

Heterogeneous Beam-space Design for 5G Millimeter-wave Systems

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Abstract—In the last years, the interest on millimeter wave communications increased due to the high potentiality foreseen to face the continuous growth of wireless communications capacity demand. One of the major drawback is represented by the limited coverage capacity. In order to cope with it, beamformers that generate beams with very narrow beams have been studied. Special attention has to be devoted to the tradeoff between coverage distance and area covered by the beam: depending on the UEs deployment, a too narrow beam might result into a low throughput and spectrum efficiency. In this paper a new solution to improve the cell coverage and the spectrum efficiency is proposed. The idea is based on the fact that the beamformers are designed to be flexible to choose the beam from a codebook of beams with different widths and different directions. The choice depends on a scheduling algorithm designed to maximize the performance of the system.

Keywords—Millimeter waves, beam space, access point, beamformer.

I. INTRODUCTION

Millimeter wave (mmW) communications have been considered an important technology [1][2] to be employed for future 5G mobile systems.

One of the main problems related to high frequency transmissions is the severe path loss and the really limited penetration capability, which reflects into a very limited coverage capability (i.e., the coverage radius is really reduced) [3][4]. In order to cope with this, beams with very narrow bandwidths (with then high beamforming gains) have been studied [5][6]. If on one side narrow beams with high gains are beneficial for the coverage distance, on the other side they have the disadvantage that the narrower is the beam, the longer time is needed for illuminating the cell (more directions must be covered) and the more is the sensitiveness to the beam direction mismatch (potentially caused by the feedback delay and others beam alignment imperfections). Considering the fact that the access point (AP) can be equipped by a limited number of multiple beamformers, only few parallel beams can be transmitted simultaneously then, if the beams are narrow, only a small portion of the cell can be covered at the same time. Depending on the user equipment's (UEs) distribution, this solution might be inefficient, resulting into a low throughput and area spectrum efficiency (bits/s/Hz/m²).

In this paper we propose a solution to improve the cell coverage and the spectrum efficiency. Instead of equipping the

AP with beamformers that generate only beams with a fixed beamwidth, we enable the beamformers to generate beams with variable beamwidths chosen from a pre-designed codebook. Each element of the codebook is characterized by the pair of beamwidth degree and beam direction so that the codebook can be defined by a bi-column matrix. As a result, the beamforming codebook, also known as beam space, is comprised of heterogeneous beams with different shapes. This provides the AP with additional flexibility in choosing the beamwidth (and the related cell coverage) so that the overall system throughput and/or the target scheduling metric can be optimized.

With the proposed codebook, each beam can serve multiple UEs and the decision on beamwidths and beam directions to be used in parallel is taken in order to maximize the overall performance in the entire cell.

The paper is organized as follows. In section II a general description of the proposed idea is provided, and the novelty introduced is underlined. In Section III an example of a system designed by using our idea is described: a possible beamforming codebook, a possible reference signal transmission and timing configuration for the CSI feedback, and an efficient resource scheduling algorithm are discussed. Finally Section IV concludes the paper.

II. HETEROGENEOUS BEAMFORMING CODEBOOK

The technical concept described in this paper is to design and exploit a heterogeneous beam codebook in order to optimize the overall data rate into the cell, by selecting the best combination of beams (beamwidths/beam directions) so that each beam covers simultaneously multiple UEs, (e.g., by means of frequency multiplexing). This is possible because we equip the beamformers with a codebook of beams with different widths and different beamforming gains.

In the beam alignment solutions proposed so far [7][8] (and references therein), the AP is typically equipped with beamformers capable of searching for the optimal beam direction, but of generating beams with a fixed width. The parallel beams can have different directions according to the resource usage, and each beam can also serve different UEs at the same time.

In the proposed solution, the AP is equipped with beamformers that can generate parallel beams. The developed technical concept has the characteristic that each beamformer can generate beams with variable width by means of a flexible codebook of heterogeneous beams that can have different widths. This provides the AP with an additional degree of freedom, so that the effective cell coverage is improved to be adapted to the actual UE/traffic distribution thus maximizing the overall efficiency. The performance are expressed by means of a pre-defined metric to be optimized (for example the latency to be minimized, the throughput to be maximized etc).

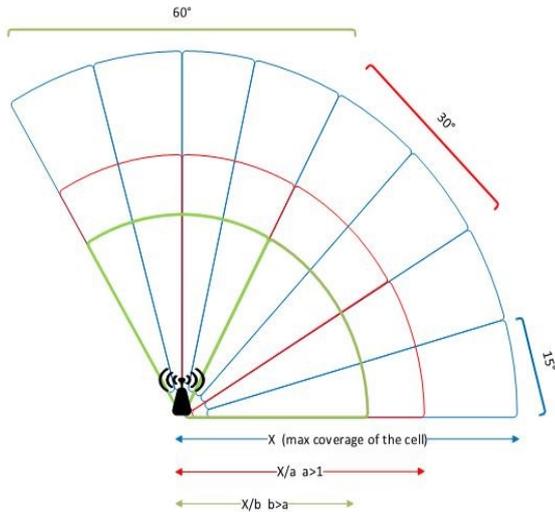


Fig. 1. Heterogeneous beam space (codebook)

In our model the following assumptions and prerequisites are considered:

- The AP is equipped with multiple beamformers, and each beamformer covers a different area of the cell;
- Each beamformer is equipped with a finite codebook of beamwidth/beam directions. The beamformers are independent one from the others, meaning that at the same time they can generate beams with different directions and beamwidths;
- The AP knows the channel quality of each UE in its range, for each resource triple frequency (f), beamwidth (b) and beam direction (d). We consider only a limited number of beamwidths so that the amount of information for each UE is manageable from the AP and the UE feedback overhead is reasonable;
- Each beam can serve multiple UEs. If a beam is serving multiple UEs, a resource multiplexing technique is used to serve the UEs (e.g., FDMA, TDMA or CDMA).

One example of heterogeneous beam space/codebook design is drawn in Fig. 1.

An example of the heterogeneous beams codebook is shown in Fig. 1. The codebook consists of eight beams of width 15° (blue), four beams of width 30° (red), two beams of width 60° (green), and the largest beam of width 120°, so that three beamformers are needed to cover the entire cell. Since the AP knows the UEs channel quality, the best combination to optimize the performance (for instance the throughput) can be found in subsequent refinement steps by exploiting the nature of the beamwidths.

In Fig. 2, an example of UEs deployment and beams generated by the AP is shown. Three UEs, namely UE1, UE2 and UE3 are served by an AP that can generate simultaneously only 2 beams with different widths, pointing to different directions. The initial search in the cell is conducted with the narrowest beam (so that the radius of the cell is maximized) and the presence of the 3 UEs in the cell and their position is detected. As a first step, by fixing the beamwidth to the narrowest one available, the optimal beam directions to maximize the throughput are established, and the throughput that will be achieved is computed. The information about the position of the UEs is further used in the refinement steps to decide whether a better choice of beamwidths (and beam directions) can be taken in order to increase the throughput. With the deployment shown in Fig. 2, if only beams with the narrowest width can be generated, UE1 and UE2 cannot be served at the same time and the scheduling algorithm has to decide which one to serve. On the other hands, with the proposed solution, UE1 and UE2 can be served at the same time by a beam with a larger width.

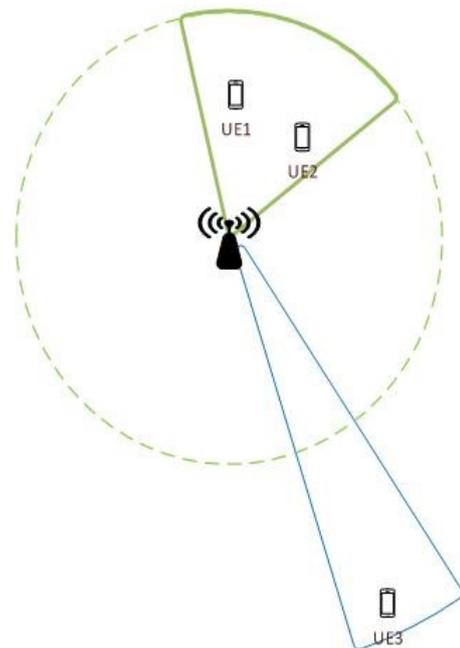


Fig. 2. Three UEs served by two heterogeneous beams of 15° and 60° beamwidths

The beamwidth flexibility can be exploited in different ways depending on how the algorithm (devoted to determine the best beam) is designed, or in other words on how the scheduling metric is defined. In the next section an example is described.

III. DETAILED DESCRIPTION OF THE PROPOSED SOLUTION

The general idea proposed in this paper can be applied to a large variety of problems, depending on how the system is designed. In this section we explain the proposed idea by means of a more concrete example in terms of a possible beamforming codebook, reference signal transmission for the CSI feedback, and resource scheduling.

A. Heterogeneous beamforming space

The codebook can be based on an “elementary beam” with beamwidth w_{\min} , e.g., the narrowest beam that can be generated by the beamformer. The beam codebook may consist of beams with widths being multiple of the elementary beam. The AP is equipped with $B > 1$ beamformers and the cell can be divided in several non-overlapped sectors of $\frac{360^\circ}{B}$ degrees so that each beamformer covers a specific area. The codebook can be designed to include the beamwidths $\left\{w_{\min}, 2w_{\min}, 3w_{\min}, \dots, \frac{360^\circ}{B}\right\}$, but also other design solutions can be considered. For a fixed beamwidth w and for a specific beamformer, the covered area is divided in several regions, each of which can be uniquely identified by an index $p=0, \dots, P_{\max}-1$, (where $P_{\max} = \frac{360^\circ}{Bw}$), such that p identifies the region $\{pw, (p+1)w\}$. Then for each beamformer b , the area covered by the transmitted beam is identified by the vector $\mathbf{v}_b = (w_b, p_b)^T$, and the entire cell scheduling by $\mathbf{V} = (\mathbf{v}_1, \dots, \mathbf{v}_B)$.

Let us assume for example that the AP is equipped with three analog beamformers ($b=1,2,3$), each of which is

capable of transmitting a beam with different widths (from the codebook) and of covering a dedicated sector of 120° . If the “elementary beam” has the width $w_{\min} = 15^\circ$, the codebook can be for example designed such that the possible beamwidths are $w = \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ, 105^\circ, 120^\circ\}$. A more efficient solution would be to reduce the possible choice to $w = \{15^\circ, 30^\circ, 60^\circ, 120^\circ\}$ so that the larger width is always multiple of the previous one.

B. Beamformed reference signal transmission for CSI feedback

In this paper we assume that the radio resource (beam and time-frequency resource etc.) scheduling method perfectly knows the channel state information (CSI) of the UEs: a UE associated with each detected beam defined in the heterogeneous codebook reports its corresponding CSI to the AP. The CSI can be wideband CQI or subband CQIs (or even the reference signal receive power). To measure or calculate the beam specific CSI, the UE can be configured by multiple CSI reference signals, each of which is transmitted via a corresponding beam defined in the codebook. For instance, with the above codebook example, the UE in a particular sector can be configured with 15 CSI-RSs, which include 8 CSI-RSs with 15° beamwidth, 4 CSI-RSs with 30° beamwidth, 2 with 60° beamwidth and 1 with 120° beamwidth. It is reasonable to assume that for the sector edge UEs, the beams close to sector edge can be configured for the CSI-RSs.

As example, a timing configuration of the 15 CSI-RS processes, with different periodicities, is illustrated in Fig. 3. Due to the constraint of shared physical analog beamformers, CSI-RSs scheduled in the same TTI need to be transmitted from different symbols. The AP can further specify the feedback mode of UEs for the configured CSI-RSs. For example, the UE can be requested to periodically report only M-best detected beams in terms of wideband CQI. By means of the CSI knowledge reported from all the UEs in the coverage, the AP can schedule the radio resources in an efficient manner to optimize certain performance metrics. One scheduling procedure example is described in the following.

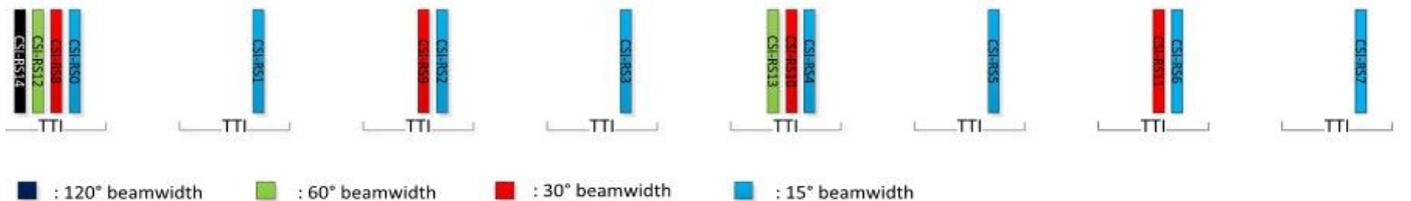


Fig. 3. Timing configuration of CSI-RS processes for the UE

C. Beam resource scheduling

The flowchart of a possible use of the beams codebook is illustrated in Fig. 4.

As shown in Fig. 4, in the initial step (Step 0) all the beamformers are set to be unscheduled. Steps 1 to 4 are repeated for all unscheduled beamformers. Specifically, each unscheduled beamformer sets a particular beamwidth in Step 1 and searches in the UEs to get the CSIs information. In Step 2, given a fixed beamwidth, the optimal beam direction to maximize the target scheduling metric is selected. Then the beam index is increased (i.e., the beamwidth is increased) and Step 2 is repeated for all the supported beamwidths (i.e., till the beamwidth reaches the maximum possible width). Once the loop on Step 2 ends and the scheduling metric table is filled, the pair beamwidth-beam direction which achieves the maximum scheduling metric is selected in Step 3. As a result, the unscheduled beamformer is set by the selected beam direction and beamwidth in Step 4.

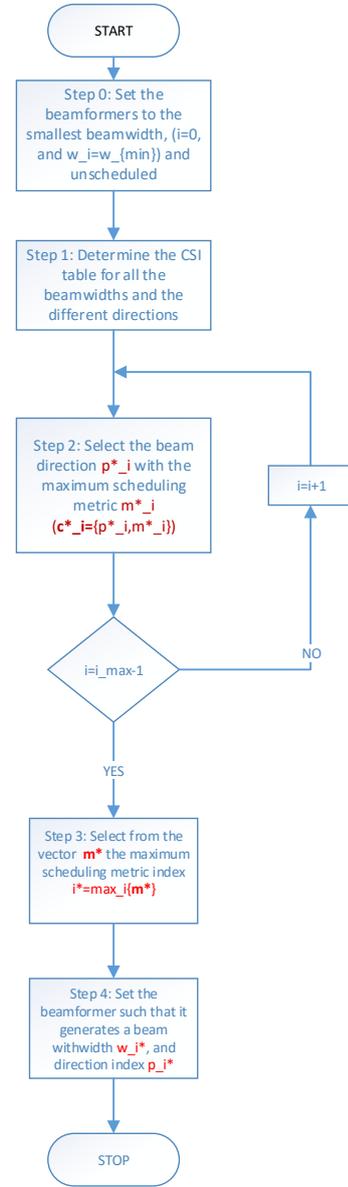


Fig. 4. Flowchart of a possible beamformer scheduling procedure

IV. SIMULATION RESULTS

In this section we show, by means of simulations, the performance gain obtained by a beamformer equipped with the proposed heterogeneous beamspace with respect to a beamformer that can generate only beams with a fixed width. In particular, we compare the average number of co-scheduled UEs and the CDF of the number of TTIs needed to schedule all the UEs. We assume that the AP is equipped with 3 beamformers (each covering a sector of 120°) and that is able to generate 3 parallel beams. The three sectors (and the beamformers performance) can be then independently studied. For this reason in the following we use the word cell to refer to a cell sector.

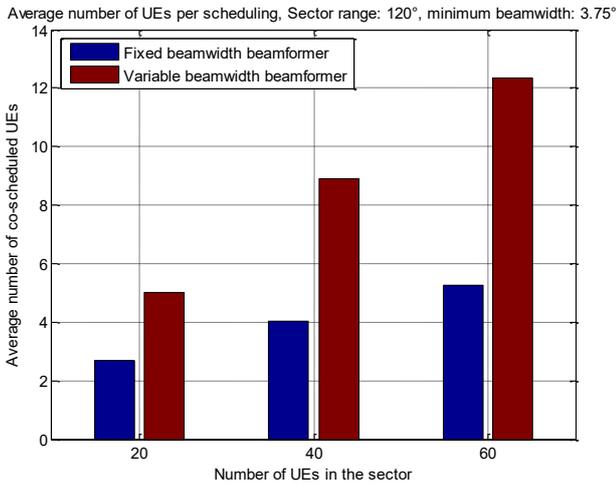


Fig. 5. Average number of co-scheduled UEs for different cell loads

In the simulations, three different cell loads are considered: 20 UEs, 40 UEs and 60 UEs served in the cell. For each cell load, the azimuth of each UE is uniformly random distributed over the 120° cell coverage. The fixed beamwidth beamformer can transmit 32 non-overlapped beams of 3.75° beamwidth to fully cover the cell. The variable beamwidth beamformer can transmit 6 different beamwidths: 120° , 60° , 30° , 15° , 7.5° and 3.75° . It is obvious that the beam with narrowest beamwidth offers the largest beamforming gain defined as g_{max} . We further assume that the beamforming gain decreases by 3dB when the beamwidth increases by 2 times. As a result, 6 different beamforming gains, namely g_{max} , $g_{max}-3\text{dB}$, $g_{max}-6\text{dB}$, ..., $g_{min}=g_{max}-32\text{dB}$, are provided by the variable beamwidth beamformer. The required beamforming gain of each UE is uniformly random distributed in the range of $[g_{min} - 3\text{dB}, g_{max}]$. The UE required beamforming gain takes both the pathloss and the required throughput into account. In the simulations, a UE can be served by a beam if it is located in the azimuth coverage of the beam, and the beamforming gain offered by the beam fulfills the UE beamforming gain requirement.

In the simulations, two relevant performance metrics are studied. The first performance metric is the average number of UEs which can be scheduled at the same TTI. The more UEs can be co-scheduled at the same time, the more scheduling flexibility is offered by the beamformer. As shown in Fig. 5, the variable beamwidth beamformer can schedule about two times more UEs than the fixed beamwidth beamformer. As a result, a significant scheduling flexibility can be provided by the variable beamwidth beamformer.

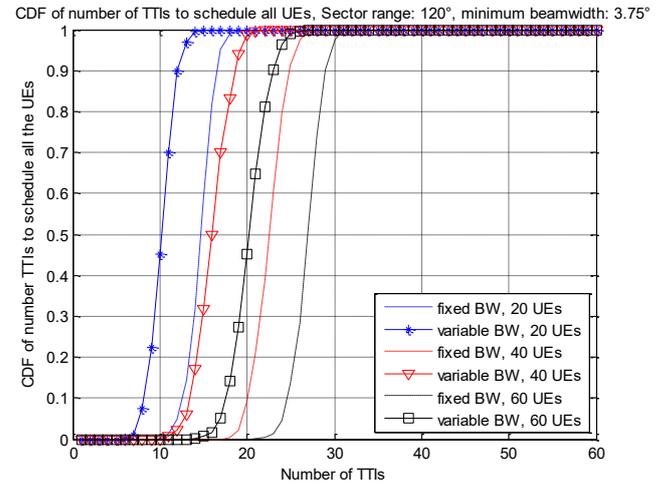


Fig. 6. CDF of number of TTIs to schedule all the UEs in the cells by fixed beamwidth beamformer and variable beamwidth beamformer

The scheduling flexibility can be translated into the latency gain in some cases. To show this advantage, in Fig. 6 the CDF of smallest number of TTIs required to serve all the UEs in the cell are illustrated. As we can see in Fig. 6, due to the increased scheduling flexibility, the variable beamwidth beamformer can serve all the UEs in the cell with about 30% less TTIs than that of the fixed beamwidth beamformer.

V. CONCLUSIONS

This paper describes a new solution based on exploiting a heterogeneous beam codebook. The proposed concept increases the cell coverage and the spectrum efficiency. The possible scheduling procedure to select the best combinations of beams (beamwidths/beam directions) has been discussed and a concrete example on how a system can be designed (in terms of a possible beamforming codebook, reference signal transmission for the CSI feedback, and resource scheduling) has been provided. With the proposed solution the bandwidth efficiency can be maximized or, more in general, the system performance can be optimized. We showed, by means of simulation results, the advantage introduced by the proposed solution.

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