Broadband Multi Hop Networks with reduced Protocol Overhead

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ABSTRACT

The BMBF founded project COVERAGE investigates broadband access to the IP core-net in public or semi-public hot spot scenarios for mobile users. The basis for our investigations are OFDM-systems (Orthogonal Frequency Division Multiplex) like H/2 (HiperLAN/2) or IEEE802.11a which provide data-rates up to 54 Mbit/s. Main topic of COVERAGE are multihop networks as a means to increase the access area of H/2 radio cells. Unfortunately the performance of multihop networks - with respect to throughput - decreases rapidly with the number of so called EPs (Extension Point) as intermediate hop devices. One reason is the protocol overhead of H/2. For single APs this protocol overhead can be accepted, while in a multihop network this overhead is required once for each additional EP. Here we propose a suitable combination of a DLC protocol with sector antennas and SFN (Single Frequency Network) concepts, which reduces the overall protocol overhead.

1. Introduction

New WLAN (Wireless LAN) techniques like H/2 [3] or IEEE802.11a provide broadband data rates of up to 54 Mbit/s. We investigate the suitability of these techniques for public Hot Spot scenarios like airports, railway stations, hotels or public places. WLANs are originally intended for indoor use and provide in outdoor scenarios only restricted transmission range of a few hundred meters. Multihop networks with EPs may increase the coverage area, as can be seen in Figure 1. The EPs forward data from the AP to other EPs or to a RMT (Remote Mobile Terminal).

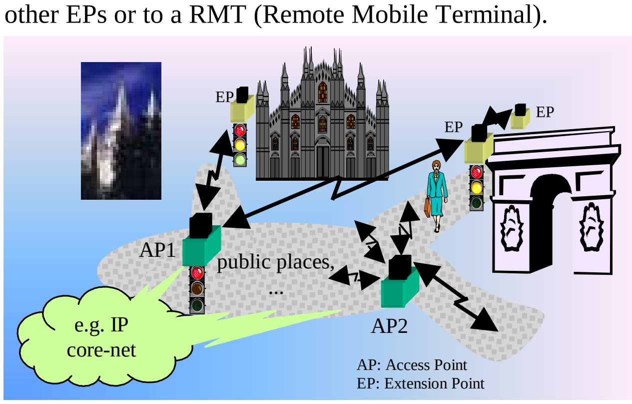

Figure 1: Typical hot spot scenario for public places with EPs for forwarding of data packets

As only the APs are connected to the IP core-net a greater area can be served with restricted infrastructure effort, as the EPs need no broadband cable connection. We assume planned scenarios, where the EPs are situated at fixed locations like traffic lights, so that we can guarantee a certain level of QoS (Quality of Sevice) and coverage.

In [9] we proposed two similar concepts – SF-FSA (Subframe with Fixed Slot Allocation) and the so-called 'BEACON concept' - as forwarding DLC-protocols. These concepts have the advantage to be able to support H/2 conform MTs, i.e. the MTs do not know whether they are connected to an AP or EP. Unfortunately these DLC protocols scale very bad due to a high protocol overhead of e.g. 12.5% for SF-FSA per additional EP, similar results were found for the pure BEACON concept. This overhead is difficult to avoid, as each AP and EP has to transmit its own frame structure with a period of 2 ms – essentially the regular BCH (Broadcast Channel) for synchronization, the FCH (Frame Control Channel), the ACH (Feedback Access Channel), the RCH (Random Access Channel) and resource requests for capacity. For details of H/2 see [2-4].

In this paper we will investigate the throughput losses of H/2 multihop networks and propose further enhancements with better scaling properties, i.e. less overall protocol overhead. The basis is a suitable combination of forwarding with SFN (Single Frequency Network) concepts [1]..

In Section 2 the BEACON concept and its protocol overhead is described. Section 3 will provide the enhancements with less protocol overhead while Section 4 concludes the paper.

2. BEACON CONCEPT

The main task of forwarding is, to handle the transmission of data packets from the AP to the EPs and from the EPs to the RMTs. A side condition is an easy implementation and support of H/2 standard conform MTs. These MTs expect every 2 ms the broadcast of the so-called BCH. The BCH contains general information like net ID etc. and a pointer, which marks the beginning of the FCH within the MAC frame. The FCH contains the information about the structure of the current MAC frame and is therefore different for each AP and/or EP. As we assume in a first step a time frame concept - i.e. all scheduling is done in time domain – the time positions of the FCHs for each AP/EP have to be different. Otherwise we would generate interference on the air interface. As a resulting requirement the time positions of all BCHs – for AP and EPs – have to be different as well, because the pointers to the FCHs must be different. These requirements and the wish to use standard conform features in AP and EPs as far as possible led to the BEACON concept, which is shown in Figure 2. The BEACON concept relies on the H/2 option for sector antennas, where different sectors get their own BCHs and FCHs – which are serially transmitted by the AP. In contrast to a single AP, where the AP transmits the BCHs/FCHs for all sectors, here the EPs synchronize first to the BCH of the AP and transmit afterwards serially their own BCHs/FCHs. This avoids collisions on the air interface, while each RMT sees a regular BCH from an EP or the AP.

The MAC frames for AP and EPs are scheduled frame-wise, i.e. in frames 2*n ($n \in Z$; n<7 for H/2) the AP and in frames 2*n+1 the EPs are busy. Frame-wise scheduling of the EPs will simplify DCA (Dynamic Channel Allocation) and protocol implementation, as the EPs are active only at predefined timing positions.

Every second frame the AP/EPs transmit crosswise empty frames. For this purpose the MAC scheduler at the AP/EP has to know additionally that it is an AP/EP, i.e. a slightly modified scheduler is needed for the AP and EP. The MTs/RMTs need no modification, as they are told in the FCHs when they have to receive or send PDUs (Protocol Data Units).

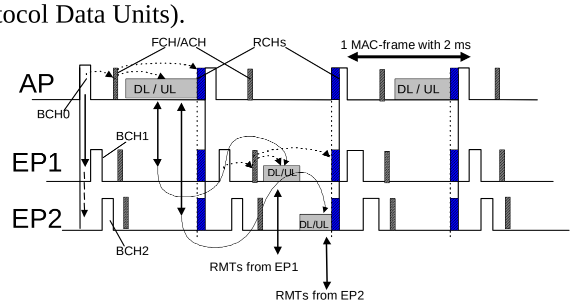

Figure 2: Schematic DLC-protocol for BEACON concept

This concept works well and provides a lot of flexibility for scheduling while it is able to provide QoS in a MultiHop network – as far as possible for wireless links - as long as the number of EPs is small. For higher numbers of EPs the performance degrades significantly due to a high amount of protocol overhead. Table 1 shows the minimal numbers of octets, which have to be transmitted by an H/2 conform AP within one 2 ms MAC frame (preambles and guard times have been converted to octets sent with BPSK1/2). The number of FCHs depends on the number of DLC connections, but the minimum is one FCH. So the minimum number is 87 octets, all coded with the most robust PHY mode BPSK1/2. BPSK1/2 allows transmitting 24 net bits - which is equal to 3 octets – for each symbol with duration Tsymbol = 4 µs, so that the minimum POH (Protocol Overhead) for one AP is:

$$POH = (87/3 * Tsymbol)/2ms = 5.8\% \quad (1)$$

While 5.8% is acceptable small for one single AP, POH increases further if the number of DUC (DLC User Connections) requires additional FCHs or if the AP uses sector antennas. In case of forwarding this overhead has to be added for each EP. The POH increases further, if we want to guarantee full flexibility and have to handle additionally the resource requests of RMTs or EPs to the AP. This part of the POH may become quite significant, depending on the envisaged scenario.

Figure 3 shows a further general challenge for forwarding. As forwarding requires at least two orthogonal resources in time, frequency or code - to transmit data packets in a first step from AP to EP and in second step from EP to RMT – the gain in throughput and/or distance by EPs in a LOS scenario is very small. Under the assumptions described above the achievable throughput decreases very rapidly with the number of EPs. In Figure 4 a star arrangement of EPs – i.e. all EPs are located around the AP – is investigated under the parameter settings of table 2 under different PHY mode selections for the first hop between AP and EP and the second hop between EP and RMT. As can be seen already for 7 EPs throughput breaks down completely and no user data can be transmitted at all. The simulations in Figure 4 have been done for the so-called SF-FSA-concept (Subframe Fixed Slot Allocation, [9]). The BEACON concept performs only slightly better.

In the following we are searching for concepts, which are able to support H/2 conform MTs but have a POH, which scales better than BEACON or SF-FSA.

Transport channel	Direction	PHY Mode	Length [octets]	Comments
BCH + Preambel	DL	BPSK1/2	15+12	for each sector
FCH	DL	BPSK1/2	l * 27	for each sector
ACH	DL	BPSK1/2	9	for each sector
RCH + Preambel	UL	BPSK1/2	9+15	contention based access

Table 1: Equivalent Number of necessary octets in the H/2 MAC frame without data transmission. l = # of FCHs

3. ENHANCEMENTS

In this chapter we propose some enhancements to the above-described BEACON concept. One simple solution for delay critical DUCs (DLC User Connection) – which should be transmitted over a chain of EPs, e.g. to serve a

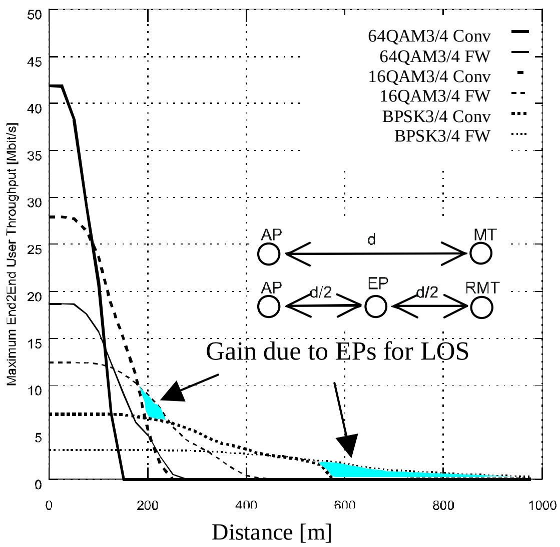

Figure 3: Maximum End2End User Throughput vs. Distance for Forwarding under LOS Conditions

Parameter	Setting	
Noise (N)	-90dBm	
PER(C/I+N)	According to [4]	
ARQ	used hop wise	
MAC	add. control info taken into account	
H/2-PHY-Modes used	64QAM3/4 16QAM3/4 BPSK3/4	
Path loss model:	$P_R = P_s \cdot g_s \cdot g_R \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d^\gamma}$ PR: received power Ps: sending power (23dBm) gs, gR: antenna gain of sender andreceiver set to 1, if not stated otherwise λ: wavelength (ass. Operational frequency for H/2: 5.3 GHz) γ: slope factor (open space scenarios: 2.4)[6]	
Parameter	1.Hop	2.Hop
No. RCHs	4	1
PhyMode LCH	16QAM3/4	64QAM3/4
PhyMode FCH	BPSK1/2	BPSK3/4
PhyMode SCH	BPSK1/2	BPSK3/4

Table 2: Parameter Setting for Throughput Analysis

long street - is shown in Figure 5. Here we reuse the FSA option of H/2 intensively. In a first MAC frame the PDUs are transmitted to/from AP to EP. For the time critical DUCs all EPs have reserved with FSA certain time periods, where they can retransmit the PDUs within the same MAC frame to the next EP - or to the RMT - without further scheduling. Beside a low delay the POH is reduced as well, as the negotiation of resource requests between AP and EPs can be omitted. The drawback is the loss of flexibility for scheduling.

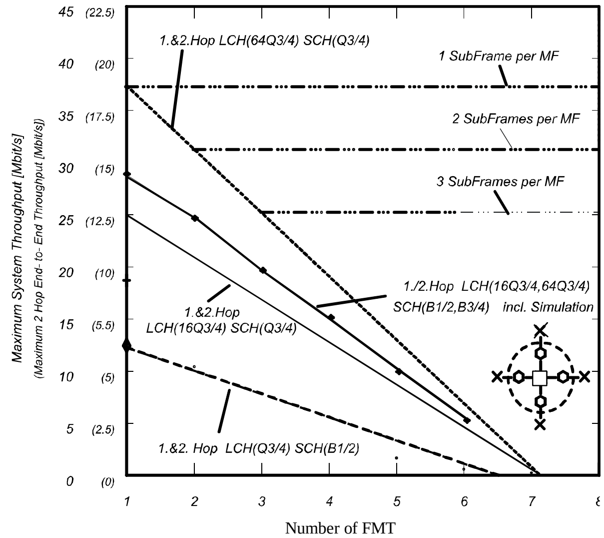

Figure 4: End2End throughput for multihop networks with SF-FSA DLC-protocol

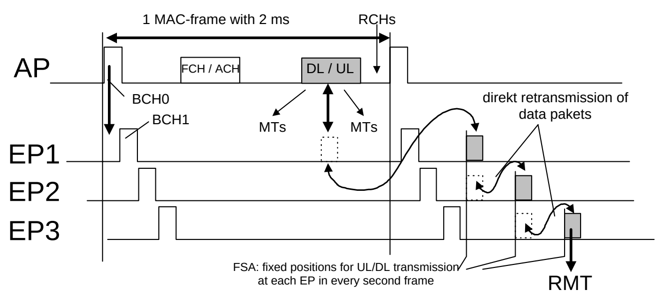

Figure 5: BEACON concept with FSA for forwarding

In the following a suitable combination of sector antennas, partial SFN-techniques and protocol enhancements will be investigated with the goal to minimize the POH while the flexibility for scheduling is maintained. The new proposal is called BEACON-SFN.

Figure 6 depicts for better understanding of BEACON-SFN the benefits of directional receiver antennas for multihop networks. In contrast to Figure 3- where omni-directional antennas have been used - EPs with directional antennas in LOS scenarios have significant performance gains with respect to throughput and distance. The directional antennas are located in the receive path. Directional antennas in the transmit-path are of less value, as the maximum EIRP (Equivalent Intrinsic Radiated Power) transmit power is typically restricted by regulation. In [1] and [9] we proposed the use of SFNs as a special type of a multihop network. Partial SFNs will be a major building block of BEACON-SFN.

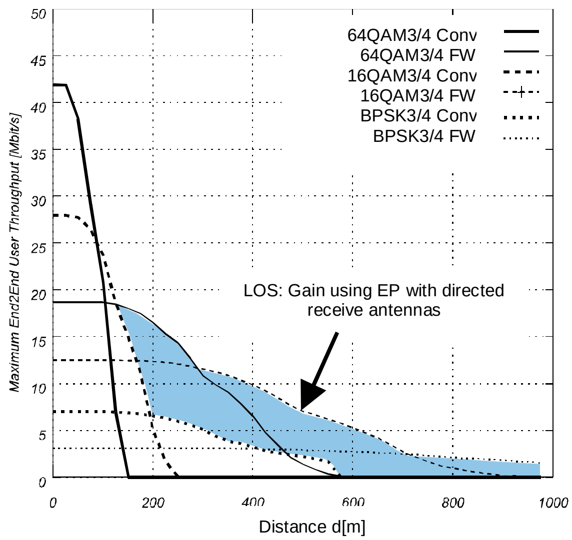

Figure 6: Maximum End2End Throughput vs. Distance for Forwarding under LOS Conditions with directed receive antennas, gain +11.8dB

Figure 7 shows a SFN with two EPs. In a first step the data packets are transmitted from AP to all available EPs and in a second step simultaneously to the RMTs. The transmission may be synchronized or unsynchronized. In case of synchronized transmission the phases of all subcarriers of the OFDM symbols (Orthogonal Frequency Division Multiplex) are pre-rotated at the EPs, so that they add constructively at the RMT. Synchronization increases the SNR (Signal to Noise Ratio) at the RMT theoretically by 6 dB for each doubling of the number of EPs [8], while interference is reduced into other directions. Figure 8 depicts the spatial power distribution for two EPs and one single RF-frequency. The maximum power gain is in the direction of the assumed RMT.

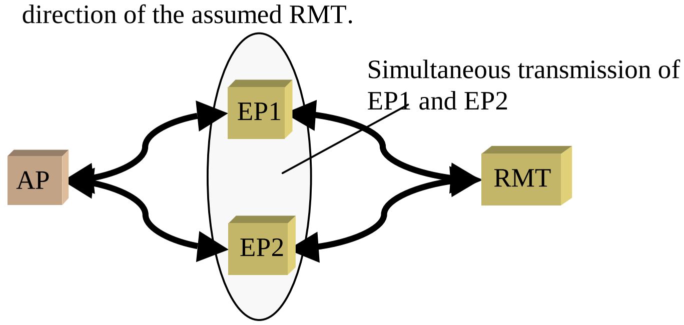

Figure 7: Typical SFN with two EPs

In the following the gain of SFN in combination with forwarding will be analyzed in a realistic environment, here the inner part of the city of Munich. In Figure 9 the net data rates (ARQ throughput) without forwarding and SFN are given for a noise level of -93dBm at the receiver. Figure 10 shows the gain in net data rates considering a pure multihop-forwarding concept. This approach fixes obviously shadowing effects, as visible in the street on east side of EP2. In LOS conditions (north east of EP2) no performance is gained.

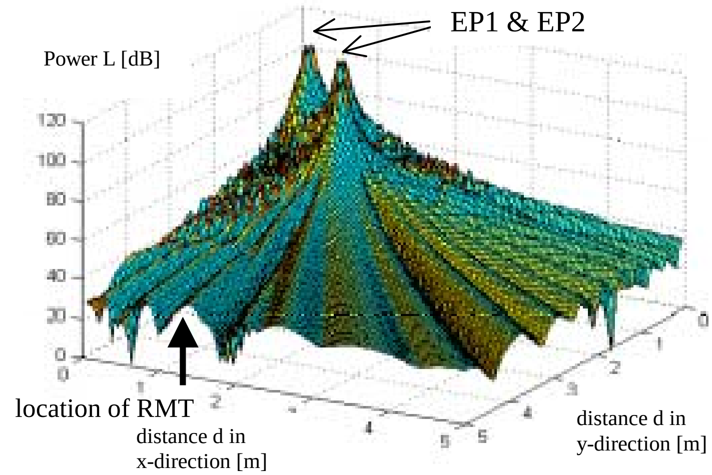

Figure 8: Spatial power distribution for two EPs and one subcarrier with RF-frequency of 5 GHz

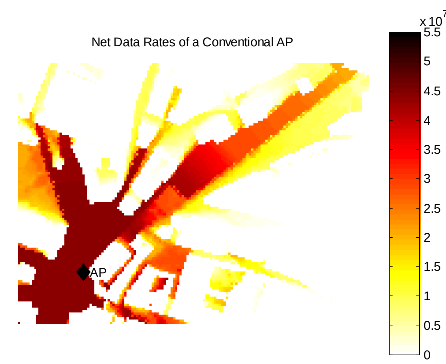

Figure 9: Net data rates based on Ray tracing simulation of a place in the city of Munich (Karlsplatz/Stachus) for one AP (no forwarding nor SFN)]

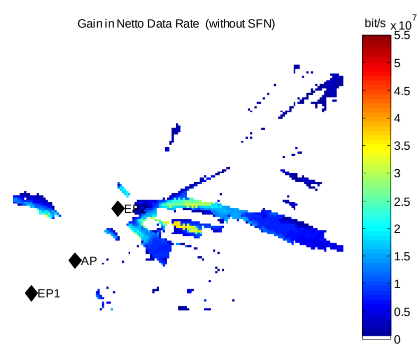

Figure 10: Gain in net data rates with forwarding only

These results can be outperformed by the use of a synchronized SFN, i.e. an additional pre-distortion scheme ('equal gain' according to [8]) within the transmitters. This reveals a comparison of
Figure 10 with Figure 11. It should be noted, that the POH for SFN multihop networks is fixed, as we have always a two-hop connection from AP to all EPs and from the EPs, which build the SFN, to the RMTs.

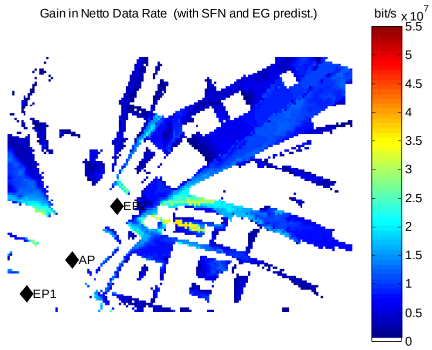

Figure 11: Gains in net data rates with optimum SFN combined with forwarding

BEACON-SFN results from the statements above and introduces following enhancements for POH reduction compared to the standard BEACON concept or SF-FSA:

a) BEACON schedules – in contrast to SF-FSA - frame-wise, so that every second frame is essentially empty, i.e. the POH for these frames is minimal, e.g. only one BCH + one RCH.

b) SFNs have advantages due to limited POH, good coverage and SNR gain but broadcast the same data over the whole multihop cell, i.e. there is no spatial reuse of resources in frequency or time domain in different areas of the multihop network. BEACON-SFN creates several SFNs in restricted and well-defined areas of the multihop network - so-called partial SFNs - and enhances thereby the overall capacity of the network. Partial SFNs decrease the interference within the multihop network so the frequency/time reuse factor can be increased. As we assume EPs on fixed locations the effort for a synchronized partial SFN is relatively moderate.

c) The EPs are equipped with sector antennas, which will allow to build up the partial SFNs. Additionally the sector antennas are used in receive direction as directional antenna to improve the link budget between EP and AP which give a similar multihop performance gain as shown in Figure 6. Sector antennas can be used with one single RF-transceiver and a fast switch, so the implementation effort is restricted.

d) The higher link budget due to directional receive antennas (see above) in combination with the fixed location of the EPs in planned scenarios allows to use high modulation formats like 16QAM3/4 instead of BPSK1/2 for exchange of protocol information (e.g. FCH, ACH) on the AP-EP links. This is not conforming to the H/2 standard, but – in contrast to the MTs/RMTs - the AP-EP link can be proprietary.

e) All resource requests for network capacity of the RMTs and from other EPs, which have been accepted by an EP, are combined into one single request on the AP-EP link. This decreases the number of resource requests in scenarios with high number of RMTs or cascaded EPs significantly.

f) The number of TTAs (Transceiver Turn Around Time: time required to switch RF-frontend from receive into transmit mode) is minimized on AP-EP link by a suitable combination of transmit and receive blocks.

g) The BCHs of the EPs are broadcasted omni-directional – i.e. by all sector antennas – by all EPs simultaneously, which generates a network wide SFN for the BCH. The schematic of the resulting DLC protocol can be seen in Figure 10. In contrast to BEACON - where the BCHs for the EPs are transmitted serially for each EP - there is now only one BCH for the AP (BCH0) plus - independent of the number of EPs - one BCH for all EPs. Additionally to the reduced POH this increases the received power of the BCH at the RMTs, which guarantees a good synchronization at the RMTs.

h) As the BCHs are broadcasted (see above), the information of the BCH is the same for all EPs. Two main information elements of the BCH are the net-id and the pointer to the timing position of the FCH. As a consequence all EPs which are served by the same AP have now the same net id and the FCHs of all EPs have to be transmitted in parallel. In contrast to the BCH, the FCHs contain different information for each EP or each partial SFN, as the FCHs define the content of the actual MAC-frame and collisions on the air interface have to be avoided. For this reason the EPs switch for the rest of the MAC-frame from broadcast mode to sectorized transmission. The sectorization of the multihop network in partial SFNs avoids interference between the concurrently transmitted FCHs of different EPs as well as for the further content of the MAC-frame. It should be noted that the FCH of each second empty frame is identical for all EPs and could be broadcasted omni-directional or omitted at all.

Figure 11shows a proposal, how the partial SFNs could be situated and generated in an open space scenario for BEACON-SFN. Shown are a number of EPs with three 120° sector antennas each. The shaded areas are partial SFNs, all generated by 2 EPs, where each EP transmits on its appropriate sector antenna. E.g. .EP 1 & 2 create partial SFN # 2 and use the sectors according to the depicted arrows, while EP 3 & 4 create partial SFN #22 where RMT1 is located. Partial SFN #2 supports not only RMTs but also EP4, as EP4 wouldn't be reachable otherwise with high data rate. In Figure 13 the partial SFNs have sharp boarder lines, but in reality they will interfere between one another. For this reason adjacent areas have to use either different frequency bands or different time slots for forwarding. All EPs transmit on all three sector antennas concurrently their BCH – shown as circles around each EP - and generate thereby a network wide SFN during the BCH transmission phase of the DLC protocol.

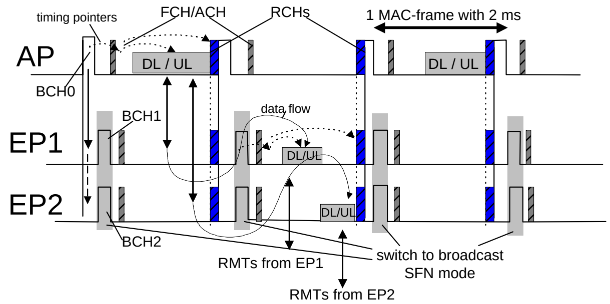

Figure 12: BEACON-SFN DLC protocol with simultaneous transmission of BCH1, 2, … for all EPs

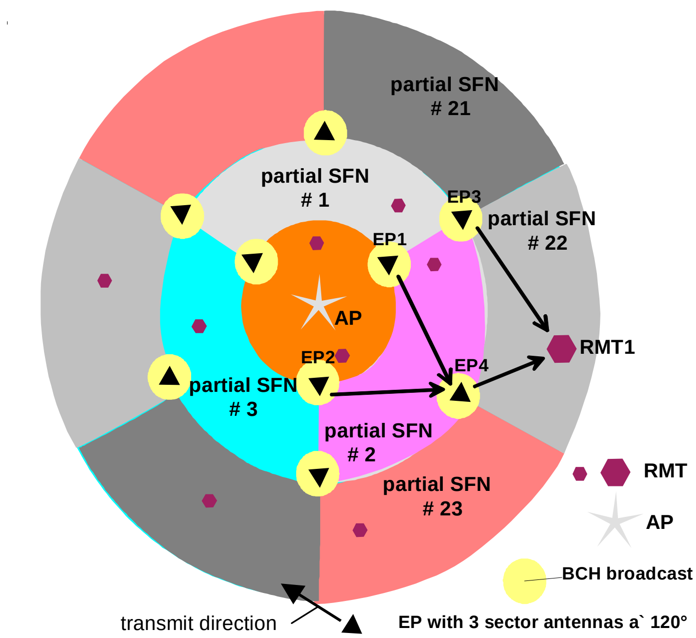

Figure 13: BEACON-SFN concept with sector antennas and partial SFNs (shaded areas) for a LOS scenario. The EPs are equipped with sector antennas. BCHs are transmitted omni-directional by all EPs concurrently

Figure 14 allows calculating the POH for BEACON-SFN by summing up all required protocol elements. Shown is one AP-EP and EP-RMT link. The thick arrows show the direction of transmission. As all partial SFNs transmit concurrently, the POH on the EP-RMT link occurs - independent of the number of EPs - only once for a reuse factor $\alpha=1$ (see below). In another way one could say partial SFNs increase capacity by adding space domain for multihop networks. Figure 14 shows one super frame, consisting of two MAC-frames a´ 2 ms. Besides the already mentioned BCHs, FCHs, ACHs and RCHs additionally guard times, TTAs (Transceiver Turn around Times) and UL- as well as DL-requests for capacity have to be taken into account. The overall POH is:

$$POH_{BEACON\text{-}SFN}[symbols] = 116 + n*(6.6\ldots11) + m*4.5 \quad (2)$$

n is the number of active EPs and m the number of active RMTs for the envisaged EP. The actual figure in the expression (6.6…11) depends on the FCH Phy mode. Equation 3 gives the POH with respect to one super-frame a´ 2 MAC-frames of length 2 ms - i.e. for 1000 symbols - and a symbol length of 4µs:

$$POH_{BEACON\text{-}SFN}[\%] = 11.6 + n * 1.1 + m * 0.45 \quad (3)$$

Figure 15 shows the resulting End2End throughput in Mbit/s for BEACON-SFN with m, the number of RMTs, as a parameter. A comparison with Figure 4 reveals the performance gain for BEACON-SFN. m is not the number of RMTs of the whole network, but for one single EP, i.e. the overall POH depends on the distribution of RMTs in the network. It should be remarked, that parts of the POH occur only for active EPs and/or RMTs, i.e. there will be a traffic gain for scenarios, where not all terminals are active all the time simultaneously.

A frequency or time reuse factor of $\alpha=1$ has been assumed, which in reality will be difficult to achieve due to interference between different partial SFNs. For calculations concerning the frequency reuse factor in multihop networks see [10]. According to [10] small reuse factors of e.g. $\alpha=3$ are possible in city scenarios, where buildings separate different parts of the network. The concept of sector antennas and synchronized partial SFNs decrease interference further for BEACON-SFN. The minimum POH, which has to be added due to a reuse factor greater than one, is at least one BCH, FCH, ACH and RCH protocol element:

$$\Delta POH_{BEACON\text{-}SFN}[symbols] = \alpha * 87 \quad (4)$$

4. Summary and Conclusions

Multihop communication suffers from the need for orthogonal resources for different hops and from the significant protocol overhead in case of high number of EPs and/or RMTs. We have proposed some enhancements of our former BEACON concept - based on sector antennas, partial SFNs and protocol enhancements – which decreases protocol overhead significantly. Full scheduling flexibility and support of standard conform MTs (H/2) could be maintained. We focused on synchronized multihop networks based on H/2, as performance of best effort systems like IEEE802.11a suffers from forwarding losses in unsynchronized sub-networks. The benefits of sector antennas and SFNs are well known for cellular networks. Here we combined these techniques with a proprietary DLC-protocol on the AP-EP link to get scalable multihop networks.

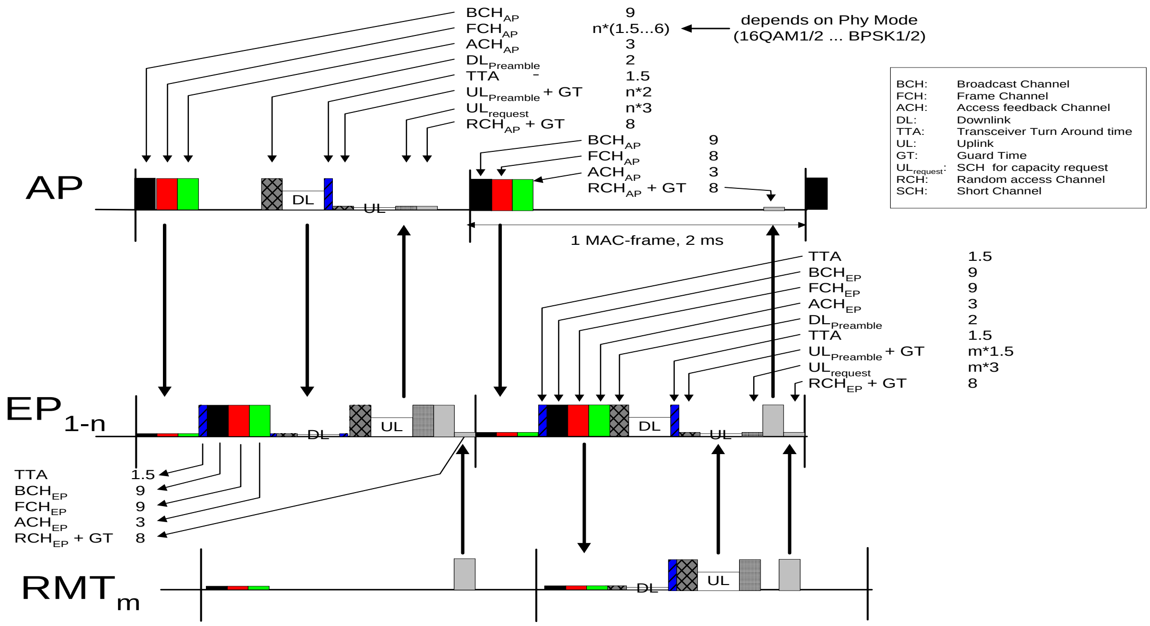

Figure 14: Schematic frame structure for calculation of POH for BEACON-SFN on AP-EP and EP-RMT link. All given numbers are counted in # of symbols of length 4 µs

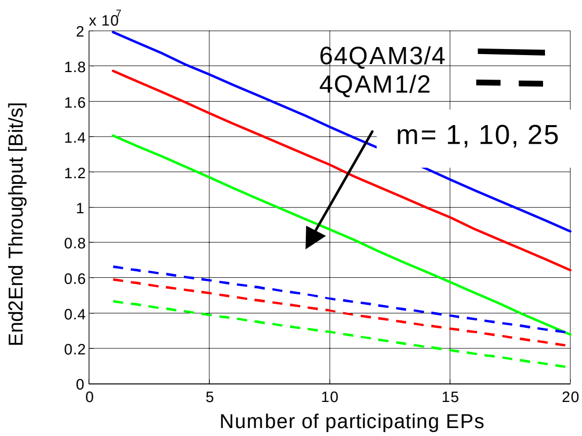

Figure 15: End2End throughput vs. # of EPs for BEACON-SFN with m - the # of RMTs for one EP- as parameter. α=1

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