi-hop path, leading to two types of ad-hoc extensions: one-hop and multi-hop. The main difference is that multi-hop extensions require the usage of ad-hoc routing protocols within the ad-hoc network. Though currently a hot topic in wireless communications research [1], they will not be dealt with here.

When cellular systems are extended by means of ad-hoc networks, three main benefits can be identified:

– Coverage of the cellular system can be increased by serving end terminals located outside the coverage area via ad-hoc extensions.

– Interference caused by end terminals requiring large transmission powers in the cellular network can be lowered by serving those terminals via intermediate relaying devices requiring lower transmission power. Therefore, a capacity increase can be achieved in the cellular system. In particular, reduction of intra-cell interference results especially relevant for CDMA-based systems (e.g. UMTS).

– Load balancing between cells could also be provided by diverting end terminals to neighboring cells via ad-hoc extensions.

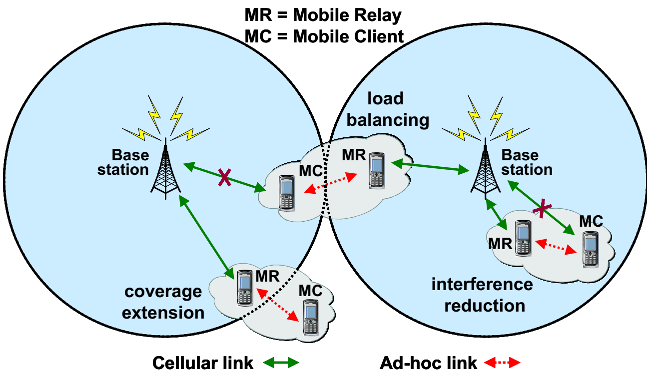

Fig. 1. Benefits of one-hop ad-hoc extensions of cellular systems

The chance to apply ad-hoc extensions depends on the availability of potential relaying devices. Consequently, using this technique to enhance coverage provides no guarantees unless operator-owned fixed relays are used. However, when ad-hoc extensions are applied to enhance network capacity, the intermediate relays need not be fixed, since their temporary unavailability would only imply no improvement on the usual capacity of the cellular system. Obviously, the higher the number of potential relaying devices is, the better capacity improvements can be reached. Previous work developed by the University of Kassel and Alcatel Research and Innovation includes some preliminary simulations showing a very promising potential for intra-cell capacity enhancement in UMTS [2].

In this scenario, the most critical aspect to be taken into account when deciding whether to use a relayed connection for a particular terminal is the power level required to serve the terminal within the cellular network. This is determined by two main factors: the distance between the base station and the terminal and the required bandwidth. Of course, this distance should not be understood as a physical distance but rather as an "equivalent distance", which would take into account all propagation losses caused not only by physical distance but also by other phenomena such as shadowing.

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This paper proposes a model for the application of ad-hoc extensions to the UMTS cellular system, based on the split of control and user plane connections as well as the separation of the different UMTS air interface protocols between the MC and the MR. The proposed design has two main motivations: on the one hand, usage of direct cellular signaling can improve robustness of ad-hoc relaying; on the other hand, an appropriate distribution of UMTS protocols between MR and MC must be identified, which maintains end-to-end ciphering. Both aspects are covered in detail in the paper.

II. UMTS Air Interface Protocol Architecture

In addition to the physical layer, air interface protocols in UMTS include a number of layer 2 protocols as well as several layer 3 protocols responsible for signaling [3]. The WCDMA-based physical layer includes a higher sublayer in charge of macrodiversity splitting and combining (required for soft/softer handover). Layer 2 protocols include MAC (Medium Access Control) and RLC (Radio Link Control). For packet-switched services, an additional layer 2 protocol named PDCP (Packet Data Convergence Protocol) provides header compression for packet-switched services.

RLC supports three modes of operation: Acknowledged Mode (AM) and Unacknowledged Mode (UM) for reliable and unreliable packet-switched services, respectively, and Transparent Mode (TM) for circuit-switched services.

With respect to layer 3 protocols, they include RRC (Radio Resource Control), responsible for all signaling exchanged between the terminals and the access network, and several higher sublayers in charge of Non-Access-Stratum signaling (NAS signaling) between the terminals and the core network.

UMTS specifications define three types of channels:

- *Logical channels,* defined between MAC and RLC and characterized by the kind of information they transport, either signaling or traffic associated to a particular user or cell.

- T*ransport channels*, onto which logical channels are mapped by MAC, defined between the physical and MAC layers and characterized by the way in which data is formatted. Transport channels can be dedicated or common / shared, i.e. associated to a particular user or cell.

- *Physical channels*, onto which transport channels are mapped by the physical layer and corresponding to the actual radio channels used through the air interface.

For the purposes of this paper, the most important logical channels are those associated to a particular user: the dedicated control channel (DCCH) and one or several dedicated traffic channels (DTCH). Depending on service characteristics, they can be mapped to dedicated channels (DCHs), or to common / shared transport channels, including RACH (Random Access Channel), FACH (Forward Access Channel) and optionally CPCH (Common Packet Channel), DSCH (Downlink Shared Channel) and HS-DSCH (High Speed Downlink Shared Channel, introduced in 3GPP Release 5). Mapping from transport to physical channels is not relevant for this paper and will not be further discussed here.

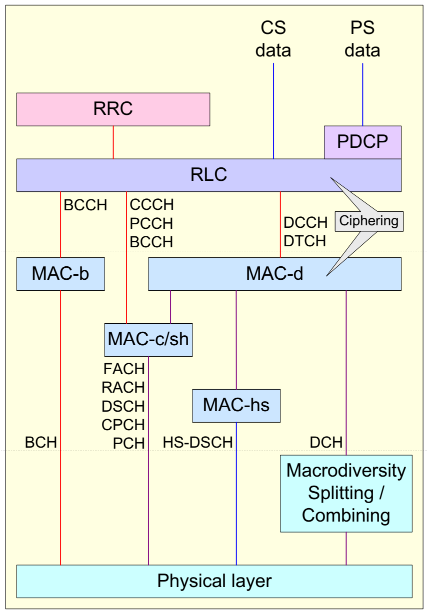

Fig. 2. UMTS air interface protocol architecture

There are four MAC sublayers responsible for the different types of transport channels: MAC-d (for dedicated channels), MAC-c/sh (for most common/shared channels), MAC-b (for the broadcast channel) and MAC-hs (for HS-DSCH).

III. Establishment of Radio Bearers in UMTS

One characteristic feature of the UMTS system is a strict separation between control and user planes, across the air interface and within UTRAN interfaces. From the point of view of the access network, the establishment of the communication is carried out in three stages:

1) Establishment of a signaling connection (named RRC connection) between a terminal or user equipment (UE) and its associated Serving Radio Network Controller (SRNC), which provides access to the core network. As a result, a dedicated control channel (DCCH) is created between the terminal and the SRNC, which will be used for any further signaling exchange.
2) Negotiation of service characteristics between the core network and the terminal, through the use of Non-Access-Stratum (NAS) signaling, which is forwarded between the core network and the terminal transparently by the SRNC (through the DCCH established in stage 1).
3) Establishment of a data connection between the terminal and the SRNC, consisting of one or several Radio Bearers (RBs). This establishment is triggered by the core network through the transmission of a message describing service characteristics according to the previous negotiation between terminal and core network. Radio Bearers make use of dedicated traffic channels (DTCHs).

Except for HSDPA, which will be discussed later, signaling and data are usually mapped onto the same physical channel across the radio interface, i.e. either one of the common channels of a particular cell or a dedicated channel associated

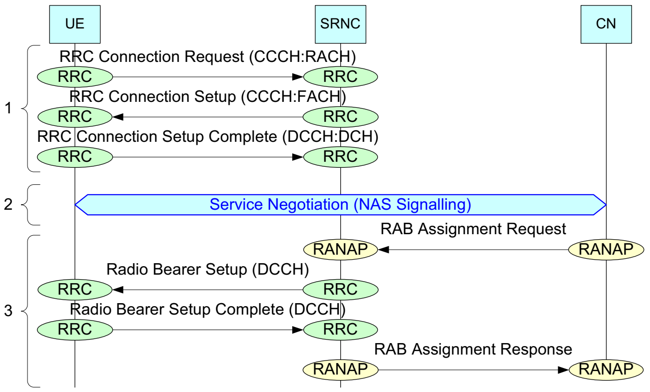

Fig. 3. Three-stage connection setup in UMTS

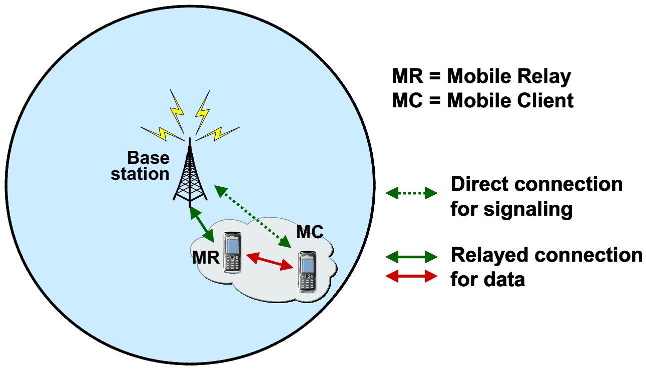

Fig. 4. Ad-hoc extensions with direct cellular signaling

to the user connection. When a dedicated physical channel is used, it is initially set up during stage 1 and reconfigured to cope with service requirements in stage 3.

IV. Direct Signaling for Ad-Hoc Extensions of UMTS

From the perspective of ad-hoc extensions, the three-stage establishment mechanism discussed in the previous section is especially relevant. According to the discussion, the expected benefits in terms of capacity enhancement will depend mainly on the quality of the radio link between the end terminal and the base station as well as the required bandwidth. Moreover, timing requirements could render ad-hoc extensions unsuitable for some particular services. Since the access network is not aware of service requirements until stage 3, it will not be able to evaluate whether a particular terminal should better be served through a direct or a relay connection during the initial establishment of the RRC connection.

By splitting control and user plane connections, a direct cellular connection for the dedicated control channel (DCCH) can be used while applying ad-hoc relaying to dedicated traffic channels (DTCHs). With such an approach, a standard RRC connection is directly established between the MC and the access network, according to stage 1. After this point, service negotiation is carried out through standard UMTS procedures, corresponding to stage 2. Finally, as the establishment of the data connection starts, the access network is made aware of service characteristics and it can decide upon the usage of a direct or relayed connection (through an MR) to serve the MC.

An important advantage derived from the usage of a direct cellular connection for signaling is that a failure on the ad-hoc link between the MC and the MR would only affect the data connection. This would allow for a fast reconfiguration of data bearers through the signaling connection, hence avoiding a call drop by selecting a direct connection or a different relaying device to support the end terminal. With traditional ad-hoc relaying mechanisms, failure on the ad-hoc link would result in a call drop, since both the signaling and data connections would be lost. Though relayed signaling would allow for slightly higher capacity gains, using a direct cellular connection for signaling can be afforded due to its reduced bandwidth consumption in comparison to high speed services. Nevertheless, it must be emphasized that direct signaling can only apply if the terminal is located within the cellular coverage area.

V. Ciphering Aspects for Ad-Hoc Extensions of UMTS

Another important aspect which must be addressed when applying ad-hoc extensions is security. In particular, ciphering and deciphering should take place end-to-end between the cellular network and the end terminal, preventing malicious third-party relaying devices from intercepting valuable information. Although it is possible to apply encryption mechanisms at higher layers above the UMTS-specific air interface protocols (e.g. IPSEC), this would result in extra processing load in the end terminal as well as a higher amount of overhead across the radio interface, hence contributing to a decrease in the effective system capacity. Consequently, data secrecy must be kept while performing ciphering and deciphering preferably at the usual level in the air interface protocol stack. This can only be accomplished through an appropriate distribution of air interface protocols between the MR and the MC.

In UMTS, encryption is only applied to dedicated logical channels, including both traffic and signaling (i.e. DTCH and DCCH). When ad-hoc relaying with direct cellular signaling is applied, only user plane data is relayed through the MR. Consequently, the protocols carrying out ciphering for the DTCH(s) must be placed in the MC in order to maintain data privacy despite the use of an intermediate relay. Ciphering is carried out either in the RLC layer (for RLC AM and UM) or the MAC-d sublayer (for RLC TM). Therefore, the RLC layer and the MAC-d sublayer associated to the DTCH(s) must be placed in the MC.

VI. Layered Model for the Ad-Hoc Interface

The paper is focused on the impact of ad-hoc extensions with direct cellular signaling on the UMTS system. Therefore, no specific technology has been selected for the ad-hoc interface, which could be based on WLAN, Bluetooth or any other technology. For each potential technology, an in-depth analysis should be carried out in order to determine its suitability for the integration with UMTS. However, this paper analyses the influence of relaying mechanisms on UMTS, isolating UMTS protocols from the particularities of any particular underlying ad-hoc technology.

In order to describe relaying across the ad-hoc interface, a layered model inspired on the general model for the description of UTRAN interfaces has been used [4]. According to this model, protocols used across the ad-hoc interface could be separated in two horizontal layers, named Radio Network Layer (RNL) and Transport Network Layer (TNL), and two vertical planes, corresponding to the control and the user plane. The split between RNL and TNL protocols allows to keep all UMTS-related mechanisms in the RNL, isolating them from the specific protocols used in the ad-hoc network, which are considered as TNL protocols. Therefore, ad-hoc protocols are only seen as a means to provide RNL protocols with transmission services for the control and user plane, i.e. signaling and data bearers, respectively.

For different ad-hoc technologies, TNL protocols will of course be different, but RNL protocols will not be affected (or only slightly) as long as TNL protocols provide the required signaling and transport bearers. Therefore, the proposed model would be applicable to one-hop as well as multi-hop ad-hoc extensions as long as this condition is kept. It must be noted here that TNL protocols could include, in addition to native ad-hoc protocols, some additional adaptation layers to provide the required transmission services to RNL protocols (e.g. SCTP/IP for signaling bearers or UDP/IP for data). Obviously, a detailed analysis of other aspects such as signaling or routing mechanisms, linked to a particular ad-hoc technology, is also required, but it is out of scope here.

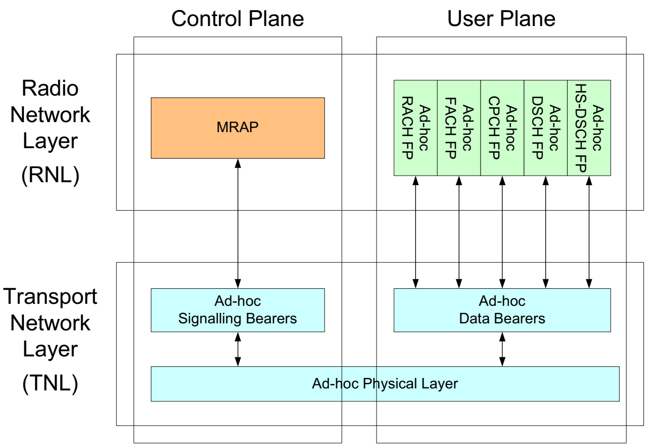

Fig. 5. Model for the ad-hoc interface between MR and MC

With respect to the RNL, it includes a single signaling protocol in the control plane, which has been named MRAP (Mobile Relay Application Part) in analogy to UTRAN protocols. The user plane contains a number of Frame Protocols (FPs) associated to the different types of transport channels, which basically provide synchronization and flow control mechanisms between MR and MC. They are also analogous to Frame Protocols used across the Iub interface between RNC and Node B in UTRAN, although they must cope with the peculiarities of ad-hoc transmission, which is far more critical than transmission across terrestrial interfaces.

VII. Protocol Stacks For Ad-Hoc Extensions of UMTS

In most previous proposals for the integration of cellular and ad-hoc networks, layer 2 protocols from the cellular interface were usually terminated in an intermediate ad-hoc relay and not in the end terminal ([5], [6]). However, unless inefficient ciphering mechanisms are applied above UMTS protocols (e.g. IPSEC), end-to-end privacy would be violated. In order to preserve privacy without compromising efficiency, those layers performing encryption and decryption must be located in the end terminal. Consequently, the RLC layer and the MAC-d sublayer associated to dedicated traffic channels (DTCHs) and responsible for their ciphering must be located in the MC, hence forcing PDCP to be placed also there. However, other MAC sublayers below MAC-d in the protocol stack are kept together with the physical layer in the MR.

Dedicated logical channels can be mapped onto different transport channels by the MAC layer. When a DCH is selected, the MAC-d sublayer is responsible for scheduling. Otherwise, the MAC-d sublayer will forward this information to the appropriate MAC sublayer responsible for scheduling. Since the MAC-c/sh and MAC-hs sublayers are located in the MR, radio frames must be transported across the ad-hoc interface by means of the different types of ad-hoc Frame Protocols discussed before.

When direct signaling is applied, the MC also contains the RLC, MAC and physical layers involved in processing logical control channels, either dedicated (DCCH) or common (CCCH, BCCH, PCCH). Of course, the MR makes also use of common logical channels and its own DCCH, and it also contains related layers. According to this discussion, UMTS protocols must be distributed between MR and MC, leading to the protocol stacks depicted in Fig. 6, which shows also TNL protocols across the ad-hoc interface between MR and MC.

The extension of UMTS by means of ad-hoc relaying requires the introduction of new signaling procedures between MR and MC, which are carried out through the MRAP protocol. Moreover, the redistribution of UMTS protocols has an influence on UMTS signaling procedures. In UMTS, configuration parameters for air interface protocols are sent by the network as information elements within different RRC messages (e.g. for Radio Bearer setup). With the proposed protocol distribution, current RRC messages must be split in their MR-related and MC-related parts (depending on the location of each particular protocol) and sent through their respective RRC connections. In addition, it may be necessary to introduce some new mechanisms, for instance the exchange of ad-hoc related measurements with the network. A detailed study of signaling procedures can be found in [7].

Other distributions of UMTS protocols could also be considered. For instance, when a terminal is using multiple services in parallel, relaying could be applied only to a subset

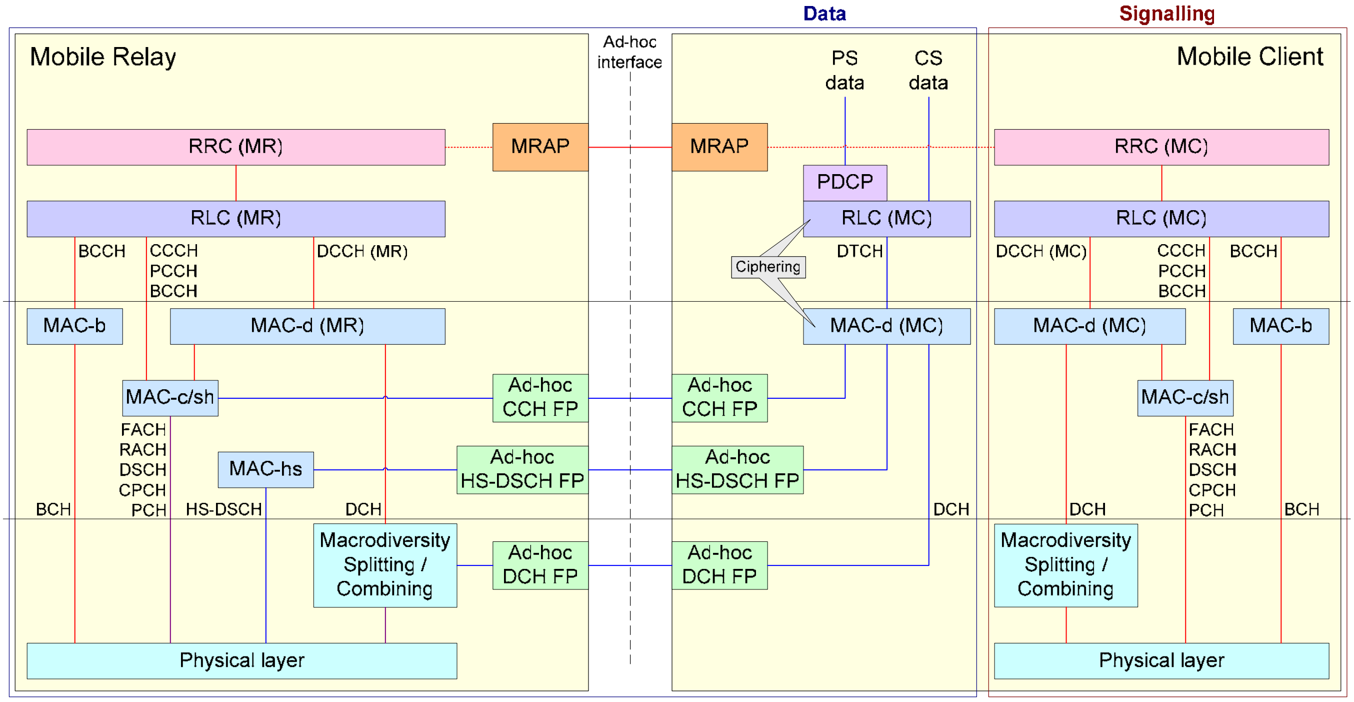

Fig. 6. UMTS air interface protocol distribution between MR and MC, with direct cellular signaling and ad-hoc relaying for data

of those services. In this case, some DTCHs would be relayed, but others would be directly transferred to the cellular network, together with the DCCH. This could be the case for services with low bandwidth, for which only a small gain can be achieved through relaying, or for services with very strict timing requirements, which can not be probably met unless a direct connection is used. Voice services have usually both characteristics and are hence not appropriate for relaying. However, a considerable gain can be obtained for packet services with high data rates, using either a dedicated channel (DCH) or the HS-DSCH (High Speed Downlink Shared Channel). This channel was introduced in 3GPP Release 5 to provide HSDPA (High Speed Downlink Packet Access) services. In the vicinity of the base station, theoretical data rates are in the order of 10 Mbps. However, the effective data rate decays quickly with the distance to the base station, making this kind of service the ideal candidate for the application of ad-hoc relaying.

VIII. Conclusions and Further Work

The design presented in this paper aims at improving the capacity of the UMTS system by applying ad-hoc extensions. Several features are desired for the resulting system, which have some implications on design, as summarized in Table I.

In addition to the proposed protocol stack, there are other alternatives which could be taken into account. For instance, if the MC is outside the cellular coverage area, direct signalling can not be applied, and the DCCH must be handled in the same way as the DTCH in the protocol stack. The opposite case occurs when the MC is inside the cellular coverage area and using several services in parallel. When relaying is not applicable to a particular service, due to its low bandwidth or its very strict timing requirements, its associated DTCH would be handled in the same way as the DCCH in Fig. 6.

Further work should deal with a deeper investigation of ad-hoc technologies and its suitability for extending UMTS as well as improved simulations to predict a more accurate value for the actual capacity gain achieved in UMTS.

TABLE I
Desired Features and Implication on Design

Desired feature	Implication on design
Increase of cellular capacity	Ad-hoc extensions for terminals requiring large transmission powers
Robustness of integrated system	Direct cellular signaling (only within cellular service area)
End-to-end data privacy	Protocols performing ciphering (RLC and MAC-d) in end terminal

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