Generic Link Layer Functionality for Multi-Radio Access Networks

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***Abstract* — An approach to multi-radio cooperation is presented in this paper, based on the concept of universal link layer processing over different radio access technologies. To this end, we propose a Generic Link Layer (GLL) which efficiently maps user service demands on to multiple "heterogeneous" radio access networks at any instant of time. Specifically, the GLL architecture and functionality are presented and investigated in the context of two novel applications, namely multi-radio transmission diversity (MRTD) and multi-radio multi-hop (MRMH). Both applications exploit various forms of multi-radio diversity in order to achieve gains in system throughput, efficient utilization of radio resources, and increased robustness in radio link quality. The evaluation of these applications by means of analysis, simulations and prototyping is a topic of ongoing and future work.**

***Index Terms* — Multi-Radio Access, Generic Link Layer, Transmission Diversity, Multi-hop.**

I. INTRODUCTION

Current research directions for future mobile and wireless systems beyond 3G involve the development of new radio access technologies (RATs) as well as their integration with existing systems. The former aims at further improving link capacity and spectrum efficiency, while the latter aims at enabling cooperation between different RATs and the corresponding wireless access networks in order to provide a continuous and technology-agnostic service to mobile users.

In this paper, a Generic Link Layer[†] (GLL) is proposed that provides universal link layer processing over different RATs for the purpose of multi-radio cooperation at the radio access level. This work builds on past research [3][4] by examining how multi-radio access can be supported via co-operation at link layer. Compared to prior research, e.g. [5]-[9], where link layer cooperation is partially addressed, the GLL defines and supports several novel multi-radio diversity mechanisms enabled by different levels of multi-radio co-operation at link layer.

The GLL amounts to a toolbox of configurable link layer functions that perform radio protocol reconfigurations for efficient mapping between user service demands and the available RAT air interfaces at any instant of time. Hence, the GLL conceptually extends the functionality of the link layer in three directions: (*i*) towards the higher layers by hiding the heterogeneity of the RATs from both users and services; (*ii*) within and across RAT link layers by integrating them at different levels into an "homogeneous" unified link layer; and (*iii*) towards the physical layer, through efficient and dynamic utilisation of underlying radio resources.

The first objective is realised by means of a generic interface towards higher layers such as Radio Resource Management (RRM) and the IP layer. The second is achieved by a set of core functions that map the different RAT link layer functions both vertically and horizontally. And finally, for the efficient utilization of radio resources, the GLL enables two novel mechanisms: multi-radio transmission diversity (MRTD) and multi-radio multi-hop (MRMH) networking. In terms of user data transmission, MRTD refers to the dynamic utilisation of multiple radios over a single hop, while MRMH refers to the dynamic utilisation of multiple radios over multiple hops. These two mechanisms are the focus of this paper, and are envisaged to be among key technologies for cost-effective and RAT-agnostic data transmission in systems beyond 3G.

This paper is organised as follows: Sections II and III introduce in general terms the concepts of MRTD and MRMH respectively, where various associated mechanisms are elaborated and their benefits and costs are discussed. Section IV presents the basic architecture and functions of the GLL and its mapping to the mechanisms of MRTD and MRMH. Conclusions are drawn in Section V.

II. MULTI-RADIO TRANSMISSION DIVERSITY (MRTD)

A. *Mechanism and Diversity Schemes*

Based on a novel extension of various PHY-layer diversity mechanisms applied in today's wireless systems, Multi-Radio Transmission Diversity (MRTD) may be broadly defined as the dynamic selection of multiple radio accesses for the transmission of a user's data. Here the term "radio accesses" (RAs) is used to refer to uncoupled radio channels, either across different RATs or within a single RAT (e.g. multiple carrier frequencies of a specific radio standard). Apart from the availability of multiple RAs, MRTD assumes devices (e.g. infrastructure nodes and user mobiles) capable of transmission and reception over multiple RAs. Implementation of MRTD principally consists of a multi-radio selection policy, which assigns a RA to each "scheduled" data-unit (e.g. MAC PDU or IP packet) according to a set of metrics. The multi-radio selection policy realizes the objectives of improving the QoS, by

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[†] This work was undertaken within the Ambient Networks [1][2] integrated project as part of the EU Sixth Framework IST program.

increasing throughput and/or robustness, while fulfilling the application and operator requirements in terms of resource usage efficiency.

Depending on the exact nature of the multi-radio selection policy, various MRTD schemes are possible as defined by the three attributes of: re-selection rate, parallelism and redundancy. The re-selection rate refers to the rate at which access selection is performed. This may correspond to the transmission time of data units ranging from a PHY- or MAC-layer PDU, to multiple IP packets, or even a whole data flow. Thus, depending on the re-selection rate, MRTD can be applied at different levels within L2 protocol layer. In this paper, the applications of MRTD to MAC protocol data units (PDUs) and to packets received from the IP layer are considered and referred to as *MRTD at MAC PDU* level and *MRTD at IP packet* level respectively. Parallelism refers to the possibility of selecting one *or* multiple RAs at any given time for the transmission of a user's data resulting in what we term switched (sequential) or parallel (simultaneous) MRTD respectively. Redundancy refers to the possibility of transmitting copies of the same data over multiple RAs as part of the MRTD mechanism. Different MRTD schemes may also be combined. For instance, in parallel MRTD multiple RAs can be used to transmit successive units of data or multiple copies of the same data unit.

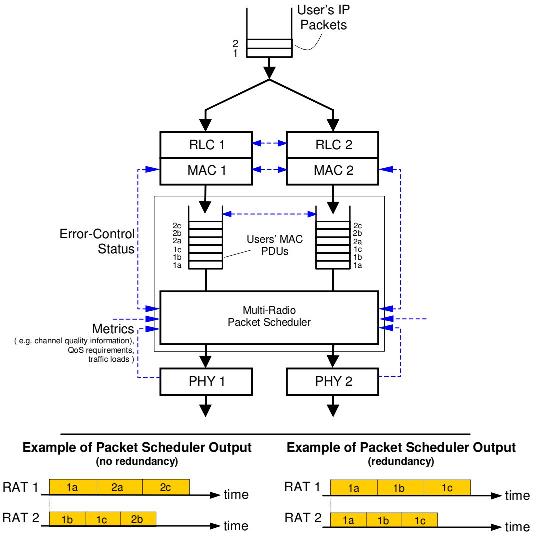
MRTD at MAC PDU level is viable in scenarios where different RAs are tightly integrated (and possibly provided by a single operator). In this case, the required high re-selection rates are feasible through exploitation of near-instantaneous measurements and reports of radio link quality. On the other hand, MRTD at IP packet level, with its lower re-selection rates, is applicable even in scenarios where the RAs are loosely integrated (and possibly provided by different operators).

To better illustrate the idea, MRTD at MAC PDU level may be thought of as multi-radio packet scheduling, an extension of the single-radio scheduling and fast cell-site selection mechanisms that already exist in 3G systems [10][11]. At slower re-selection rates, the user data transmitted on the selected RA may consist of very large numbers of PDUs. This is then, at least conceptually, similar to a form of multi-radio hard handoff, as currently exists between cellular systems such as GSM and UMTS.

B. An Illustrative Example of MRTD

This section describes an example of parallel MRTD with re-selection at the MAC PDU Level, as it represents the highest level of GLL-enabled inter-working amongst RAs. It is assumed that, so far as the multi-radio selection process is concerned, a MAC PDU intended for a specific user is the atomic unit of information. Consequently, a user's data equal in size to the payload of MAC PDUs, may be transmitted via multiple RA physical layers at any given time. Successive MAC PDUs may be transmitted via different RA physical layers, as directed by feedback from the RA protocol stacks.

Fig. 1 shows the parallel diversity process for the case of two RAs. For simplicity of description, the example illustrates a scenario where the PDU sizes are equal across the two RAs. In most common scenarios, different PDU sizes would be used, leading to different packet-numbering schemes. A book-keeping function would then maintain the relationship between these numbering schemes.



- All MAC MPDUs are assumed to contain the same number of information bits.
- RAT2 is assumed to have a higher bandwidth than RAT1.

Fig. 1: Example of parallel transmission diversity at MAC PDU level.

In the presented example, each RA-specific MAC layer segments the first IP packet into three MAC PDUs: 1a, 1b and 1c. In case of no redundancy, the scheduler simultaneously forwards PDU 1a and 1b to PHY1 and PHY2 respectively. Once the transmission over the air of 1b is complete, the scheduler forwards PDU 1c to PHY2. Upon complete transmission over the air of 1a, the scheduler forwards PDU 2a to PHY1, and so on. Note that the parallel scheduling implies that, at any time, multiple PHY layers may be processing a particular user's data simultaneously.

In the case with redundancy, a copy of each MAC PDU is forwarded to both RA-specific PHY layers. This raises some interesting possibilities in terms of diversity combining at the receiver. In principle, soft information (i.e. log-likelihood ratios) on the same bits but received from different PHYs can be combined at the decoder input in order to reduce the bit error rate. In this way, redundancy in parallel MRTD can also be exploited via multi-radio reception diversity. The associated gains, however, are at the expense of information exchange and synchronization between multiple receivers at the PHY layer.

It is interesting to note the impact of multi-radio packet scheduling on the RA-specific ARQ mechanisms. Upon successful reception of the transmitted data, the receiver replies with an acknowledgement (ACK) transmitted via the same RA as the original data. Upon such positive acknowledgement, the successfully received MAC PDUs are removed from the buffers of all RAs, and the scheduler proceeds to service the remaining packets. Should the transmitted MAC PDUs be received unsuccessfully, they may be re-transmitted via a new RA as determined by the scheduler, resulting in multi-radio ARQ. It should be pointed out that MRTD operation can be transparent to any ARQ mechanism operating at the Radio Link Control (RLC) layer (e.g. in acknowledged mode). This is subject to the RA-specific RLC layers sharing information regarding the successful transmission of RLC PDUs.

C. Benefits and Costs

It is envisaged that greater diversity gains can be attained with higher re-selection rates. This is because the diversity mechanism can better respond to rapid variations in the individual RA link capacities. However, diversity gains have to be traded-off against the costs associated with increased re-selection rates. High re-selection rates rely on the availability of up-to-date and accurate channel quality information across the cooperating physical nodes, which imply an increase in signalling traffic and relevant processing. It is also apparent that higher re-selection rates imply co-operation amongst the RAs at lower protocol layers, which increases the complexity of such solutions.

Parallel MRTD can provide the possibility of increased data rates and/or improved robustness (redundancy) through the simultaneous use of multiple RAs. However, this also has significant implications in terms of power consumption and complexity, particularly for the mobile terminal. In comparison to the parallel mode, switched MRTD implies that a user's data is processed via a single RA-specific protocol stack at any given time. Consequently, switched MRTD is likely to lead to lower power consumption and hardware complexity at the mobile terminal. This may be a significant advantage in radio transceiver architectures where analogue and digital sub-systems are shared by different RAs.

III. MULTI-RADIO MULTI-HOP (MRMH)

A. *Concept and Functions*

Based on a novel extension of current state of the art in multi-hop relaying, Multi-Radio Multi-hop (MRMH) may be broadly defined as the transmission of user data over multiple hops operating via different radio accesses. A multi-hop link comprises of three types of nodes: a source node (e.g. an infrastructure node), one or more relaying nodes (e.g. fixed or mobile nodes), and finally a destination node (e.g. a user terminal). In a manner similar to wireless ad-hoc networks, MRMH allows source and destination nodes that are not within range, to communicate by enlisting the aid of a relaying node in forwarding the packets between them. With nodes capable of transmission and reception over multiple RAs, MRMH adds spatial and route diversity to the GLL's arsenal of diversity schemes.

Fig. 2 illustrates a typical MRMH scenario where a link layer connection may span over a route containing multiple hops. Note that for simplicity of presentation, the GLL is depicted as a layer above the RLC. In fact, a number of different options exist with regards to the level of radio access integration through the GLL.

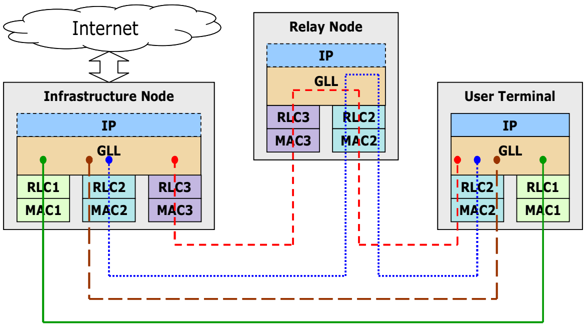


Fig. 2: A typical Multi-Radio Multi-hop scenario.

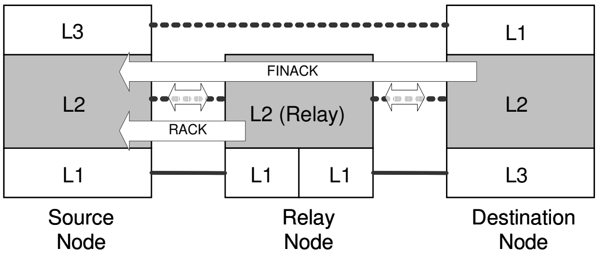


Fig. 3: Relay ACK (RACK) and Final ACK (FINACK) feedback report in Multi-Hop ARQ.

The aim of MRMH is to hide the diversity of the different RATs along a multi-hop route, while providing the same level of reliability as in the case of a single hop. Depending on the level of integration, the MRMH mechanism extends basic link layer functionality to address the complete route as opposed to each individual hop. The link layer functions considered for the realisation of MRMH include error control and recovery, flow control and segmentation, and reassembly over multiple hops operating via different RAs. Additionally, MRMH extends link layer (L2) packet forwarding to accommodate transmission over multiple routes and traffic priority based on QoS demands. Several features of MRMH are described next.

1) *Multi-Hop ARQ Scheme*

Multi-hop ARQ refers to a unified error recovery protocol spanning over the complete multi-hop route. It may be described in terms of a two-stage error recovery process, as illustrated in Fig. 3. When an intermediate relay node successfully receives a data unit it responds with a Relay Acknowledgement (RACK), indicating to the previous node that a data packet has been successfully received. Consequently, the previous node delegates the retransmission responsibility to the next node and switches from an active ARQ state into a passive ARQ state. However, the transmitted data is not yet deleted from its ARQ buffer. It is only when the data packet has been received at the final receiver and upon reception of a final acknowledgement (FINACK), that the data is removed from the ARQ windows of all the nodes along the route.

2) *Adaptation to different RATs on different hops*

In general, different RATs will be used along a multi-hop route, implying different L2 segmentation sizes per hop. This poses the problem that no common sequence-numbering scheme can be used along the route. In one solution, received data can be re-segmented and new sequence numbers re-assigned at the transition from one RAT to another. Another solution is to perform RAT-specific segmentation per hop.

3) *Multi-hop flow control and priority-based queuing*

The capacity of a multi-hop route is typically determined by the bottleneck hop or "weakest link". It is therefore not sensible to have more data in flight on the multi-hop route than the bottleneck capacity (or some anticipated variations thereof). A further advantage of a common multi-hop ARQ layer is that a bottleneck node can use a flow control mechanism in order to avoid extensive data buffering. This reduces the amount of data that needs to be recovered in cases where the route changes. To facilitate the prioritisation of certain types of packets (e.g. ARQ signalling) a priority based queuing discipline is required.

4) *Multi-Route Transmission Diversity (MRoTD)*

Assuming that routing functionality is provided by the upper layers or by a Multi-Radio Resource Management (MRRM) entity, route selection mechanisms can be built on two distinct combinations of MRMH and MRTD: (i) those that address the problem from within the route (i.e. at the relay nodes) and, (ii) those that address it from the edge-nodes of the route (i.e. infrastructure nodes or user terminals). In the former, relay nodes perform MRoTD by means of MRTD-assisted MRMH. In contrast, in the centralized route selection, it is the edge nodes that decide upon the route to take, while the relaying nodes forward data in accordance. In this sense, edge-nodes perform MRoTD in terms of MRMH-assisted MRTD. A multi-hop channel quality indication metric is required for this latter solution to be effective.

B. *Benefits and Costs*

In the context of radio cooperation, previous research studies have primarily focused on exploiting multi-hop relaying for efficient spectrum use in wireless infrastructures such as cellular networks, e.g., [12]-[18]. The results obtained show better data rates on the fringes of a cell and larger numbers of serviced users. MRMH extends previous work to the case of multiple heterogeneous RAs. Each node in an MRMH network is capable of communication via a number of RAs facilitating the utilisation of multiple routes for data transmissions. The probability of all such routes experiencing similar deep fade conditions simultaneously is very low. Consequently, by selecting among multiple alternative routes in case of individual route outages, the rich MRMH network connectivity results in increased spectrum efficiency, network throughput, and robustness.

Naturally, all potential benefits come at a certain cost; namely, that of additional complexity and the resources expended by the signalling required to maintain transmission reliability over multiple hops.

IV. GENERIC LINK LAYER

A. *Main Objectives*

The main objective of the GLL-assisted multi-radio cooperation proposed here is to create a “homogeneous” access network from multiple “heterogeneous” radio access networks by means of unified link layer processing that (*i*) hides the heterogeneity associated with the use of multiple RATs; (*ii*) enables the integration of different RATs into a common network that would seamlessly provide all functionalities inherent in conventional radio access networks including mobility, context transfer, security and QoS support; and (*iii*) efficiently utilises the radio resources of the underlying networks for optimal service support. In order to meet these objectives, the GLL provides

- a *common link layer interface* to support control functions and higher layer data transmissions.
- a set of *generalized link layer control and data processing functions*, responsible for efficient cooperation between RATs.
- a set of *complementary link layer functions* corresponding to missing functionality in legacy RATs and to inter-working functions for enhancing the level of integration among RATs.
- a set of link layer functions supporting MRTD and MRMH networking.

Based on a modular architecture, the GLL comprises a toolbox of link layer functions partially carried out by the GLL itself and partially by RAT-specific protocols. Due to its modularity, existing software and hardware for processing and control of different RATs can be re-used and the integration of legacy and new RATs can be facilitated.

B. *GLL Functions and Architecture*

This section briefly presents the GLL toolbox and some of its core functions. As illustrated in Fig. 4, the set of generalized link layer control and data processing functions are broadly divided into control (GLL-C) and data (GLL-D) functions. These provide a common interface towards higher layers’ control and data plane functions respectively. The complementary set of functions is realised in terms of GLL-RLC and GLL-MAC. The latter is deployed for full radio access integration including MRTD at MAC PDU level (e.g., applicable to a new 4G air interface), while GLL-RLC and GLL (both control and data) would facilitate cooperation at RLC and GLL levels respectively. GLL-RLC and GLL-MAC support the unified link layer processing in two ways. Firstly, they complement RLC and MAC layers in cases where RAT-specific functionality is missing. Secondly, they utilise existing RLC and MAC functionality for the purpose of multi-radio cooperation. Basic GLL functions that enable cooperation between different RATs include link layer configuration management (dynamic access selection and instantiation of GLL parameters), mobility support, context transfer, data compression and security management.

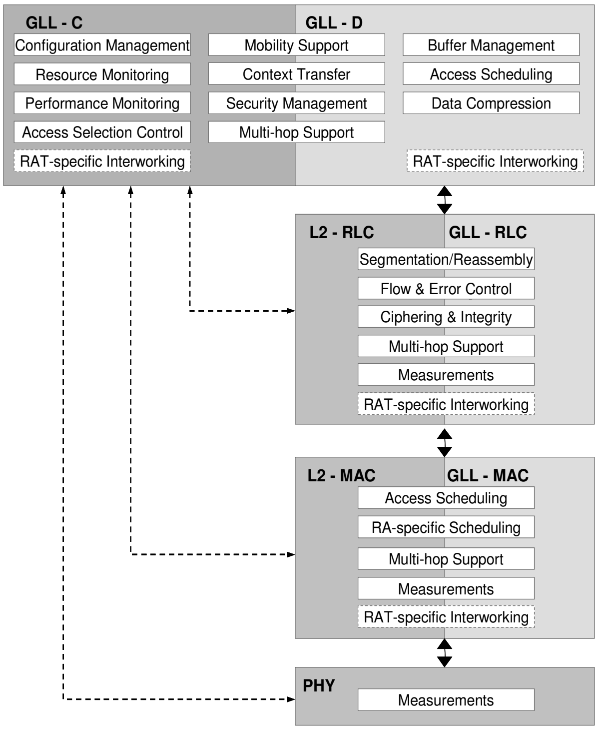


Fig. 4: Configurable GLL Toolbox.

In order to enable MRTD and MRMH, GLL functions such as access scheduling, resource and performance monitoring, error & flow control, segmentation & reassembly, can be found at different levels of cooperation. As an example, for MRTD at IP packet level, access scheduling is supported at the GLL-D. However, for MRTD at MAC PDU level, access scheduling performs multi-radio packet scheduling at the GLL-MAC. Regarding the performance monitoring function, MRTD at IP packet level will involve measurements of average channel conditions, while MRTD at MAC PDU level will involve measurements of instantaneous channel conditions, whereas MRMH will necessitate aggregate metrics (multi-hop channel quality indication) providing distance/cost of reaching the destination node. In order to enable MRMH, error control may take the form of a 2-stage error recovery process, including both relay and final acknowledgements and supported by multi-hop support functionality. As in the case of MRTD, multi-hop support is provided for different levels of cooperation.

V. CONCLUSIONS

The concept of the Generic Link Layer (GLL) was introduced and investigated in this paper in terms of a collection of functionalities which enable and facilitate efficient link-layer inter-working among multiple radio accesses.

The role of the GLL was specifically detailed with regards to the support of two *novel* technologies: Multi-Radio Transmission Diversity (MRTD), and Multi-Radio Multi-Hop (MRMH) networking. Based on an extension of well-known physical-layer multi-antenna diversity mechanisms, MRTD refers to the sequential (switched) or parallel use of multiple radio accesses for the transmission of a traffic flow. Through selection of the most suitable radio access, switched diversity helps to mitigate the dynamics of the radio channel (e.g. via mechanisms such as multi-radio ARQ), thereby resulting in improvements in throughput and delay. In addition, parallel diversity can help to further improve the quality of the wireless link through transmission of redundancy. Alternatively, parallel diversity can be used to simply pool the capacities of multiple radio accesses in order to increase the user data rates.

Both transmission efficiency and coverage area can be improved by MRMH networks, where multiple radio accesses exist along each wireless connection over a multi-hop route. Appropriate management of interactions between the error-control mechanisms of multiple radio accesses over multiple hops was highlighted as a critical role for the GLL. The potential for combining multi-radio transmission diversity and multi-hop networking was also discussed in the form of multi-route transmission diversity.

The net improvements in robustness, throughput and delay promised by novel GLL-assisted technologies such as MRTD and MRMH, and their impact on the QoS for traffic classes with varying degrees of sensitivity to delay and loss, is indeed an important area of research. To this end, the feasibility of the GLL concept, its role in efficient realisation of novel MRTD and MRMH technologies, and the resulting gains are scheduled for further study in the second year of the Ambient Networks project.

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