Time-to-Space Division Multiplexing for Tb/s Mobile Cells

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Abstract—Space division multiplexing increases the capacity of mobile cells by reusing the frequencies in various directions. Yet, today's concepts scale badly to millimeter wave and therefore cannot provide Tb/s capacity. In this paper, we introduce time-to-space division multiplexing as a novel scheme to steer multiple beams simultaneously to different users. The main benefit of the proposed method relies in the fact that simple hardware can be used to generate the beams. In other words, it provides the advantages of space division multiplexing without relying on the complex array feeders that are usually required. Thanks to this advantage, the proposed technique can be easily combined with millimeter wave systems as recently demonstrated.

Index Terms—5G communication, millimeter wave (mm-wave) communication, phased array antennas (PAA), radio access network (RAN), time division multiplexing (TDM), space division multiplexing (SDM), ultra-fast beam steering, time-to-space division multiplexing (TSDM).

I. INTRODUCTION

Space division multiplexing (SDM) and millimeter wave communication - if applied together – could offer Tb/s of wireless capacity [1], [2]. Yet, an affordable solution to merge the advantages of both technologies is very challenging to be found [3]. SDM requires either massive hardware in the form of multiple phased-array antennas or large digital signal processing (DSP) capacities. Yet, DSP is particularly expensive at highest speed such as those needed to encode millimeter wave signals. If Tb/s wireless links are to become practical new solutions that rely on low complexity and low-cost hardware will be needed [4].

Among the most promising implementations of next generation radio access networks (NG RAN), two trends can be distinguished: First, concepts relying on current 4G-LTE microwave frequencies (2.4, 5 GHz) with approaches such as massive multiple input, multiple output (MIMO) [5], [6] or smarter networks [3], [7]. Second, concepts based on millimeter wave (mm-wave) technologies [2], [4], [8]–[10]. In the case of massive MIMO [5], e.g. E. Larsson et al. take advantage of low-cost, reliable, and mass producible components to generate multiple beams, but suffer from the limited bandwidth available at microwave frequencies. On the other hand, mm-wave technologies leverage the large bandwidth available at mm-wave bands to considerably increase the bitrate. However, the increased cost and complexity of the components diminish the benefits and often prevent the implementation of advanced concepts such as massive MIMO. Nonetheless, combining advanced system architectures such as massive MIMO or smarter networks with mm-wave technologies could potentially combine the benefits of both approaches to provide both a larger bandwidth and spatial diversity at the same time [11]. Yet, merging both approaches has shown to be challenging with current designs due to the large number of mm-wave components in the base band units (BBU), the remote radio head (RRH), and the user equipment (UEs) [5], [12].

In this paper, a next generation (NG) RAN scheme relying on already published ultra-fast mm-wave beam steering demonstrations is presented [13], [14]. The scheme, which is termed time-to-space division multiplexing (TSDM), increases the capacity of a mobile cell while simultaneously drastically reducing the hardware requirements on the UEs. In other words, TSDM enables multiple beam steering capabilities comparable to concepts such as known from massive MIMO [5] or multiple beam array feeders [15], but with a fraction of the hardware requirements at mm-waves. Leveraging the advantages of TSDM, we propose the design of a mobile cell with an aggregated capacity above 1 Tb/s, meeting the frequency band specifications of the IEEE 802.11ad standard.

The paper is organized as follows: First, the requirements of a cell with Tb/s capacity is described. Second, the fundamental principles of TSDM are explained. After presenting results of a system level simulation the paper is concluded by summarizing the key aspects of TSDM.

II. TOWARDS Tb/s MOBILE CELLS

The required throughput per square meter of a mobile network is highly dependent on the type of environment. Particularly, high capacity will be required in hotspots such as public transport stations, stadiums, airports, or special event venues, where a large number of closely located users may consume high definition video streams directly to their terminals. In such hotspot scenarios, a very high cell capacity must be installed to cope with the demands. The important unit to consider here is the throughput per square meter. Some of the current major trends to improve this metric rely on reducing the size from macro to picocells, better
reuse of the available bandwidth, or the installation of smarter network schemes to reduce cell interference [3]. However, these solutions do not increase the capacity by several orders of magnitude, as would be required for the above-mentioned hotspots. In this chapter, two of the major envisioned solutions to increase the capacity by orders of magnitude are reviewed: Namely millimeter wave communication and space division multiplexing. Ultimately, it is concluded that Tb/s cell capacity is achievable using existing hardware compatible with actual standard by combining both mm-wave and SDM in the same system.

A. Millimeter Wave Communications

In communication standards at millimeter wave frequencies, such as IEEE 802.11ad-2012 (60 GHz), the channel bandwidths can be as high as 2.16 GHz [16]. The maximal physical data rate defined therein is 6.757 Gb/s for a chip rate of 1.76 GBd, using an OFDM 64-QAM modulation scheme and a 13/16 low-density parity-check code (LDPC) [16]. To simplify the discussions in this paper, a symbol rate \( R_s \) of 2 GBd (still fitting in the 2.16 GHz channel bandwidth) instead of 1.76 GBd is considered. Combined with a 4 bit/symbol modulation (16QAM) a bit-rate \( R_b \) of 8 Gb/s is encoded in the channels.

In the band definitions of the IEEE 802.11ad standard, up to four channels \( n_{\text{channel}} \) at various carrier frequencies can be used [16]. The cell capacity \( C_{\text{tot}} \) is thus given by

\[
C_{\text{tot}} = R_b \cdot n_{\text{channel}} \cdot n_{\text{sector}} \tag{1}
\]

Using a bit-rate \( R_b \) of 8 Gb/s, 4 channels, and 3 sectors, the aggregated capacity is 96 Gb/s.

Recent research has shown even higher bitrates at millimeter wave frequencies, but mostly for point-to-point communication [17]–[22]. Yet, one of the main limiting factors for NG RAN at millimeter wave frequencies is the increased free space path loss that either reduces the reach of the access network or forces the utilization of beam steering systems. For the first generation of 802.11ad RAN, the envisioned applications are mostly short range such as indoor communication or mobile docking (up to 10 m) and thus may avoid complex beam forming systems. On the other hand, outdoor applications will require higher reach and therefore a more sophisticated architecture.

B. Advanced Beam Forming

Another way of increasing the cell capacity by orders of magnitude is to use SDM. SDM is based on reusing the same frequency band in various directions by forming spatially separated, non-interfering radio beams [1]. This corresponds to the creation of virtual cell sectors with adaptive coverage. If a user receives the signal from only one beam at a time, it results in two advantages: first, the cell capacity is increased by the number of spatially separated beams. Second, the full UE capacity can be used since neither time, code, nor frequency multiplexing is required. Hence, there is a need of phased array antenna (PAA) concepts capable of simultaneous and independent steering of multiple antenna beams. In order to compare the various implementations of PAA, three main categories of feeders can be defined, see Fig. 1.

In Fig. 1(a), a simple feeder for a PAA is depicted. The signal \( s_1(t) \) provided at the input of the PAA is transmitted in a direction defined by the phase or delay \( \Delta T \) added in front of each antenna [23], [24]. Such concepts allow for electronic scanning and longer reach, but they do not offer multi-beam capability and therefore cannot increase the cell capacity. PAA can be implemented as electronic or microwave photonic schemes. Using electronic array feeders, the feeding signal \( s_1(t) \) is usually directly modulated onto the wireless carrier. The delay element \( \Delta T \) is then implemented as a radio-frequency component [25]–[27]. In the case of a microwave photonic array feeder, the feeding signal \( s_1(t) \) is encoded
onto an optical carrier. The delay element is then usually implemented as a photonic component [13], [15], [28]. Right after applying the delay, the optical signal is down-converted to the wireless domain by heterodyning with an optical local oscillator.

In Fig. 1(b), a PAA with multiple feeders is depicted. Many variations of this scheme can be found in literature, united by the fundamental principle to add multiple feeder networks in parallel (depicted here with different colors). Such concepts enable larger capacity by creating fully independent multiple beams. Yet, the hardware requirements for a large number of beams make this approach complex and costly.

In Fig. 1(c), the most flexible multi-beam system is shown. This is usually referred to as massive MIMO or digital beamforming and relies on digital signal processing to form the different beams. The signals for each antenna with their requested delays are generated by a DSP stage with a dedicated digital to analog converters (DAC). In [5], it is rightfully claimed that the cost and complexity of the hardware is not an unsurmountable issue at microwave frequencies. This statement unfortunately cannot be extended to mm-waves frequencies. [1]

Systems based on Fig. 1(b) are usually limited to a few beams while systems based on Fig. 1(c) are limited by the number of antennas that can be integrated with reasonable cost and complexity. For both Fig. 1(b) and Fig. 1(c), the first advantage is that the cell capacity is increased by the number of beams generated at the PAA. Assuming a system capable of generating 10 separate beams, the cell capacity will at best increased by a factor of 10. Another advantage is that the complexity of the UEs does not change with the number of beams - low-cost components can still be used at the UE.

C. Reaching Tb/s Cell Capacity

Cell capacity in Tb/s can be realized by combining mm-wave with multiple beam solutions as depicted in Fig. 1. Merging a mobile cell at mm-wave fulfilling 802.11ad (see (1) above) and a SDM system supporting 11 beams could bring the capacity $C_{\text{tot}}$ to

$$C_{\text{tot}} = R_b \cdot n_{\text{channel}} \cdot n_{\text{sector}} \cdot n_{\text{beams}} \quad (2)$$

With a bit-rate $R_b$ of 8 Gb/s, 4 channels, 3 sectors, and 11 beams, the aggregated capacity is now 1056 Gb/s.

By generating separated beams, each user can use the full channel capacity (8 Gb/s). In systems implementing SDM, the total cell capacity is increased by the number of beams. If more users are located in the proximity of the cell, the capacity of each beam could still be shared by closely located users using time or frequency division multiplexing.

III. TIME-TO-SPACE DIVISION MULTIPLEXING

In RANs such as 4G LTE and most of the IEEE 802.11 wireless protocols, multiple UEs share the same transmission channel using time division multiplexing (TDM) and/or frequency division multiplexing (FDM). This requires components with processing capabilities corresponding to the full capacity of the base station. A drawback of this scheme is that only a fraction of the receiver’s capabilities is exploited. On the other hand, SDM implementations do not suffer from this limitation: in SDM-based mobile networks, the total cell capacity can be increased without changes to the UEs by parallelizing multiple streams.

As explained in the last section, combining mm-wave and multiple beam steering is an attractive solution for 5G RAN, but new architectures are needed to overcome the hardware complexity or high costs of approaches such as those depicted in Fig. 1(b) and (c) [1]. A promising solution with the hardware of Fig. 1(a) but the capacity of the more advanced approaches relies on a PAA with ultra-fast beam steering capabilities [13], [14] - a system in which the beam direction could be adjusted with extremely short settling times and allow for - what we call - time space division multiplexing [14].

The concept of TSDM is to emulate a multiple beam system by steering a single beam in between the transmission of each symbols. To perform this operation, a PAA with low settling times is needed.

A. Steering Multiple Beams With Simple PAAs

The principle of TSDM is illustrated in Fig. 2. First, the signals for the different user equipment (UE) are time-division multiplexed (TDM) symbol-by-symbol. This feeding TDM signal could be, depending on the implementation of the feeder, in baseband, passband, or encoded onto an optical carrier. The different colors in Fig. 2(I) represent the time slots allocated to the different beams. The TDM sequence is subsequently transmitted to the PAA in the base station (BS). In a realistic scenario, the transmission would likely rely on radio-over-fiber [2].

In the BS, see Fig. 2(II), a control signal synchronized with the incoming data stream is used to perform time-to-space mapping to redirect the different tributaries in their time slots, to a specific direction. Using this symbol-by-symbol steering, the different UEs receive signals that correspond to a return-to-zero modulation scheme, see left part of Fig. 2(III). Therefore, a low-pass filter can be applied to the signal without causing inter-symbol-interference (ISI).

As can be seen from the signals after the low-pass filter, right part of Fig. 2(III), the sequence assigned to each user is received at a symbol rate 3 times smaller than the one of the transmitter. In other words, TSDM enables steering of multiple beams with a PAA built using a simple array feeder.

B. Replacing Low-Pass Filters by Band-Pass Filters

To stay compatible with channel specifications and low-end commercial UEs e.g. defined in 802.11ad [16], the low-pass filters from Fig. 2(III) can be replaced by band-pass filters (BPF) in front of the antennas in the BS. Such a scheme with BPF is depicted in Fig. 3. The difference compared to Fig. 2 lie in the part II of the figures. To understand the working principle with BPF instead of LPF, a reminder of the signal characteristics in SDM system is needed. As shown in Fig. 1(b) & (c), the signals transmitted by the antenna in SDM systems are a superposition of multiple inputs with various delays. This superposition is either performed with an
analog combiner in front of the antenna or within the digital processor. In the case of Fig. 3(II) with BPF, this superposition of the signals is achieved by the time broadening effect that occurs when using a filter with bandwidth smaller than the transmitted signal bandwidth usually leads to inter-symbol-interference (ISI) and distorts the signals. Yet, in the TSDM case, ISI matches the desired effect. Indeed, in SDM schemes, as shown in Fig. 1(b) and (c), signals for various beams are added on top of each other in front of the antennas. Such an addition of different signals also take place through ISI - through a time broadening, the symbols extend into their neighbours and information is added. Note that the signals in front of the antennas are passband signals, for the sake of readability only the envelope of the signals are plotted.

The main advantage of this approach compared to a multiple feeders, shown in Fig. 1(b), or massive MIMO, shown in Fig. 1(c), is that the PAA only relies on a single simple feeder, see Fig. 1(a). Neither complicated wiring nor a large quantity of expensive hardware is required.

C. Conditions for Proper Operation of TSDM

Time-to-space division multiplexing enables multiple beam steering with low complexity PAA. However, there are two intrinsic limitations and corresponding conditions that must be respected a TSDM system. In this section, these limitations are summarized for a PAA build with true time delays (TTD). Further insight can be found in Appendix A. The first limitation is simply related to the fact that the angular width of the beam

### Fig. 2.
Principle of time-space division multiplexing (TSDM). I) Signals for the different user equipment (UE) of the base station (BS) are encoded using symbol based time division multiplexing (TDM). II) The BS performs a time to space mapping using symbol-by-symbol steering. III) The UE down-converts the mm-wave signals and performs a low-pass filtering (LPF). The signal after the LPF is similar to the one received with other space division multiplexing (SDM) schemes. Note that the signals in front of the antennas are passband signals, for the sake of readability only the envelope of the signals are plotted.

### Fig. 3.
TSDM scheme with filtering in the base station (BS). In contrast to Fig. 2, where the filtering is performed in the UEs, the filtering now takes place in the base station. Band-pass filters (BPF) are placed in front of each antenna to match the bandwidth of the channel. Such a filter with a bandwidth smaller than the transmitted signal bandwidth usually leads to inter-symbol-interference (ISI) and distorts the signals. Yet, in the TSDM case, ISI matches the desired effect. Indeed, in SDM schemes, as shown in Fig. 1(b) and (c), signals for various beams are added on top of each other in front of the antennas. Such an addition of different signals also take place through ISI - through a time broadening, the symbols extend into their neighbours and information is added. Note that the signals in front of the antennas are passband signals, for the sake of readability only the envelope of the signals are plotted.
must be small enough to avoid interference between adjacent users. This is a limitation common to all SDM beam steering schemes. The second limitation is related to the memory-less nature of the TTDs used in the PAA feeder. In other words, the first symbol entering the TTD must be the first one leaving. This limitation is further explained with the help of Fig. 4.

For the sake of clarity, the signals are depicted here as baseband signals (i.e. we plot the envelope of the signals) while in reality they are passband signals. If the beam is to be scanned between two directions (blue and red), the required feeder delay $\Delta T$ is proportional to the relative angular separation $\Delta \theta$ between the two directions multiplied by the antenna spacing $d$. For the antennas at the edge of the PAA, the required delay is therefore $p \cdot \Delta T$ with $p$ the position of the antenna ($p = 0$ at the center of the PAA). To avoid inter-symbol interference between the blue and red time slots, $p \cdot \Delta T$ should be smaller than $RZ \cdot T_s$ with $RZ$ the return-to-zero duration and $T_s$ the transmitter symbol duration. Due to this limitation, the relative steering angle $\Delta \theta$ between two beams is limited to small angular steps.

To provide the highest capacity despite these limitations, design rules should be followed. First, the beam should be steered continuously from one edge of the sector to the other and then reset at the initial angle. Second, the transmitter pulse should feature a return-to-zero characteristic.

In the case of a PAA build with phase shifters, an analog limitation is to be found, see appendix A for more details.

1) The Beamwidth Condition: The beamwidth condition simply implies that the angular width of the beam should be smaller than the coverage of the sector divided by the number of users. Indeed, in a cell sector covering 120° with 10 independent beams, the beamwidth must be smaller than 12° to avoid interference. This condition, which defines a minimum number of antennas $N$ required in the PAA, is given by

$$N \geq 1 + \frac{2 \cdot \text{acosh}(A_{SL})}{\text{asech}\left(\cos\left(\frac{\Theta_{\text{sector}}}{n_{\text{users}}} \cdot \frac{\lambda_{RF}}{d}\right)\right)}$$  \hspace{1cm} (3)$$

where $A_{SL}$ is the desired side lobe attenuation at the position of the adjacent user when using Dolph-Chebyshev tapering, $\Theta_{\text{sector}}$ is the size of the sector in radians, $n_{\text{users}}$ is the number of equispaced users using the cell sector, $d$ is the antenna element spacing and $\lambda_{RF}$ is the wavelength of the mm-wave carrier frequency $f_{RF}$. See (A.3) in the appendix for more details on (3).

2) The Symbol Transition Condition: The symbol transition condition implies that the requested delay to steer the beam should limit the ISI to a maximum of 3dB between adjacent time slots. As an example, if one uses a 50% RZ scheme in the transmitter, the maximal delay allowed between two consecutive symbols corresponds to 50% of the symbol duration. The condition can be calculated using

$$N \leq 1 + \frac{RZ \cdot T_s \cdot c}{d \cdot \sin\left(\frac{\Theta_{\text{sector}}}{2 \cdot n_{\text{users}}}\right)}$$  \hspace{1cm} (4)$$

where $RZ$ is the return-to-zero duration $0 < RZ < 1$ (0.5 for 50% RZ), $T_s$ is the symbol duration at the transmitter data rate and $c$ is the speed of light. See (A.11) in the appendix for more details.

3) The Frame Transition Condition: The third condition, i.e., the frame transition condition, corresponds to the pause in transmission that should be inserted while steering the beam back to the initial angle. In fact, the requested delay to steer the beam back from one end of the cell sector to the other is related to the sector size, e.g. 120°, and to the array size. Indeed, the larger the array and the steering angle, the larger the requested delays. If this requested delay is larger than the symbol duration, one must pause the signal transmission by inserting empty time slots in order to avoid interference. The frame transition condition can be stated as

$$N \leq 1 + \frac{(n_{\text{slots}} - n_{\text{users}}) \cdot T_s \cdot c}{d \cdot \sin\left(\frac{(n_{\text{users}} - 1) \cdot \Theta_{\text{sector}}}{2 \cdot n_{\text{user}}}\right)}$$  \hspace{1cm} (5)$$

where $n_{\text{slots}}$ is the length in symbols of the frames (including active and “empty” users). See (A.16) in the appendix for more details on (3).

To make TSDM simpler and easier to implement, we define two aspects of the transmitted signal generation. First, the symbols for the different beam directions are grouped in frames comprising both the symbols to be transmitted and the pauses from the frame transition condition. There are thus time slots at the transmitter that are filled by user data and others that are empty. For example, a frame could comprise 4 user slots out of 5 time slots. Second, the transmitter pulse shape corresponds to a return-to-zero modulation scheme. At the first glance, it seems that the spectral efficiency of the mobile cell is reduced as RZ and empty slots are implemented. However, this reduction of spectral efficiency only applies to the feeding signal in front of the array, not to the wireless signals. Indeed, the spectral efficiency related to the low bandwidth wireless channels is not impacted by the frame configuration as each individual beams could be mapped to a specific wireless channel bandwidth. The reduction of the spectral efficiency of the feeding signal only implies that a larger bandwidth will be required in the backbone network. Yet, the limitations in cell capacities comes from the wireless channel, not from the backbone network.
In Fig. 5(a), the three conditions stated above are exemplarily plotted for a configuration with 5 time slots in the frame. The figure shows the supported area (green) in which the TSDM scheme will work when using a 10 GBd transmitted signal with 50 percent RZ in a 60 GHz carrier cell covering 120°. The ideal working point corresponds to 4 equispaced users and requires at least 13 antennas. In addition, the results show that RZ50% is not needed for the system to perform correctly, as the ideal working point requires only a RZ of 21.6%. The array weights are tapered with a Dolph-Chebyshev side lobe level of 30 dB. Serving 4 active users implies a cell capacity increase by a factor 4. In Fig. 5(b), the corresponding transmitted frame is depicted. Fig. 5(c) describes the beam switching scheme. In the simplest case, the beam will be steered from the left to the right from users 1 to 4. Once the beam has been scanned through the sector, an additional slot is used to return to the initial angle.

The system has been optimized for three frame length configurations. The results, summarized in Table I, show how to shape the frames in order to increase the cell capacity by a factor of 4, 8, and 11. The total cell capacity in Gb/s corresponds to the sector capacity in GBd multiplied by the number of sectors per cell (3 for 120° cells), the number of possible carrier frequencies (4 in 802.11ad-2012), and the spectral efficiency (4 b/s/Hz using 16-QAM).

### A. Reaching Tb/s

The principle of TSDM has been experimentally demonstrated in [13] and [14]. However, these demonstrations were limited in array size and aggregated cell capacity. To demonstrate that the required capacity per sector can be reached with TSDM, simulations have been performed. For this purpose, a time-domain simulation framework supporting symbol-by-symbol beam steering has been implemented. It comprises the following key features: For the generation of the feeding TDM signal, multiple DeBruijn sequences are multiplexed onto the various tributaries. The calculation of the delay lines is made with finite impulse response (FIR) filters. Here, the development was very specific as the requested delays are changing for each transmitted symbols, thus, the FIR filter is updated for each symbol from a lock-up table supporting various types of delay lines. The channel is only modeled through its free-space path losses, this assumption
Fig. 6. Simulation Results. (a) EVM for a TSDM system with 11 active users reaching an aggregated capacity of 1056 Gb/s (16-QAM). The EVM (∼6 percent) only accounts for the distortion due to TSDM and can therefore be considered as a noise-equivalent penalty of the proposed concept. (b) The ideal low-pass filter bandwidth in the receivers is given by 1/n slots with n slots being the number of time slots in the transmitted frames and Tx BW the bandwidth of the feeding TDM signal. In the three cases, the ideal receiver filter bandwidth is 2 GHz (20% of 10 GBd, 9% of 22 GBd, and 5.5% of 36 GBd), fulfilling the Nyquist ISI criterion.

holds as focused beam are used. The filtering is performed either in pass-band in front of the antennas of the array or in the baseband in the receivers. In the receivers, standard digital signal processing is performed such as timing estimation, carrier recovery, and equalization.

In this section we present simulation results for a TSDM scenario. Fig. 6(a) depicts the error vector magnitude (EVM) results for a cell reaching a capacity of 1056 Gb/s (16-QAM). The EVM (∼6 percent) only accounts for the distortion due to TSDM and can therefore be considered as a noise-equivalent penalty of the proposed concept. (b) The ideal low-pass filter bandwidth in the receivers is given by 1/n slots with n slots being the number of time slots in the transmitted frames and Tx BW the bandwidth of the feeding TDM signal. In the three cases, the ideal receiver filter bandwidth is 2 GHz (20% of 10 GBd, 9% of 22 GBd, and 5.5% of 36 GBd), fulfilling the Nyquist ISI criterion.

18 times slots requires a symbol rate of 36 GBd in the transmitter and a roll-off factor of 1 is used as it is best when delaying signals. An optimized Dolph-Chebyshev array tapering with side lobe level of 32 dB is implemented to reduce the inter-user interferences. The receivers are using 2 GHz bands and receive 16-QAM signals at 2 GBd (8 Gb/s), thus filters with low-roll-off (0.05) are implemented. The results show EVM values (rms) around 6 percent for all users. The EVM values are here limited by the signal distortion resulting from symbol-by-symbol steering. As other noise sources are not considered, the resulting EVM can be considered as the inherent TSDM penalty.

In Fig. 6(b) the impact of the bandwidth of the filter of the receiver is investigated. It can be seen that the first minimum EVM is reached at a receiver low-pass filter bandwidth of 2 GHz. The 2 GHz is matched with the 2 GBd transmission capacity of each of the 5, 11 or 18 tributaries of the of 10, 22, and 36 GBd TDM signal. The first minimum occurs at 2 GHz when the Nyquist ISI criterion is met. With smaller filter bandwidths (<2 GHz), the EVM increases to 60 percent where demodulation is no longer possible. At integer multiple of a 2 GHz filter bandwidth, the EVM is also small as the Nyquist ISI criterion is partially fulfilled. Using filter bandwidths other than integer multiples of the received symbol rate results in a decrease in signal quality due to the introduced inter-symbol-interference.

While this work focuses on a 60GHz carrier frequency, the TSDM concept is frequency independent. As mentioned, the key advantage of TSDM is the low complexity and potentially low cost of the array feeder compared to alternative approaches. However, this advantage is rational only if the carrier frequency is large enough. Indeed, at low frequencies (<10 GHz), the costs and complexity to implement concept such as massive MIMO seems to be a surmountable challenge.

B. OFDM Implementation

In most mobile communication standards, the highest bitrates are reached by switching from single carrier (SC) to multi-carrier data formats, more specifically orthogonal frequency division multiplexing (OFDM) is commonly used. In the example of 802.11ad, the maximum bit rate is based on 512 subcarriers using a 64QAM modulation scheme. In this sub-section, the implementation of TSDM for OFDM data format is detailed as it requires special considerations comparing to the SC case explained in the previous sections.

As depicted on Fig. 7, OFDM is compatible with TSDM if the multiplexing is performed at the correct rate. As an example, we have depicted the situation where 2 OFDM sequences are TDM multiplexed to one TSDM frame. In our example, the OFDM symbols of two users (Fig. 7(a) and Fig. 7(b)) are generated and time division multiplexed sample by sample in the central office, see Fig. 7(c). The system rate in Fig. 7(c) is twice as high as the one of Fig. 7(a) and Fig. 7(b). The signals transmitted to the PAA, see Fig. 7(c), would thus be unreadable with standard OFDM techniques as two OFDM symbols are interleaved. Yet, after the sample based beam steering occurring in the PAA, Fig. 7(e), the two
Fig. 7. OFDM Implementation of TSDM. As opposed to the single carrier implementation, TSDM with OFDM sequences has to be performed at the sampling rate of the sequence. (a–c) Two OFDM symbols are generated for two users (red and blue) and consecutively interleaved sample-by-sample. (d–g) The PAA performs a sample based ultra-fast steering to send the two sequences in different directions. (h–i) The UEs only receive one of the data streams and can recover the original OFDM symbols after low pass filtering.

original sequences (a and b) will be mapped to separate directions (f) and (g). The steering control signal is, in this simplified case, rectangular, see Fig. 7(d). In the UEs, low pass filtering could also be implemented to restore the original OFDM sequence. Fig. 7(h) and Fig. 7(i) show that the received symbols would fully match the transmitted sequences (a) and (b) with proper filter design. As for the single carrier case, the LPF could also be replaced by a BPF placed in the PAA to be fully compatible with commercial receivers. Note that the ultra-fast beam steering is performed at the sample rate of the OFDM frame, not at the slower symbol rate. In Fig. 7, OFDM symbols comprising 8 samples are used. If one would change the beam direction after the OFDM symbols only, the capacity of the cell would match the capacity of the users. Indeed, the feeding signal would have to match the receiver sample rate.

The generated beams with an OFDM scheme, considering a BPF implementation, are fully comparable to those generated with other SDM schemes. Thus, OFDM in a TSDM based feeder could also be leveraged to mitigate fading.

C. TSDM Challenges

The main challenge specifically tied to TSDM lies in the fabrication of the microwave array feeder that performs the time-to-space mapping in the RAU. However, the experimental demonstrations presented in [13] and [14] have already proven the feasibility of this approach. TDSM also shares limitations with other SDM approaches, yet standard solutions can be reused:

- To steer the beam towards one specific user, the position of the user must be known in the transmitter. In a first approach, the users could collaborate with the cell by providing channel state information back to the transmitter. Yet, an easier way of solving this issue with TSDM would consist of having fixed beam directions, equidistantly split through the sector. The system would then perform standard handover between the generated virtual pico-cell
- Even though uplink bandwidth requirements are usually lower than those of downlinks, a future-proof RAN concept should still increase the capacity of the uplink. In this paper, the downlink scheme is discussed primarily. Yet, TSDM could also be used in the uplink. In this case, the users would continuously transmit in the full 2 GHz bandwidth while the RAU would scan through the sector to perform a direction-based sampling.
- The practical implementation of an electronic system with very large fractional bandwidth is extremely challenging when using electronic systems. In the exemplary simulation, the feeding TDM signal has a bandwidth of more than 36 GHz for a targeted carrier frequency of 60 GHz. To avoid this challenge and thus reduce the complexity, the demonstrations in [13] and [14] rely on microwave photonic processing in the array feeder. Yet, in less extreme cases with a lower number of beams or a smaller channel bandwidth, TSDM could be implemented using electronic subsystems

V. Conclusion

In this paper, time-to-space division multiplexing (TSDM) has been presented as a solution to increase the capacity of future radio access network (RAN) without affecting the user equipment (UE) requirements. Simulations have been performed to demonstrate a mobile cell reaching an aggregated
capacity over 1 Tb/s while fulfilling the frequency band restrictions of the IEEE 802.11ad standard. The capacity is augmented by generating multiple beams from the remote antenna unit (RAU) in the RAN.

TSDM can thus be considered as a space division multiplexing concept that enhances the spectral efficiency by generating multiple beams in different directions. The same capacity enhancement could also be reached with multiple feeders based phase array antenna (PAA) or with a digital signal processing (DSP) based PAA. Yet, both approaches are complex to implement for mm-wave communication systems. TSDM offers therefore a solution in which:

- The complexity of the PAA is reduced to a single array feeder without the need of complex feeding schemes.
- The cell capacity can be adapted easily. If a user with higher-end equipment is in the sector, it could also use a higher capacity. On the other hand, if fewer users are in the cell, the transmitter symbol rate can be adapted to reduce the resources usage without influencing the user requirements.
- TSDM is compatible with OFDM by performing a sample-by-sample steering at the system rate of the OFDM scheme.
- TSDM could generically be applied to any type of analog input signals. The requirement is that each of the analog inputs, meant to be transmitted in various directions, should be sampled at least with the Nyquist sampling rate.

**APPENDIX**

**DERIVATION OF TSDM OPERATING CONDITIONS**

To mitigate inter-symbol interference (ISI), the design of a TSDM system must respect three conditions:

A. The beamwidth condition: it states that a PAA must have a minimum number of antenna to be able to generate a beamwidth smaller than the angular distance between adjacent users.

B. The symbol transition condition: it implies that the number of antenna of the PAA, i.e. its size, is limited by the maximum delay applicable on two consecutive symbols.

C. The frame transition condition: it implies that a pause has to be performed at the end of a frame transmission in order to scan the beam from its outmost angle back to its original transmission angle.

In the following, these three conditions are derived. Then, in subsection D, the conditions for a given TSDM configuration are demonstrated visually.

**A. The Beamwidth Condition**

As explained above, the beamwidth condition states that “a PAA must have a minimum number of antenna in order to be able to generate a beamwidth smaller than the angular distance between adjacent users”. This condition is relatively straight-forward to understand. Indeed, if 10 users should share a 120° sector, the beamwidth generated by the PAA should be smaller than 120/10 = 12. The equation associated with this condition is found with the following steps. First, assuming a Dolph-Chebyshev tapering of the PAA, the beamwidth \( \Theta_{DC,SL} \) at a side lobe level \( A_{SL} \) is given by [29]

\[
\Theta_{DC,SL}(N) = \frac{\pi}{2} - \text{acos} \left( \frac{1}{z_0(N,A_{SL})} \right) \cdot \frac{\lambda_{RF}}{\pi \cdot d}
\]

(A.1)

where \( N \) is the number of antennas, \( \lambda_{RF} \) is the wavelength of the millimeter wave carrier frequency \( f_{RF} \), and \( d \) is the antenna spacing and \( z_0 \) defined in [29]. Fig. 8 shows a typical array pattern when using Dolph-Chebyshev array tapering. When decreasing the desired side lobe level \( A_{SL} \), the beamwidth becomes larger. In the definition of equation (A.1), the beamwidth is defined as the width where the array gain corresponds to the side lobe level, as opposed to the more common 3 dB definition.

Therefore, the number of user \( n_{users} \) that could share a sector of size \( \theta_{sector} \) is given by:

\[
n_{users} = \frac{\theta_{sector}}{\Theta_{DC,SL}(N)}
\]

(A.2)

Rearranging (A.2) according to [29] leads to the beamwidth condition:

\[
N \geq 1 + \frac{2 \cdot \text{acosh}(A_{SL})}{\text{acosh} \left( \sin \left( \frac{n_{users}}{\theta_{sector}} \cdot \frac{\pi \cdot d}{\lambda_{RF}} \right) \right)}
\]

(A.3)

where \( A_{SL} \) is the desired side lobe attenuation with the Dolph-Chebyshev tapering, \( \theta_{sector} \) is the size of the sector in radians, \( n_{users} \) is the number of users using the cell sector, \( d \) is the antenna element spacing, and \( \lambda_{RF} \) is the wavelength of the millimeter wave carrier frequency \( f_{RF} \).

**B. The Symbol Transition Condition**

The symbol transition condition implies that “the number of antenna of the PAA, i.e. its size, is limited by the maximum delay applicable on two consecutive symbols”. The underlying problem leading to this limitation can be better understood with the help of Fig. 9. In Fig. 9 an exemplary PAA with \( N \) antennas is depicted. It is used to steer the beam towards two users (green and blue) at angle \( \theta_i \) and \( \theta_{i+1} \), respectively.
where \( d \) is the symbol duration, \( T \) as the spacing between two symbols. Considering a data steering: The introduced delay on a symbol can be as large as \( 2 \cdot T \) before entering the array feeder. (c) After the TTD in the array feeder, the symbol should not overlap too much to avoid ISI.

For ideal operation of the PAA, the delays computed with equation (A.4) will have to be applied using TTDs. However, a limitation arises while performing symbol-by-symbol steering: The introduced delay on a symbol can be as large as the spacing between two symbols. Considering a data signal as depicted in Fig. 9 with a symbol duration \( T_S \), two consecutive symbols can only be delayed as long as ISI is not an issue. The maximum allowed time delay difference between adjacent users, occurring at antenna position \( p = \pm (N - 1)/2 \), is limited to

\[
|\Delta t_{p,i} - \Delta t_{p,i+1}| \leq RZ \cdot T_S \tag{A.6}
\]

where \( RZ \) is the return-to-zero duration with \( 0 < RZ < 1 \). The \( RZ \) duration depends on the type of pulse shape that is used and its resilience against ISI. Ideally, a return-to-zero (RZ) modulation scheme [30] should be used. As example, if one uses a 50% RZ modulation scheme, \( RZ \) can be set to 0.5. Inserting equation (A.4) and (A.5) in equation (A.6) leads to

\[
\frac{(N - 1)}{2} \cdot \frac{d \cdot |\sin(\theta_{i+1}) - \sin(\theta_i)|}{c} \leq RZ \cdot T_S. \tag{A.7}
\]

By rearranging the terms, the symbol transition condition is defined as

\[
N \leq 1 + \frac{2 \cdot RZ \cdot T_S \cdot c}{d \cdot |\sin(\theta_{i+1}) - \sin(\theta_i)|} \tag{A.8}
\]

To make the equation easier to use, some variables can be adapted. Thus, instead of using \( \theta_i \) and \( \theta_{i+1} \) for the user positions, let’s consider the median steering angle \( \theta_0 \) (angle between users \( i \) and \( i+1 \)) and the angular spacing between users \( \Delta \theta_{\text{user}} = \theta_{\text{sector}}/n_{\text{users}} \). \( \theta_i \) and \( \theta_{i+1} \) can thus be replaced by

\[
\theta_i = \theta_0 - \frac{\Theta_{\text{sector}}}{2 \cdot n_{\text{users}}} \quad \text{and} \quad \theta_{i+1} = \theta_0 + \frac{\Theta_{\text{sector}}}{2 \cdot n_{\text{users}}} \tag{A.9}
\]

Equation (A.8) thus becomes

\[
N \leq 1 + \frac{2 \cdot RZ \cdot T_S \cdot c}{d \cdot |\sin(\theta_0 + \frac{\Theta_{\text{sector}}}{2 \cdot n_{\text{users}}}) - \sin(\theta_0 - \frac{\Theta_{\text{sector}}}{2 \cdot n_{\text{users}}})|} \tag{A.10}
\]

The worst-case scenario in equation (A.10) occurs when the denominator is maximal. This happens when \( \theta_0 = 0 \), and inserting this value into (A.10) leads to the symbol transition condition

\[
N \leq 1 + \frac{RZ \cdot T_S \cdot c}{d \cdot |\sin(\Theta_{\text{sector}}/2\cdot n_{\text{users}})|} \tag{A.11}
\]

where \( N \) is the number of antenna in the PAA, \( RZ \) the return-to-zero duration \( 0 < RZ < 1 \), \( T_S \) the symbol duration at the transmitter data rate, \( c \) the speed of light, \( d \) the antenna element spacing, \( \Theta_{\text{sector}} \) the size of the sector in radians and \( n_{\text{users}} \) the number of users using the cell sector.

In the case of a PAA based on phase shifters, the symbol transition condition cannot be understood in the same way. Indeed, the phase shifter will not delay the signal, therefore ISI will not take place in the feeder. However, another problem arises. To have constructive interferences at the users in different directions, two conditions must be met: 1) the waves must constructively interfere at the user with the correct phases. 2) the energy transmitted by the different antennas must reach the users within the symbol duration. Using tunable phase shifters, the phase front can easily be adjusted. The second condition is however more challenging. Indeed, when transmitting ultra-short pulse, it could happen that the energies from the various antennas do not reach the user at the same time. The delay between the pulses exactly corresponds to the true time delay that is required to steer a beam in a particular direction, see equation (A.4). To ensure that the energy is, at least partially received simultaneously the maximum delay error between two antennas is limited by the symbol duration, thus an equation analog to (A.6) can be written

\[
|\Delta t_{p,i} - \Delta t_{p,i-1}| \leq \Gamma \cdot T_S \tag{A.12}
\]

with \( \Gamma \), the allowed overlap mismatch with \( 0 < \Gamma < 1 \). Note that this condition does not anymore depend on the users \( i \) but on the position of the antenna at the edge of the
PAA ± p. Replacing equation (A.4) and (A.5) in (A.12) leads to a symbol transition condition for phase shifters

$$N \leq 1 + \frac{\Gamma \cdot T_S \cdot c}{d \cdot |\sin(\theta_i)|}.$$  \hspace{1cm} (A.13)

It can thus be concluded that the steering angle $\theta_i \approx \theta_{\text{sector}}/2$ is fairly limited if one needs a minimum time overlap between the pulses reaching the users. Yet, simulations have shown that one can tolerate worse conditions at the antenna array edges. Indeed, the antennas close to the center of the array will perform very well in a phase shifter based PAA while those at the edge will suffer more from this limitation. The behavior of (A.14) is similar to the one of (A.11), it provides a very good estimation of the TSDM limitations during the conceptual design of the system. Yet, for both cases full time domain simulation are recommended to ensure proper operation. In addition to the limitation from (A.13), an array antenna based on phase shifters will also produce beam squint. Various frequencies are sent in different directions. However, this effect is negligible in our case as 1) the beamwidth is relatively large, 12° for 10 users sharing a 120° sector, and 2) the transmission distances are relatively small, from tens to a few hundreds of meters.

C. The Frame Transition Condition

The third condition implies “a pause has to be performed at the end of a frame transmission to scan the beam from its outmost angle back to its original transmission angle”. As already explained, it is better to use TSDM with consecutive angles between users and large angular steering at the end of a frame transmission to go back to the original angle. The consequence is however that very large delays compared to the symbol duration will be required to scan back through the whole sector. Thus, ISI can be avoided by performing a pause in the data transmission.

The frame transition condition is derived starting with equation (A.8), see above:

$$N \leq 1 + \frac{2 \cdot RZ \cdot T_S \cdot c}{d \cdot |\sin(\theta_i)| - \sin(\theta_{i+1})}.$$  \hspace{1cm} (A.14)

In the case of the frame transition condition, the beam must be steered from the last user position (largest angle) back to the first user position (smallest angle). Therefore $\theta_i$ and $\theta_{i+1}$ can be replaced by

$$\theta_{i, i+1} = \pm \left( \frac{\theta_{\text{sector}}}{2} - \frac{\theta_{\text{sector}}}{2 \cdot n_{\text{user}}} \right)$$  \hspace{1cm} (A.15)

with $\theta_{\text{sector}}$ the size of the cell sector. Replacing (A.14) in (A.8) lead to

$$N \leq 1 + \frac{RZ \cdot T_S \cdot c}{d \cdot |\sin\left(\frac{(n_{\text{user}} - 1) \theta_{\text{sector}}}{2 \cdot n_{\text{user}}}\right)|}$$  \hspace{1cm} (A.16)

but instead of having a maximum allowed delay of $RZ \cdot T_S < T_S$, a pause in transmission can be performed replacing $RZ$ by an integer $(n_{\text{slot}} - n_{\text{users}})$ corresponding to the number of empty symbols to be transmitted during the steering of the beam. Thus, the frame transition condition is

where $n_{\text{slot}}$ is the length of the transmitted frames (including both active and “empty” users), $n_{\text{users}}$ is the number of user in the cell, $T_S$ is the symbol duration at the transmitter, $c$ is the speed of light, and $\theta_{\text{sector}}$ is the size of the sector in radians.

D. Summary and Supported Area

The supported area of a TSDM setup can be computed using the three conditions described in the previous sections.

Using these conditions, the ideal working point of a TSDM setup can be plotted. As an example, consider a 60 GHz ($\lambda_{RF} = 5\text{mm}$) mobile cell split in three sectors of 120° ($\theta_{\text{sector}} = 120°$). Dolph-Chebyshev tapering is implemented for an array with half wavelength spacing ($d = 2.5\text{mm}$). In addition, the receiver symbol rate is set to 2 GBd in order to be compatible with the channels of the IEEE 802.11ad standard at 60 GHz.
In the following figures, the transmitter symbol rate is set to 10, 22, and 36 GBd corresponding to frame length of 5, 11, and 18 time slots, respectively.

In Fig. 10, the ideal working point for a transmitter symbol rate of 10 GBd (frame length of 5 time slots) is found to be a PAA with 13 antennas and 4 active users. This corresponds to a total cell capacity enhancement of a factor 8 without impacting 802.11ad user equipment.

In Fig. 11, the ideal working point for a transmitter symbol rate of 22 GBd (frame length of 11 time slots) is found by using a PAA with 23 antennas and 8 active users. This corresponds to a total cell capacity enhancement of a factor 8 without impacting 802.11ad user equipment.

In Fig. 12, the ideal working point for a transmitter symbol rate of 36 GBd (frame length of 18 time slots) is found by using a PAA with 28 antennas and 11 active users. This corresponds to a total cell capacity enhancement of a factor 11 without impacting 802.11ad user equipment.

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Fig. 12. Supported area with a 36 GBd transmitter. The ideal working point for this configuration is found with a PAA comprising 28 elements and 11 active users in frame of 18 times slots.
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