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Citation for published version (APA):

Das, G., Lannoo, B., Okonkwo, C. M., Koonen, A. M. J., Colle, D., Moerman, I., Pickavet, M., & Demeester, P. (2009). A new architecture and MAC protocol for flexible radio over fiber home networks. In *Proceedings of the IEEE 3rd International Symposium on Advanced Networks and Telecommunication Systems (ANTS)*, 14-16 december 2009, New Delhi, India (pp. 6.28-1/3). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/ANTS.2009.5409886>

DOI:

[10.1109/ANTS.2009.5409886](https://doi.org/10.1109/ANTS.2009.5409886)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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A New Architecture and MAC Protocol for Flexible Radio over Fiber Home Networks

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Abstract— In this paper we propose a new architecture and a novel media access protocol based on IEEE 802.11 for the home network. We use radio over fiber technology for our architecture where data multiplexing is considered in both wireless and wavelength domain. Our solution enhances the wireless bandwidth usage capability and can provide dynamic bandwidth allocation among users according to the user demands. Our proposed scheme also supports full range mobility for the users.

I. INTRODUCTION

Radio over fiber (RoF) with distributed antenna system (DAS) has emerged as a viable alternative for home networks [1] which can exploit the advantages of both wireless and optical data transmission. The free radio spectrum available in the millimeter-wave region (30 – 300 GHz) has been considered for such application. In particular, two frequency bands in 40-42 GHz and 57-66 GHz have recently gained significant interest among the researchers due to the following reasons. First of all, at 40/60 GHz, a reasonably large bandwidth (almost 2 GHz and 9 GHz, respectively) [2] is available to cope with the growing access demands. Moreover, due to the low penetration of 40/60 GHz signals, it is possible to spatially reuse the available bandwidth more frequently. Particularly, for a home application, 40/60 GHz radio cells comprise a well defined boundary (e.g., a room with its walls), which reduces the possibility of interferences at the cell boundaries. These along with a DAS with a fiber based feeder network and a centralized processing makes RoF a comparatively cheaper solution for home networks [1].

In this paper, we target specifically multi-home residential, business or shopping complexes where the bandwidth demand as well as the number of active users may vary dynamically. We assume a wavelength division multiplexing (WDM) passive optical network (PON) technology to be in place for the access data distribution, where the optical network unit (ONU) becomes the home gateway and the data aggregation and egress point for the home network.

We describe the architecture for such a network in Section II. In Section III we introduce a novel media access control (MAC) protocol based on the well-known IEEE 802.11 standard. Some basic results are provided in Section IV.

II. NETWORK ARCHITECTURE

We propose the home network to employ RoF with the central station (CS) having an interface with the ONU. Fig. 1 depicts the basic schematic diagram of a home network,

consisting of a single floor office. In this paper we assume a ring architecture for the RoF distributed antenna feeder network. Each room has an optical add drop multiplexer (OADM) to add or drop the appropriate wavelengths. The OADM can be reconfigurable to add flexibility in the architecture. Next we investigate the different architectural possibilities of the OADMs and the network resource allocation scheme to maximize the available bandwidth.

Fig 1: Home network with ring topology

Fig 2: An example (a) wireless frequency allocation scheme (b) wireless frequency and wavelength allocation scheme

We start with the description of the radio frequency allocation scheme. Fig 2(a) shows how two upstream and corresponding downstream data streams can be modulated in the 40/60 GHz window. Here two subcarriers f_1 and f_2 are assigned to carry different data streams. The number of subcarriers can be increased to enhance the flexibility of the proposed design. However, this can subsequently reduce the amount of bandwidth available for each subcarrier.

Now, the impending problem with such allocation is that the available bandwidth is limited. We next propose an overlaid wavelength assignment scheme to increase the overall data transmission capability per home.

Fig. 2(b) shows an example of wavelength assignment for the feeder fiber for a 4-rooms home scenario. Here λ_1 is assigned to room 1 and 2 and λ_2 is assigned to room 3 and 4. Because we choose different radio frequencies for different rooms fed by the same wavelength, we avoid the hidden node problem reported in [3]. Moreover, this potentially doubles the

overall data transmission capacity for the entire home. It is easy to see that a higher number of rooms will require a higher number of wavelengths and will further increase the overall data transmission capacity.

In order to make the frequency and wavelength allocation flexible to enable dynamic bandwidth allocation (DBA), reconfigurable OADM (ROADMs) will be needed. Suppose that room 1 requires additional bandwidth, while room 2 is empty. In that scenario, both radio frequencies carried over λ_1 can be shared among the users in room 1. However, if room 1 requires the extra capacity when room 3 is empty, the wavelengths have to be swapped between room 2 and 3. The new wavelength allocation should have room 1 and 3 with λ_1 and room 2 and 4 with λ_2 . This will be achieved with the help of the MAC protocol described in the next section where the data transmission in room 2 and 3 are to be held temporarily, while the CS control can reconfigure the respective ROADMs.

Fig. 3 (a) and (b) provide a schematic diagram for the RROADM and OADM architectures respectively.

Fig 3: Architecture for (a) RROADM and (b) OADM

For the RROADM in Fig. 3 (a), the 2×2 semiconductor optical amplifier (SOA) switch chooses the wavelength to be dropped in a particular room. As we have only two wavelengths for our example scenario, a 2×2 switch is sufficient for our purpose. However, as the number of wavelengths increases, the switch capacity has to increase as well. However, as a room can only accommodate one wavelength, always, a single wavelength is dropped in a room and all others are bypassed. For the dropped wavelength, the two couplers (1 and 2) are used to provide the add/drop functionality. Additionally RROADM requires a tunable LASER (LD) and photo diode (PD). The control circuitry changes the switch status as well as selects the appropriate wavelength for the transceiver pair. The LD and the PD are attached to the local radio transceiver and antenna of the room for wireless transmission. One can choose to avoid the optical couplers (1 and 2) if add/drop traffic separation is performed at the radio transceiver with filters. This will improve the overall power budget of the system with a minimal increase of radio transceiver cost.

For the OADM in Fig. 3 (b), the SOA switch is not required. Also, a fixed transceiver is used in place of a tunable

transceiver. In a practical business environment both RROADM and OADM can be used in conjunction, where bigger conference rooms can be equipped with RROADM and other office rooms with fixed traffic demand may have OADM.

While these architectures provide flexibility in terms of dynamically allocating wavelengths and wireless frequencies in different rooms, in the next section we further introduce a suitable MAC protocol to provide DBA at the time slot level.

III. MAC PROTOCOL

The MAC protocol proposed is similar to the IEEE 802.11 MAC protocol. The striking difference is that our MAC protocol has separate wireless channels for upstream and downstream data and is totally centralized. Both upstream and downstream data transmission is coordinated by the CS. Similar to 802.11 PCF, data transmission in the upstream direction is segregated into frames. Fig. 4(a) shows the timing diagram and the frame format for upstream data transmission.

Fig 4: Timing diagram of (a) upstream data (b) DCF Transmission phase

The upstream frames are divided into two parts: point coordination function (PCF) and distributed coordination function (DCF). Each part starts with the CS broadcasting a beacon. In the PCF phase we avoid using the polling protocol which conforms with the IEEE 802.11 standard. In our case, a PCF beacon indicates the start of a frame and notifies the users about their share for the upstream bandwidth. It specifies the order of the users to acquire the wireless channel and how much data each of them is allowed to transmit. The PCF beacon is followed by the data transmission from the respective users. Each user piggybacks the current queue status to assist the CS to dynamically allocate bandwidth in the next frame. The CS responds to successful uplink data transmissions by sending ACK packets to the users in the downstream channel. This DBA in the PCF phase makes our proposal more efficient than the 802.11 counterpart. The PCF phase ends with a DCF beacon that specifies the amount of time allocated for the DCF phase. In the DCF phase, new users in the room are allowed to randomly access the wireless channel and are therefore prone to collisions. The DCF phase uses the same collision avoidance mechanism as 802.11 MAC [4]. However, unlike 802.11 all transmissions from the new nodes in this phase are targeted to the CS to notify their presence in the room. Therefore, it requires no actual data delivery and hence it is sufficient to have a two-way handshake instead of a four-way handshake of 802.11[4]. Fig.

4(b) shows the timing diagram for DCF transmission. Here user k , if succeeded, transmits a request to join (RTJ) message to the CS including its node ID and the queue status. Unlike in PCF phase, here CS sends the downlink ACK packet in the upstream channel instead of in the downstream channel, for avoiding complex time sync between DL and UL channel. The gap between RTJ and ACK accounts for the propagation delay between user node and CS.

The DCF phase also accounts for user mobility and related handoff mechanism. In [5], the authors have used the concept of extended cell to address mobility. However, as it needs to transmit the same content in the entire extended cell, it lacks flexibility in terms of bandwidth management. We alleviate it with the following MAC extension. For our case, when a user enters a room adjacent to where it has been previously, it can encounter following three scenarios: (a) the node was using different wireless frequency compare to what is used in that room, (b)-(c) the node was using a wireless frequency of the room it enters, with (b) the node was not transmitting and (c) the node was transmitting. In scenario (a), the user node will not get an ACK from the CS and will listen to the wireless channel with a time-out set. If it fails to find any transmission in that time-out period, it assumes a hand-off and starts seeking for the wireless frequency the new room is fed with. Once tuned to the required frequency, it waits for the DCF beacon to send a RTJ packet to the CS. In scenario (b), the concerned user node listens to the channel with a time-out. Here we need to mention that every data and control packet transmission in the upstream channel has to include a room ID field supplied by the CS. If the user node sees any data transmission with a different room ID, it waits for a DCF beacon. Otherwise, it follows the same procedure as described in scenario (a). In scenario (c), the concerned user node may collide with some ongoing transmission. Again the node fails to get an ACK from the CS. Moreover, the node whose transmission it has corrupted also fails to get an ACK. Therefore both nodes wait for the DCF phase and compete for access of the upstream channel with the joining node having lower priority set for its channel access.

In case the CS realizes a need for wavelength switching to shift capacity from one room to another one, it issues a *hold beacon* to the rooms that will be affected by the wavelength switching. The hold beacon also mentions the wireless frequency that the users should tune to after the change. All the users after receiving a hold beacon stop transmitting till the wavelength switching functionality is performed. The CS then issues the PCF beacon and resumes the transmission.

IV. RESULTS AND DISCUSSION

In this section we provide results showing the bandwidth wastage due to the protocol overhead. Fig. 5 shows the plot for the layer-2 (L2) throughput and access delay in one of the uplink wireless channels for varying frame sizes. We have assumed a 1 Gb/s channel transmission rate, with an average of 10 active mobile users and 2 new users present in the same

room. The different packet formats in bytes (B), assumed for the L2 throughput analysis, are shown in Fig. 6. Propagation delay and DIFS, SIFS are taken as specified in 802.11 standard. As the frame size increases, the MAC has more data to accommodate within a frame and hence bandwidth wastage due to the protocol overhead reduces. However this comes with a penalty of a higher access delay. Therefore, the MAC protocol has to be optimized for an appropriate frame size. It should be noted that our MAC can achieve a high throughput of about 96%. Other studies for WiFi show a maximum L2 throughput of only 50-60% for 802.11a DCF CSMA/CA [6].

Fig 5: MAC channel access delay and channel throughput vs. frame size

Fig 6: Packet formats for different MAC packets

V. CONCLUSION AND FUTURE DIRECTION

We have proposed a new architecture and a MAC protocol for the RoF home network. This architecture provides a fully flexible DBA and accounts for user mobility. In the future, we will be looking at how our MAC protocol can be affected if the number of existing and new users in the room dynamically varies. We will also evaluate its performance compared to 802.11 with respect to the packet size and the number of users.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the EC in the FP7 ICT-ALPHA project. D. Pareit thanks the IWT-Vlaanderen for funding his Ph.D. grant.

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