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A Fast Link Initialization Protocol for Beam-Steering based Cellular Backhaul Systems

Markus Petri, Marcus Ehrig, Markus Günther

IHP

Im Technologiepark 25, 15236 Frankfurt / Oder (Germany)

E-mail: {petri, ehrig, guenther}@ihp-microlectronics.com

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Abstract

To deal with the enormous increase of mobile data traffic, new cellular network topologies are necessary. The reduction of cell area and the usage of light-weighted base stations serving only a handful of users, commonly known as the small cell approach, seems to be a suitable solution addressing changes in user expectations and usage scenarios. This paper is an extended version of [1], where current challenges of small cell deployments were presented from a backhaul perspective. A mesh-type backhaul network topology based on beam-steering millimeter-wave systems was proposed as a future-proof solution. In this paper, we focus on a link initialization protocol for beam-steering with highly directive antennas. Special requirements and problems for link setup are analyzed. Based on that, a fast protocol for link initialization is presented and it is evaluated in terms of the resulting initialization speed-up compared to state-of-the-art solutions. Furthermore, a potential approach for extending the fast link initialization protocol to support point-to-multipoint connections is given.

Keywords: Beam-steering, cellular backhaul, high gain antennas, link initialization, millimeter-wave communication, millimeter-wave MAC

1. Introduction

During the recent decade, the Internet usage scenarios have completely changed. While it was once used by stationary computer equipment, the development of Smartphones enables the mobile usage and the "anytime and anywhere" connectivity model. Additionally, the amount of data consumed by the users explodes. A data traffic study from Cisco forecasts an annual data traffic growth rate of 66 percent between 2012 and 2017 and shows that the mobile data traffic of 2012 was 12 times higher than the total global Internet traffic in the year 2000. The main reason for this exponential growth is the mobile video traffic, which encompasses today more than 50 percent of the total mobile traffic [2].

The described increase of mobile data traffic poses tremendous challenges onto network operators. On one hand, they have to implement and roll-out new generations of radio access networks like LTE [3] to guarantee data rates above 100 Mbit/s for every user between the mobile device and the cellular base station. With LTE-Advanced [4], the next generation standard for radio access networks, a peak data rate of 1 Gbit/s shall be available for each user. Even with an enlarged access spectrum of several 100 MHz and features like MIMO for spatial multiplexing, the high data rate can only be guaranteed when much smaller cell areas are employed, serving only few users. On the other hand, network operators have to build up a backhaul and transport infrastructure to connect the base stations with the core network.

The current topology of the backhaul network can be described as a flat architecture, as shown in Fig. 1. The macro cells use a copper- or fiber-based connectivity to the operator's core network. Wireless links are also common for rural areas. When using small cells, this traditional backhaul network topology is not feasible anymore. Instead, the topology will turn to a hierarchical design with a large number of small cells which are wireless or wired connected to an upper layer of macro cells or aggregation points, as shown in Fig. 2. The macro cells and aggregation points will be connected by fiber, copper or wireless links with increased capacity.

The deployment of a large number of small cell base stations is a very big challenge for mobile operators. While some of them are of general nature and mostly related to the enormous amount of base stations, e.g. site acquisition and power supply, some others are

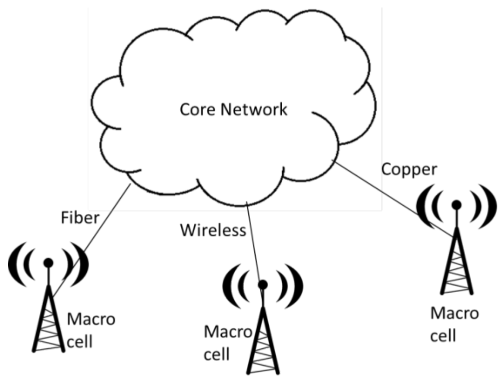

Figure 1. Current backhaul network topology

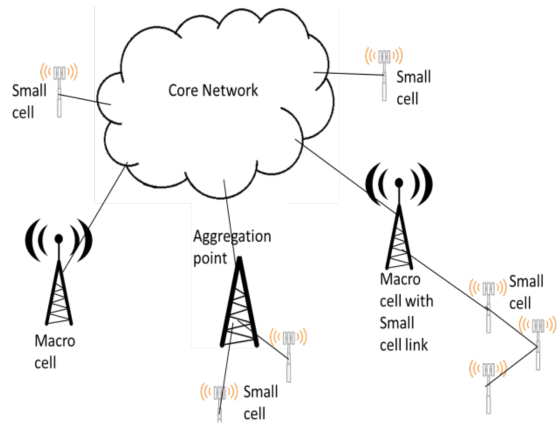

Figure 2. Future backhaul network topology

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directly related to the chosen backhaul technology. This paper analyses the special requirements for millimeter-wave (mmWave) backhaul systems and presents a fast communication link setup protocol for millimeter-wave backhaul systems based on antenna beam-steering.

The paper is organized as follows: In chapter 2, the general small cell network architecture and its challenges are described. Chapter 3 discusses the advantages and requirements of beam-steering based millimeter-wave backhaul systems, whereas chapter 4 presents the mentioned link initialization protocol. Simulation results are given and possible improvements and extensions of the protocol are shown.

2. Small Cell Network Infrastructure

As indicated in the previous section, the increasing data traffic requires new cellular architectures and access schemes. To guarantee a very high data rate for every user, the number of users per cell has to be significantly decreased. Currently, most macro cells consist of 3 sectors. Sticking to the flat macro cell topology, an upscaling of sectorization to 6 or more sectors provides a significant downlink capacity gain [5], while the inter-sector interference limits the number of sectors, especially for vertical sectorization [6].

Another widely proposed approach is the deployment of small cells and, therefore, the usage of a heterogeneous network infrastructure, as shown in Fig. 3. To cope with the capacity crunch at certain places in the macro cell, additional base stations serving only a small part of the macro cell area are deployed. Contrary to sectoring, two access layers are available: The macro cell provides coverage for basic services in the whole cell area, while the small cells are used for higher capacity at certain places, e.g. shopping streets, stadiums or public parks in city centres. Additionally, in-house femto cells as a subtype of small cells might be used to guarantee seamlessly high quality of service by improving indoor coverage.

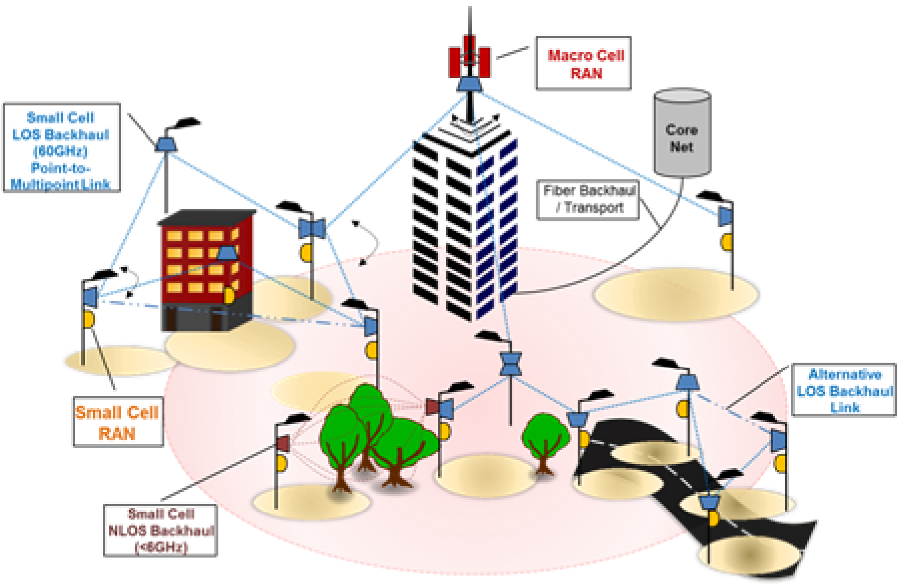

Figure 3. Small cell infrastructure

Obviously, the interference problem also applies to small cells when using the same spectrum resources. But some other difficulties are very special for small cells. Due to the smaller cell diameter, the likelihood of handovers increases and, therefore, the signaling overhead is enlarged. The deployment of base stations with a scaling factor of 10 to 100 in comparison to macro cells is another challenge.

2.1 Challenges of Small Cell Backhauling

Despite the technical challenges on the radio access site, backhauling of small cells is a very critical issue when deploying small cells. Especially in urban areas, the connection between the macro cell and the operator's core network is mostly based on copper or fiber. From a network operator's perspective, fiber is always the best choice if possible. But a fiber connection is mostly not feasible when deploying small cells on lamp poles or traffic lights. Fiber is currently the most expensive backhaul technology, according to [7]. The total cost of ownership of a fiber-connected small cell base station over a five years period is $85'000, compared to $35'000 for a small cell backhauled by a 60-GHz point-to-point connection. Therefore, wireless connectivity with data rates of at least 1 Gbit/s and above will play a dominant role in small cell backhaul.

There are a lot of different backhaul scenarios as indicated in Fig. 3. E.g., there are street canyons with daisy-chained lamp poles, concentrator nodes on roof tops with very high data rate line-of-sight (LOS) connections and small cell base stations without any line of sight to the next aggregation point. To deal with those different environments, a toolbox of wireless backhaul solutions is necessary. Up to now, two solutions gain the most attention: Non-line-of-sight (NLOS) systems below 6 GHz and mmWave LOS systems in the V- and E-Band. While the first enables connectivity without a direct line-of-sight, the latter ones offer data rates of several Gbit/s.

The advantage of Sub-6-GHz-systems is the possibility to build up meshed network topologies, whereas current mmWave backhaul solutions are based on simple point-to-point connections. The main challenges for V-band backhaul solutions are the high oxygen absorption and, mainly for the EU, the frequency regulation, which make it necessary to use high gain – and therefore highly directive – antennas (antenna gain > 30 dBi) to transmit data over distances of several 100 m. Thus, a point-to-multipoint connection would require changing the direction of the antenna beam. In the E-band, the oxygen absorption is much less and therefore not crucial for big distances, but due to the frequency regulation, even more gain than for V-band is required.

A V-band point-to-multipoint scenario based on beam-steering is defined in the IEEE802.11ad standard [8] as WLAN amendment for very high data rates. There are a lot of reported V-band antenna solution focusing on this amendment and indoor applications, e.g. [9][10]. Most recently, a commercial V-band backhaul system with beam-steering and point-to-multipoint connections was announced [11]. While this system is intended for use in backhaul applications, it is built on existing IEEE802.11ad chipsets and has therefore a lower antenna gain compared to reported V-band backhaul systems, e.g. [12], and its use case is limited to short-range links.

3. Beam-Steering for Backhauling Systems

As previously described, mmWave backhaul connections offer very high data rates, but the use cases are limited to line-of-sight conditions. Furthermore, high gain antennas with pencil beams and high directivity have to be used for distances of several 100 meters. The half power beamwidth of a directive antenna with 32 dBi gain is below 3°. In the E-band, pencil beams with beamwidths below 0.5° are common [13][14]. It is obvious that the installation of those highly directive systems is very challenging, if it is not assisted by automatic alignment methods. Several commercially available mmWave backhaul systems have electromechanical alignment units, e.g. [15][16]. Those alignment units consist of one or more electric motors and a gear, which allows tilting the antenna in a predefined range. A control unit with access to the communication part of the backhaul system is used for the automatic or semi-automatic antenna alignment. The alignment unit might be a different tool which is temporarily attached during installation or it might be integrated.

A much better alignment solution is a built-in alignment functionality which uses electronic antenna beam-steering. With electronic beam-steering, each element of an active antenna array – also known as smart antenna – has its own feed point. The individual feed signal amplitude and / or feed signal phase can be changed. Usually, a digital processor is used to control the phase and amplitude. The phase shift between adjacent antenna feed signals results in a tilt of the antenna beam. Since no mechanical devices are involved, the process of changing the beam direction is very fast and mostly determined by the processing time of the control. This allows for fast and automatic alignment of two backhaul stations.

After the initial alignment, the backhaul system suffers from pole sway due to wind load, shocks and vibrations from road traffic and so on. Therefore, a continuous tracking is necessary. This tracking can also be done much better by electronic antenna beam-steering than with fault-prone integrated electromechanical units. The high speed of beam adaptation supports the tracking of pole sway with high frequencies and results in a very short alignment time (see chapter 4).

Besides ease of installation due to automatic alignment, electronic antenna beam-steering offers another advantage. The software controlled dynamic steering of the antenna beam allows steering the beam to different locations, as shown in Fig. 4. Thus, the very fast and dynamic steering ability of smart antennas enhances mmWave backhaul systems with support for point-to-multipoint connections based on a time division multiple access (TDMA) scheme. Point-to-multipoint connections are a subset of meshed networks and a need for future backhauling networks. They enable the possibility of dynamic radio access network topology changes. For example, during night time with low data traffic, some base stations can be powered down. If a backhaul link is temporarily broken due to a blockage, the backhaul network can dynamically adapt and transmit the data through an alternative route.

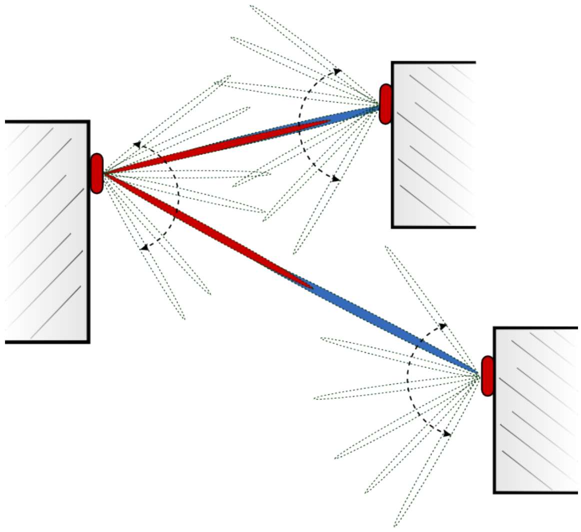

Figure 4. Beam-steering for p-t-mp connections

Although beam-steering with highly directive antennas offers advantages in backhaul networks, some problems arise. One of the major issues is the link initialization, which is discussed in the following chapter.

4. Link Initialization Protocol for Highly Directive Beam-steering Antennas

As previously discussed, the use of beam-steering in backhaul systems with highly directive antennas provides additional functionality like automatic alignment and dynamic switching to different stations. But before using these features, the links between a newly deployed station and other stations need to be initialized, i.e. the new station needs to find its communication partners. Since the deployment process should be fast and easy, an automatic link initialization routine is necessary. This routine should automatically find neighbored stations without any manual interaction. For the following discussion, we assume a point-to-point link between two stations. The necessary adaptations and enhancements of the proposed link initialization protocol for point-to-multipoint connections are discussed at the end of this chapter.

4.1 State-of-the-art link initialization protocols for highly-directive antennas

The simplest solution for a link setup between two stations is an exhaustive search among all possible beam combinations. Let N_{BP} denote the number of beam positions of one station. In total, $N_{BP} \cdot N_{BP} = N_{BP}^2$ combinations of beams need to be examined. To find the best combinations, one station is set to a master role and the other one to a slave role. The master periodically iterates through all of its beam positions, sends signals in these directions and waits for a receive signal for a predetermined time in each beam position. The time spent in one beam position is t_{bd}, so the total time for one iteration through all beam positions is $t_{itr} = N_{BP} \cdot t_{bd}$ for the master station.

The slave also iterates through all beam positions, but it remains in one beam position for $t_s = N_{BP} \cdot t_{bd} = t_{itr}$ and listens for an incoming signal. Once the slave iterated through all beam positions, it restarts the phase from the first beam position. So, the total time for finishing all beam combinations is $t_{Round} = N_{BP} \cdot t_s = N_{BP}^2 \cdot t_{bd}$. (Please note that this rough calculation does not include guard times.)

Both devices, the master and the slave, will automatically start this iterative link search after the first power-up or by request. So if both devices are powered up, after the time t_{Round} all possible combinations are tested and the link is initialized. Since the necessary time for testing all beam positions is depending on the square of the number of beam positions, this approach does not scale well for highly directive antennas with several thousands of distinct beam positions. Even if the beam initialization is stopped after establishing a first link with sufficient quality (and not looking for the optimal beam combination), the worst case link setup time is given by t_{Round}.

A more sophisticated solution based on two initialization phases is presented in [17]. The first-phase search space of beam combinations is reduced by providing side information, i.e. by selecting the maximum antenna beamwidth based on the known link budget and distance between two stations. Once a first communication link is established, the second phase starts and the beam is moved in the direction of the RSSI gradient to improve the communication quality. This solution reduces the beam initialization time, but it requires a side channel for communication between both stations or a manual interaction to provide the link budget. Additionally, it might not be allowed to change the beamwidth of the transmit antenna due to frequency regulation. The second step of moving the beam in the direction of the RSSI gradient of the first established link will only find an optimum setup in line-of-sight conditions without any reflections or NLOS paths.

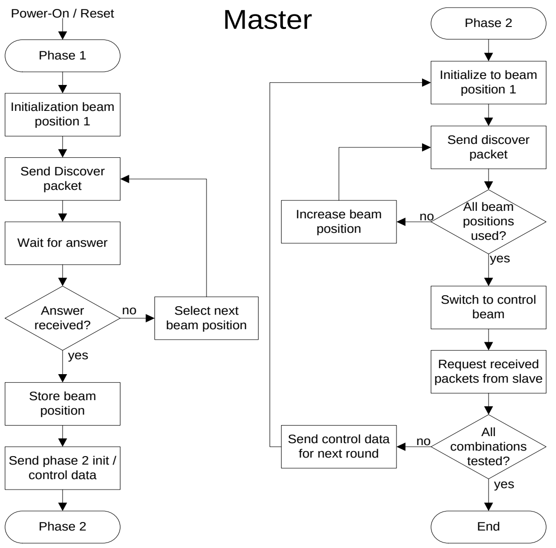

Figure 5a: Process diagram master

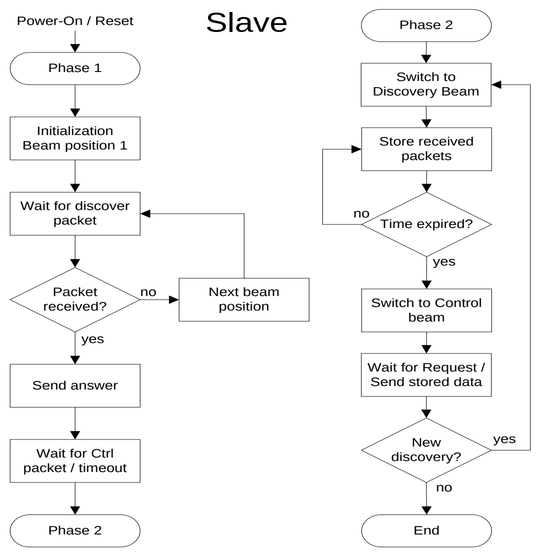

Figure 5b: Process diagram slave

4.2 Proposed link initialization algorithm

To speed up the initialization process, a two phase approach of link initialization is proposed. It avoids side channel information, control channels in different frequency bands and manual interaction. Additionally, it finds the best beam combination even in the presence of reflections and NLOS signal paths. One station acts as a master, the other one as a slave. Fig. 5a and 5b show the sequence of operation diagram of the algorithm for the master respectively the slave. For the sake of clarity, error handling (e.g. timeouts at different states or unsuccessful handshakes) was not included in these diagrams.

In the first phase, link search is done according to the simple exhaustive search. Master and slave cycle through their beam positions. Once a first communication link is established, the first phase is stopped and both stations enter the second phase. The second phase is controlled by the master using the established first communication link, which is called control channel. The set of the beam positions for a link is called beam configuration. First, the master requests the current cycle state from the slave and determines the beam combinations which are not tested yet (based on his own state). Through the existing communication link, the master orders the slave to steer its beam to a certain direction and to listen for a defined time before returning to the control channel beam position. While the slave listens, the master sends packets containing the particular beam position to all of its beam directions without waiting for an answer. After cycling through all of its beam positions, the master returns to the control channel and establishes the communication link again. The master requests from the slave information about the reception of packets, the respective signal quality and the master beam position information from the respective packets. This process is repeated until all remaining combinations are examined.

The next two subsections describe the detailed timing of the beam search algorithm for an exclusive initialization process (i.e. the first initialization of a point-to-point-link) and a setup with an already operational communication link (e.g. adding stations in a point-to-multipoint-environment or continuous beam tracking and optimization). As mentioned before, the beam search algorithm needs a communication system for information interchange between both devices. The sequential control is integrated in a separate module or is part of the medium access controller (MAC). The timing of the beam search algorithm is derived from the parameters of the physical layer (PHY), e.g. modulation and forward error correction scheme with the dedicated processing delays. Additionally, the programming of the smart antenna introduces timing delays. The following timing relations are based on the OFDM baseband processor (BB) published in [18] and on the implementation of the smart antenna.

4.3 Initial Link Setup in P-t-P Configurations

This subsection describes the detailed timing of the beam search algorithm for an exclusive link initialization between two devices. In *phase one* of the algorithm, the controller sends a request and waits for a response. The PHY frame consists of the preamble, the PHY header and the data payload. The duration of the preamble is 4.5 µs. The PHY header and the data payload fit into two OFDM symbols which take 2*0.593 µs, so the smallest PHY frame transmit duration is 5.1 µs. After the last sample of the PHY frame was received, the processing takes additionally 12 µs. The uncertainties of the internal communication between the controller and the baseband processor will be considered with an extra delay of 0.2 µs. The decoding time t_{dec} of the smallest PHY frame is calculated by (1). The duration of the switching of the smart antenna takes 0.7 µs. An important timing part is the propagation delay in the transmission medium which adds 3.3 µs for one way for the expected maximum distance of 1 km. The duration t_{bd} consists of two times of the PHY frame duration t_{phd}, the processing delay t_{prd}, the uncertainty t_{ud}, and the propagation delay t_{pgd}. The controller has to wait for the switching delay t_{swd} after switching to a new beam position for the purpose of component settling. The summarized delays result in 41.9 µs per beam configuration and are calculated by (2). The second column of Table 1 shows the worst case execution durations (t_{Round}) for *phase one* depending on the number of total beam positions N_{BP}. They are calculated by (3).

$$t_{dec} = t_{phd} + t_{prd} + t_{ud} \quad (1)$$

$$t_{rr} = 2(t_{dec} + t_{pgd}) + t_{swd} \quad (2)$$

$$t_{Round} = N_{BP} N_{BP} t_{rr} \quad (3)$$

Table 1. Explicit beam search execution durations for the maximum distance of 1 km

N_{BP}	Phase 1 [mm:ss]	Phase 2 [mm:ss]
1000	0:42	0:14
2000	2:48	0:56
4000	11:11	3:43
8000	44:42	14:51

In *phase two* the communication is controlled by the master. After the negotiation of the control channel between master and slave, the master controls the further timing. The performance improvement of the second phase depends on the parameters of the BB and of the programming interface of the smart antenna. The mentioned BB requires a minimum gap t_{gap} of 13 µs between the preambles. The programming of all components for the next beam position (t_{SPI}) takes 11.4 µs using an SPI clock of 40 MHz. The master switches the beam position before sending a PHY frame which takes 0.7 µs. This programming and switching of the next beam position can be done within the preamble gap $t_{gap} > t_{SPI} + t_{swd}$. The remaining time of 1.1 µs can be used as guard time. Depending on the BB parameters it is also possible that there is no preamble gap and only the PHY frame transmit duration is taken into account. Then the programming time of the smart antenna may dominate. This can be improved by increasing the SPI clock or changing the programming interface, which implies possibly more control wires between the controller and the smart antenna.

In the following the detailed timing of the *phase two* is described. At the start of every iteration the master sends a control packet to the slave over the control channel. The control packet contains the next slave beam position which should be examined and the listening time. The slave responds with an acknowledgement. This response can be sent not until the PHY frame of the control packet was successfully decoded. The analogue front-end settings for the specified next beam position of the slave can be programmed in parallel to sending the acknowledgements if several addressable beam tables are available. Both devices switch to the evaluation phase of the new slave beam position at the predefined point in time. Now, the master sends the Hello-packets for all of his beam positions with an interval of the preamble gap. The next beam position is programmed in parallel and the master switches to the new one until the end of this interval. At the end of a round, the controller needs to wait for the difference of t_{dec} and the preamble gap t_{gap} plus the propagation delay t_{pgd} of the last packet. The duration of one round is given by t_{rs}, which is calculated by (4). After this time both devices switch to the control channel beam configuration. The master requests the received packets and the examination results from the slave. The response duration depends on the parameters which the slave stores for a successfully received Hello-packet. The simplest way is to set a bit in a bit-array related to the received beam position. Additionally, the quality information (RSSI) of the received PHY frame can be stored. This takes more resources in the slave and increases the transmit duration. But with the RSSI values, the master is able to sort the possible beam configurations by the quality information. This saves time and resources in the final evaluation phase of the found links. The described operations will be executed for all beam positions. The duration t_{gr} of getting the response after a request is calculated by (5). N_{PL} is the amount of bits of the data payload per beam position, T_{Sym} is the duration of an OFDM symbol and N_{Sym} the data payload of an OFDM symbol in bytes. The transmit duration of the data payload is extended to a multiple of an OFDM symbol. Column two of Table 1 shows the worst case execution times (t_{Round2}) for *phase two*, which are calculated by (6). For the described scenario N_{PL} is 8, N_{Sym} is 96 and T_{Sym} is 0.593 µs.

$$t_{rs} = N_{BP}\left[\max\left(\left(t_{SPI} + t_{swd}\right), \left(t_{gap} + t_{ud}\right)\right)\right] + \left(t_{dec} - t_{gap}\right) + t_{pgd} \quad (4)$$

$$t_{gr} = t_{rr} + \left\lceil \frac{N_{BP}N_{PL}}{8N_{Sym}} \right\rceil T_{Sym} \quad (5)$$

$$t_{Round2} = N_{BP}\left(t_{rr} + t_{rs} + t_{gr}\right) \quad (6)$$

Since the second phase is controlled by the master and there is no need to wait for an answer in each beam direction, the link setup time is reduced. Table 1 summarizes the necessary link initialization times for different numbers of beam positions. The minimum link setup time for 8000 beam positions, e.g. the first beam combination establishes a link, is 34 percent smaller than the time for testing all combinations in *phase one* or a simple exhaustive search algorithm. But it needs to be mentioned that the worst case for all presented solutions is the same: If the link setup is established only at the last possible combination, the setup time equals t_{Round}. In practice, the two phase approach will decrease the link initialization time, since the stations will be roughly aligned and the most meaningful first beam position to be tested will be the perpendicular. The next beam positions will be the neighbored and so on.

After the processing of all beam positions the collected and sorted beam configurations (master ⇔ slave) will be tested to get the best one, e.g. the one with the lowest bit error rate.

This takes about 30 ms for 1000 PHY frames with 2048 bytes data payload for each connection (beam configuration). The best connection(s) will be used for the further communication in the system.

4.4 Link Setup in P-t-M-P Configurations

The previously described algorithm uses the whole bandwidth of the channel. But it is also possible to do the search during the runtime of an initialized communication link. This is necessary when a station has to be later added or when a station has to be replaced. The runtime search also increases the reliability of active communication links, due to the unnecessary interruption for the new search process. In this case the search algorithm has to be synchronized to the running MAC protocol [19]. Fig. 6 shows the structure of the superframe. Let's assume the duration of the superframe with 1 ms and a device setup of one master and four slaves. The superframe starts with a beacon slot of 50 µs. The TDMA scheme divides the remaining time into equal time slots of 237 µs and assigns one slot for each slave device. In this example the first slave was already initialized and uses the first data slot (Data #1). The remaining three slots are available for the beam search of further slaves. The beam search of the second slave can be located in the last three data slots. After each successful beam search the additional link will be established, using one of these data slots. The fewer slots available and the higher the amount of beam positions the longer is the search duration.

The runtime search algorithm also supports two phases. In *phase one* a request with an immediate response is used. In *phase two* an accelerated request-store method decreases the execution time of the searching procedure. All transmissions must be aligned to the slot borders when the slots are not successive. The algorithm in the slave needs the following information to start: the superframe duration and the number of tests (request-response) per superframe. The duration of one data slot allows the test of 5 beam positions. Two successive data slots allow 11 tests, and three successive slots allow 17 tests. The second column of Table 2 shows the duration of *phase one* of the search algorithm during the superframe with three available slots. After a successful answer to a Hello-packet the processed tests per superframe increases to 50 within three data slots and 33 within two available slots. The last two columns of Table 2 show the execution time in *phase two* with three and two available slots. The execution time of the beam search during the runtime of a MAC protocol depends on the remaining free data slots and the amount of beam positions.

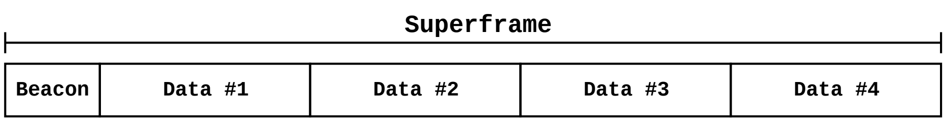

Figure 6. Superframe structure

Table 2. Beam search execution durations during the runtime of the MAC protocol

N_{BP}	Phase 1 3 Slots [mm:ss]	Phase 2 3 Slots [mm:ss]	Phase 2 2 Slots [mm:ss]
1000	0:59	0:21	0:31
2000	3:56	1:21	2:02
4000	15:41	5:21	8:05
8000	62:44	21:21	32:19

5. Conclusion

60 GHz links will become a requirement for future backhaul networks to support the tremendous data rates. Due to propagation characteristics and frequency regulation, a very high antenna gain has to be used, resulting in a very narrow antenna beam. Therefore, an automatic initialization of the communication link is necessary to avoid costly manual link alignment during installation. Electronic antenna beam-steering based on phased arrays is a highly suitable solution. Additionally, electronic beam-steering enables features like dynamic beam tracking and point-to-multi-point connectivity.

The main challenge for the automatic alignment of highly directive beam-steering antennas is the high number of potential beam combinations. State-of-the-art link initialization algorithms and protocols need side channel information or side channel communication links to establish the communication link in an acceptable time. The presented two phase approach will find the optimum beam combination without any side channel link or side information, while it accelerates the initialization time by more than 66% in the best case, compared to an exhaustive search among all possible combinations. It is not only applicable for the first link initialization, it can be also used for continuous beam tracking and to find new communication links in point-to-multi-point environments.

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