An Inter-MAC Architecture for Heterogeneous Gigabit Home Networks

Torsten Meyer
Information & Communications
Siemens AG, Corporate Technology
Munich, Germany
torsten.meyer@siemens.com

Vincenzo Suraci
Department of System and Computer Science
University of Rome "La Sapienza"
Rome, Italy
vincenzo.suraci@dis.uniroma1.it

Peter Langendörfer
System Design
Innovations for High Performance Microelectronics (IHP)
Frankfurt (Oder), Germany
langendoerfer@ihp-microelectronics.com

Stefan Nowak
Communication Technology Institute
Dortmund University of Technology
Dortmund, Germany
stefan.nowak@tu-dortmund.de

Michael Bahr
Information & Communications
Siemens AG, Corporate Technology
Munich, Germany
bahr@siemens.com

Ralf Jennen
Department of Communication Networks
RWTH Aachen University, Faculty 6
Aachen, Germany
jen@comnets.rwth-aachen.de

***Abstract*—The home network of the near future will be a heterogeneous broadband network supporting the use of wired as well as wireless transmission technologies. The variety of services will range from HDTV via gaming to emergency services in the telemedicine area. In this paper, we introduce a technology-independent protocol layer called *Inter-MAC* which provides a common infrastructure to all home networking devices. The Inter-MAC can establish a connection via different transmission technologies while ensuring appropriate QoS. Key to this is the capability to correctly interpret technology-dependent PHY and MAC parameters for determining QoS when selecting initial and alternative paths, as well as the feature of admission control. Our simulations indicate clearly that the Inter-MAC approach can cope with varying loads, for instance, the time the jitter needed to stabilize was as short as 4 s. The reduced QoS was not noticeable by the user since the jitter introduced by handling additional HDTV flows was less than 0.2 ms for the existing and less than 0.7 ms for the new flow.**

I. INTRODUCTION AND MOTIVATION

Due to a sustainable upgrade of access networks such as Fiber-to-the-home, operators are able to provide new broadband services to their customers such as HDTV streaming, low-latency gaming, telemedical applications or high-quality video conferencing. Admittedly, today's home area networks (HAN) are not able to deliver such services within the home, because the demands of the services regarding Quality of Service (QoS) are too high, i.e. gigabit throughput and very small latencies. However, future HANs will comprise several heterogeneous network technologies. Traditional and more innovative wired and wireless transmission technologies will be deployed. For instance, wireless transmission systems at 60 GHz with data rates of several Gbit/s for applications in home networks have recently been demonstrated during exhibition fairs and are currently being standardized [1]. Conjointly, these systems offer completely new possibilities for the distribution of high data rate content within the home.

In order to facilitate future HANs based on existing and future wired and wireless transmission technologies, we introduce a novel intermediate sub-layer. We call this intermediate sub-layer *Inter-MAC*. It is located below the network layer and above the corresponding technology dependent MAC layers. The Inter-MAC realizes the convergence of these technologies towards the network layer and enables the use of a single Internet Protocol (IP) address for multiple interfaces. Furthermore, it allows for fast and direct access to QoS-related technology-dependent MAC parameters. Thus, the associated technologies can be used in a nearly optimal fashion. Consequently, the Inter-MAC represents an essential basis for efficient cross-layer optimization. It helps to solve certain problems of middleware solutions [2] that also consider QoS. They are not aware of constraints depending on the underlying transmission technology and are not able to affect them, respectively.

In this paper, we present the initial concept for the Inter-MAC architecture and explain its functionality. We will show that it provides the means to establish a multi-technology meshed network which facilitates a reliable and high perform-

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ance delivery of application data and services with gigabit throughput within the home. In section II, we provide an overview of related work to highlight the innovation associated with the introduction of the Inter-MAC. Section III addresses the requirements which have been investigated carefully. Based on that, section IV introduces the Inter-MAC architecture. Afterwards, section V describes the interaction between the related Inter-MAC components. An extract of our simulation results is presented in section VI to demonstrate a proof of our concept. Eventually, section VII concludes the paper explaining our next steps towards a practical implementation.

II. RELATED WORK

A convergence layer has been adopted in [3] in the context of heterogeneous wireless networks. It has been located above the IP layer and guarantees quality of service, network selection, hand-over and mobility management. In the context of delay tolerant networking, a convergence layer has been adopted in the transport layer for satellite communications [4]. Regarding home networks, there has been an approach to facilitate convergence for a combined IEEE 802.15.4 and power line communication (PLC) network [5]. Unfortunately, this approach does not present any possibility to be extended to other promising home networking technologies, such as WiFi, UWB or 60 GHz radio communication. Another convergence layer located below the transport layer appeared in [6], where a technology neutral admission control procedure for core and access networks is presented.

Moreover, the IEEE has recently released the standard IEEE 802.21 [7] which defines mechanisms for media independent handovers among different transmission technologies. It provides a framework that allows higher-layer entities to interact with lower layers in order to provide session continuity without dealing with the particularities of each technology. According to the authors' view, IEEE 802.21 is mainly designed for link maintenance and session continuity for multi-technology enabled mobile devices. Consequently, it is not applicable for heterogeneous meshed home networks.

For this reason, we designed a technology-independent convergence layer operating below layer 3 interfacing with heterogeneous home networking technologies. The main focus of the Inter-MAC is to find a path through the network which is able to provide gigabit services with an appropriate level of QoS.

III. INTER-MAC REQUIREMENTS

The Inter-MAC architecture provides a feasible solution to a set of requirements. It must support the QoS required by innovative Gbit-services. QoS guarantees must be provided on a flow-by-flow basis independent of the access technologies involved. Therefore, path selection and admission control must be provided. Due to the heterogeneity of QoS related link layer parameters, these must be mapped to generic ones. The mapping must be performed vertically in the protocol stack and horizontally via the whole path. Legacy devices should retain their original performance. At the same time, the architecture must deal with a hybrid wireless/wired meshed multi-hop network topology and assert the interoperability of access technologies. The Inter-MAC must allow for secure multi-hop data transmissions in the meshed HAN. A light-weight convergence layer must make the heterogeneity transparent to higher layers. Compatibility to standard network protocols must be assured by providing a single IP address for all access technology interfaces. End-to-end security should be provided within the HAN. Neighbour authentication asserts that only trusted devices become a part of the HAN.

The path selection algorithm should be based on an technology independent metric which requires translating specific link metrics to a generic metric. It has to react autonomously to changes of the network state including user mobility. Therefore, the available links have to be monitored and controlled. If paths have to be adjusted, the handover between paths should be seamless. The architecture should consider standardization efforts in this field, e.g. IEEE 802.21. Besides, it should be possible to improve network coverage using Inter-MAC standalone relays.

The architecture must allow integration of emerging access technologies and must be capable to be realized in hardware, software, or both. Furthermore, it should be able to address different scenarios with 20 - 50 nodes with mobility and changing link qualities.

IV. INTER-MAC ARCHITECTURE

In this section the architecture of the Inter-MAC is derived which can be divided into the following three planes:

- *Data plane* is responsible for transferring the data packets. It decides what to do with packets arriving at a device. The received packets are arranged into an output queue according to their priority and the filtering rules.
- *Control plane* performs short-term actions which allow a device to decide what to do with incoming packets. The higher layer application protocol requests are handled and a path to the destination with the appropriate QoS requirements will be established if possible. Furthermore it deals with monitoring and link setup and teardown.
- *Management plane* is concerned with long-term actions which describe the behaviour of the device itself which is defined through policies. Further details of the management plane are out of scope of this paper.

A. Data plane

The data plane consists of the following engines, please refer to Figure 1:

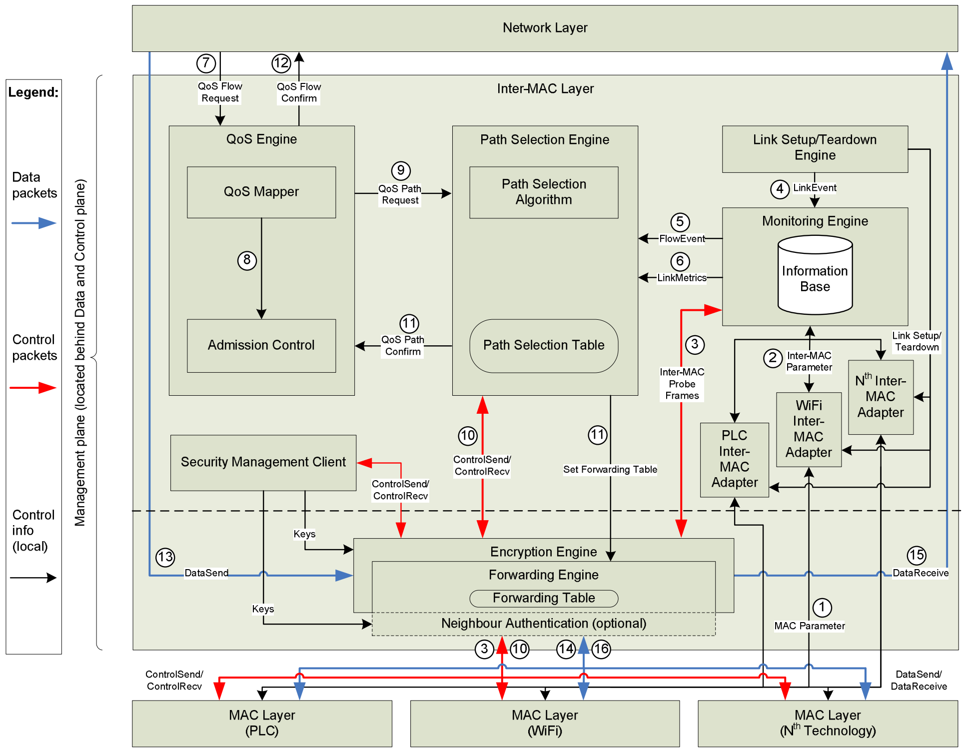

Figure 1. Inter-MAC architecture

- *Forwarding Engine* is responsible for sending and receiving packets. It uses the *Forwarding Table* which indicates which flow shall be sent via which technology-dependent MAC (T-MAC). The Forwarding Table is maintained by the *Path Selection Engine* which will be described in section IV-B.
- *Encryption Engine* is responsible for end-to-end encryption of Inter-MAC packets. Encryption and decryption of packets is only needed at source and destination. Thus, no encryption/decryption at intermediate nodes is required.
- *Neighbour Authentication* ensures that a received packet is from a legitimate member of the network. This reduces the risk of carrying illegitimate traffic. It is an optional functionality.

The Forwarding Engine is encapsulated in the Encryption Engine which provides basic security primitives to ensure secrecy of the data flows and data integrity. A detailed description of security issues is provided in [8].

B. *Control plane*

The control plane is subdivided into several components:

- *QoS Engine* consists of two sub-engines.
  - *QoS Mapper* collects the QoS requirements from the application. These are mapped to the Inter-MAC QoS classes respectively.
  - *Admission Control* determines whether a certain flow can be admitted based on a predefined policy and the current load.
- *Path Selection Engine* exchanges control traffic with Path Selection Engines of other nodes in order to determine the network topology and to maintain paths. The *Path Selection Algorithm* calculates an end-to-end path from source to destination. Path recalculations are triggered when link parameters change significantly. The *Path Selection Table* contains existing paths.
- *Monitoring Engine* retrieves recent link parameters. This information is locally stored in the *Information Base* and is used as link metrics for the path selection as well as indication if paths need to be recalculated and re-established.
- *Link Setup/Teardown Engine* discovers, prepares and makes links available which can be used for path setup.
- *Inter-MAC Adapter* translates T-MAC parameters into technology-independent Inter-MAC parameters. Each T-MAC needs a specific Inter-MAC Adapter.

V. INTER-MAC COMPONENTS INTERACTION

In order to show how the various parts of the system fit together, the actions undertaken are described step by step according to Figure 1.

1) The Inter-MAC adapters extract T-MAC parameters and translate them into technology-independent notation to make them comparable.
2) These parameters are transferred to the Monitoring Engine and stored in the Information Base.

3) If no appropriate T-MAC parameters are available, the Monitoring Engine exchanges Inter-MAC Probe Frames to measure MAC capabilities.
4) In case of significant link events, the Link Setup/Teardown Engine triggers the Monitoring Engine (e.g. LinkDown).
5) The Monitoring Engine notifies the Path Selection Engine in case of flow events (e.g. FlowDown).
6) The Path Selection Engine uses local link metric information obtained from the Monitoring Engine.
7) A QoS Flow Request with QoS application requirements arrives at the QoS Engine. The QoS Mapper translates the QoS Flow Request into Inter-MAC QoS classes.
8) The Admission Control is asked whether this flow can be admitted based on local resources.
9) The QoS Engine triggers the Path Selection Engine with a QoS Path Request to find an appropriate path.
10) The Path Selection Engine calculates paths based on network information provided from other Path Selection Engines.
11) If an appropriate path is found, the Path Selection Engine sets the Forwarding Table. Additionally, it sends a QoS Path Confirm to the QoS Engine.
12) The Admission Control accepts/blocks flows based on the path selection results and sends a QoS Flow Confirm to the higher layer.
13) Packets arrive at the Forwarding Engine. If they are received from a higher layer, the payload must be encrypted by the Encryption Engine.
14) If the packet arrives from some other node, a Neighbour Authentication is enforced optionally.
15) If the Forwarding Engine determines, the packet is destined for this node, it is sent to the application.
16) Otherwise, the Forwarding Engine looks up in the Forwarding Table to determine the specific parameters for the packet and forwards it.

VI. PERFORMANCE SIMULATIONS

The Inter-MAC architecture has been simulated in the simple scenario shown in Figure 2 where its performance has been tested in a heterogeneous gigabit home network.

Three technologies are used: *PLC* (200 Mbit/s), *Gigabit Ethernet* (1 Gbit/s), and *IEEE 802.11a* (54 Mbit/s). Node 0 and 1 are connected to each other with all three technologies, and the other four nodes are connected to Nodes 0 or 1 using a Gigabit Ethernet cable. The applications running in this home environment are a single FTP connection with peaks of 10 Mbit/s (*Inter-Request Time*: exponential distribution, mean value 10 s, *File size*: 1.25 MB) and two uncompressed HDTV flows 720p (1280×720) with the following characteristics: *Frame size*: 2.764 MB, *Frame rate*: 25 frames/s, *Bandwidth*: 552.96 Mbit/s. The deployed flows are:

HDTV 1:	Local Server	→ Node 2
HDTV 2:	Home Gateway	→ Node 3
FTP:	Local Server	→ Node 2.

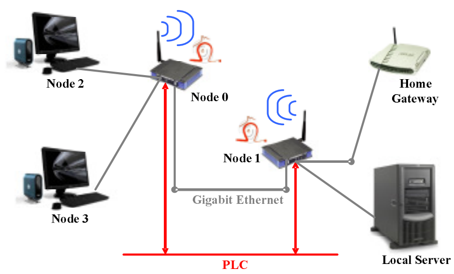

Figure 2. Simulation Scenario

This home scenario has been simulated using OPNET Modeler 11.5A. The simulation time was 60 s: the streaming application HDTV 1 starts at simulation time 20 s, the application HDTV 2 starts at 37 s, while FTP already starts at 14 s. When running together, the total bandwidth of the three flows is larger than the maximum capacity of the single Gigabit Ethernet link. It is evident, that not all flows can be supported simultaneously because the overloading of the Gigabit Ethernet link would cause unacceptable delay and packet loss. Instead, the Inter-MAC distributes the traffic flows onto different paths to satisfy the QoS requirements and to avoid overloading single links.

We used the load balancing algorithm described in [11] for distributing the total load over the network. The streaming flow HDTV 1 is entirely sent on the Gigabit Ethernet link, the streaming flow HDTV 2 splits its traffic across PLC and Gigabit Ethernet, while the FTP application splits its traffic across Wi-Fi and PLC.

Figure 3 shows the application data rate for each flow received by the corresponding destination nodes. Figure 4 shows the end-to-end delay experienced by the HDTV flows. The delay takes on very acceptable values w.r.t. the requirements of streaming applications. HDTV 2 suffers from a greater delay than HDTV 1. This is due to the fact that HDTV 2 passes through PLC and Gigabit Ethernet technologies, while HDTV 1 only exploits the Gigabit Ethernet link. Furthermore, the start of the second HDTV flow causes a delay increase in HDTV 1, but this is less than 5 ms. It is due to the increased queuing delay of the Gigabit Ethernet link when also the streaming application HDTV 2, jointly with HDTV 1, starts to use it. As shown in Figure 5, both HDTV flows experience acceptable end-to-end jitter with a maximum value of 0.66 ms. Such high values happen only in the instant in which the second flow is started and lasts for only 4 s. This jitter indicates the additional transfer time which is caused by the Inter-MAC balancing the additional load, whereas the time interval of 4 s in which the extra jitter can be measured shows the time the home network needs to gain a stable state after the Inter-MAC adapted the system paths to the new load. We observe that the split flow HDTV 2 has greater and more variable jitter values than HDTV 1. This is caused by the delay differences between the two used technologies, PLC and Gigabit Ethernet. Due to the used hybrid per-packet/per-flow approach for load balancing, the Inter-MAC sends packets belonging to the same flow through different paths. A per-flow approach, where a single flow is mapped to a single path, is assumed to have a lower end-to-end jitter. A comparison with this approach will be investigated in our future work.

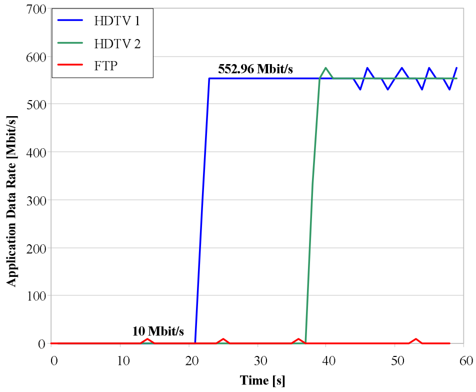

Figure 3. Application data rate

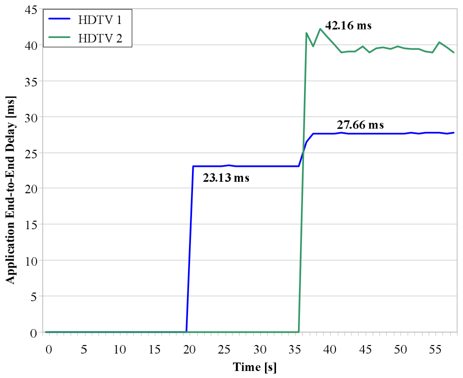

Figure 4. End-to-end delay

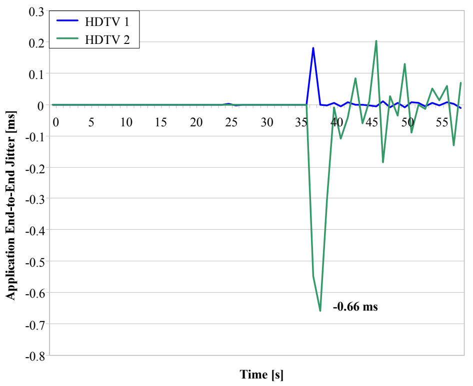

Figure 5. End-to-end jitter

VII. CONCLUSION

In this paper, we introduced the Inter-MAC architecture which allows for the integration of different transmission technologies, such as PLC, wired and wireless approaches, and for ensuring QoS in such heterogeneous network. The major tasks of the Inter-MAC are to determine whether a certain QoS requirement can be fulfilled when starting a new flow, to find an appropriate path through the heterogeneous network, and to ensure that the QoS of that connection can be maintained under varying network conditions such as wireless link failures.

Furthermore, we presented first simulation results which show that the Inter-MAC can fulfil its tasks. The results presented show that the Inter-MAC can effectively limit the effects of starting a second HDTV flow on an existing one.

One of the major benefits of the Inter-MAC architecture is that new transmission technologies can be easily integrated into the Inter-MAC architecture by providing respective Inter-MAC adapters. The other benefit is that the end user does not need to explicitly configure paths between devices of different technologies since that is done automatically by the Inter-MAC, and the paths and flows are also maintained while services are being used, even in case a certain link degrades or completely fails. Our simulations indicate clearly the efficiency of our Inter-MAC approach. The overall adaptation time for coping with a new HDTV flow was as short as 4 s. Since the jitter from both flows, existing and new, was 0.2 ms and 0.7 ms respectively, user perception was not affected.

Our next steps are the implementation of the Inter-MAC components and their testing using existing MAC protocols. The optimization of the advanced Inter-MAC protocols will be done later on.

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