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Novel Cellular System Design using Standalone and Centralized mmWave-based Multi-Spot Beam Structure

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Abstract

This paper presents new mmWave-based cellular system as one of means to achieve the capacity requirement of 5G mobile communications. The base station of new system covers its service area with spot beams formed by many beamforming antennas, and one beam can be composed of multiple frequency allocation beam component carriers in which one broadband bandwidth is divided into multiple sub-bands at the millimeter frequency. The best feature of new cellular architecture is the multi-layered FA dynamic cell configuration and it means that one or more beam component carrier(s) can be grouped and then operated as one cell. The effect of this dynamic cell configuration is to avoid interference among cells via the association among multi-layered FAs and to imitate pseudo-small cells and pseudo-macro cell like 3GPP small cell enhancement architecture (user equipment in small cell enhancement architecture can use coverage layer (macro cell(s)) for mobility robustness and capacity layer (small cells) for capacity offering). In this paper, we design new system, its basic operation and evaluate its capacity to confirm the possibility as an alternative of 5G mobile communications.

Keywords: *millimeter, mmWave, cellular, beam, beamforming, capacity, small cell, SCE, small cell enhancement, CA, carrier aggregation, CoMP, coordinated multi-point, cellular system, 5G*

1. Introduction

In recent years, studies to realize a vision [1-2] on the 5th generation mobile communication have been in progress. One of the visions of the 5G mobile communication is to increase system capacity, and it aims to provide 1000 times that of 4G network. Two main research directions related to the vision as well as the topic of this paper can be summarized as follows. The first is to use a new frequency (A6: Above 6GHz), not the existing cellular frequency (B6: Below 6GHz) as broadband [4], and the second is to separate the service area into small areas in a horizontal/vertical direction and cover each area by one or more beams [3]. In this regard, this paper seeks to design and evaluate the mmWave-based multi-spot beam cellular system (hereafter, MWMSB cellular system or MWMSB), into which these two research directions are fused, in terms of the system capacity, thereby reviewing its possibility as 5G mobile communication.

In Chapter 2, the MWMSB cellular system architecture is described in the order of base station (BS) and Mobile Station (MS). Chapter 3 describes a basic system operation. In Chapter 4, the capacity evaluation on the MWMSB is performed through simulation. Lastly, Chapter 5 presents conclusions from this study.

2. System Architecture

The MWMSB cellular system is aimed at providing the same function as that of conventional cellular system by only using millimeter. In particular, it aims to offer the capacity of peak 100 Gbps per base station and the capacity of up to more than 1 Gbps per

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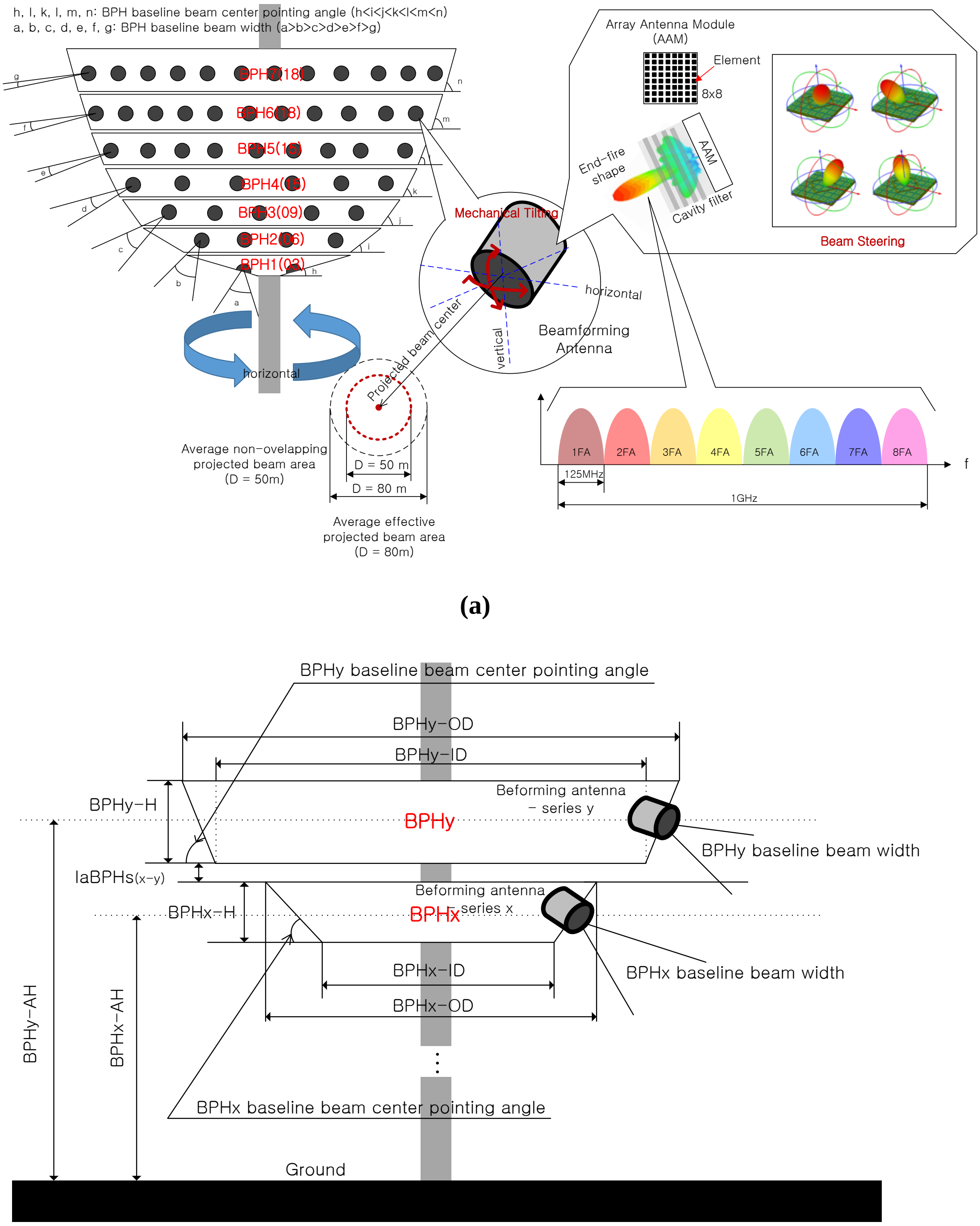
mobile station (*i.e.,* MS or user or User Equipment(UE)), subsequently helping to provide a level of LTE mobility performance.

2.1. Base Station

Figure 1 shows a schematic diagram on the overall antenna architecture of base station in the MWMSB cellular system. The entire antenna structure of one base station can be composed of multi-layered phases as shown 7 layers in Figure 1, and these layers are marked into base station phase (hereafter, BPH (Base station PHase)), and the number in brackets of the BPH signifies the number of beamforming antenna that can be mounted. For example, BPH1(03) means that three beamforming antennas can be mounted on BPH1, and BPH7(18) means that up 18 beamforming antennas can be mounted. Without regard to BPH, all beamforming antennas are assumed to make the end-fire shaped beam so that they can have the average effective projected beam area, and to enable vertical or horizontal tilting by forming a beam composed of eight FAs (frequency allocation) in which 1 GHz bandwidth is divided into 125MHz at the millimeter frequency. The beam tilting method can be divided into two classes: mechanical beam tilting and electronic beam steering via each element’s phase control on an array antenna module.

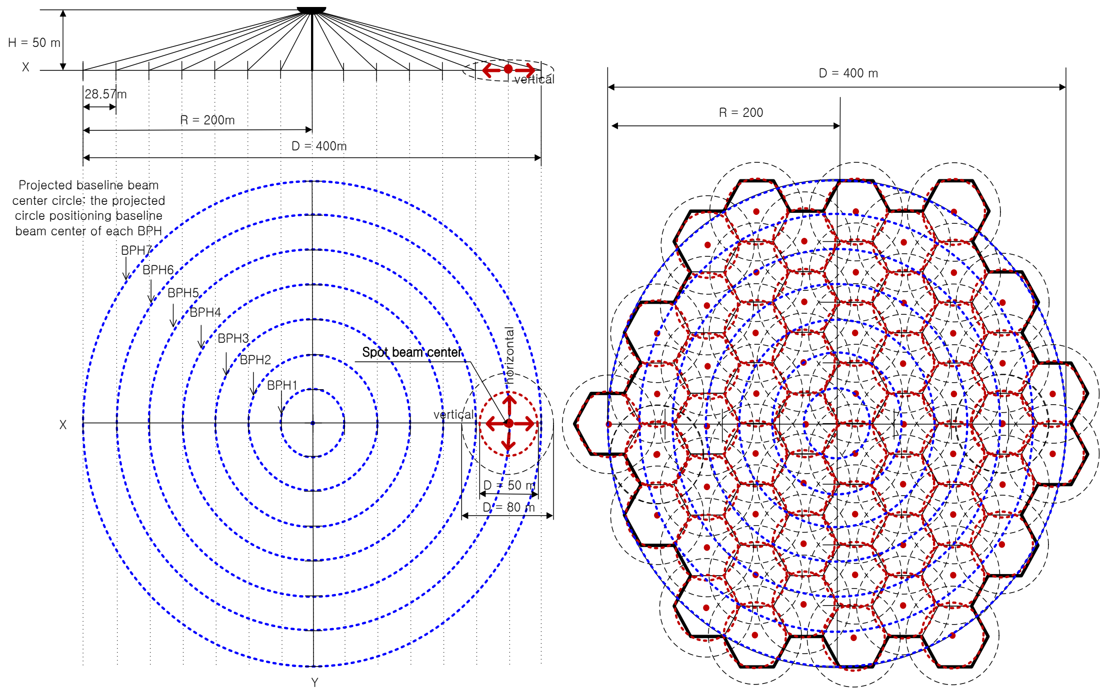
As shown in Figure 2 (a), the BPH baseline beam center pointing angle (*i.e.,* h, i, j, k, l, m, n) and the BPH baseline beam width (*i.e.,* a, b, c, d, e, f, g) are designed so that all the beamforming antennas have almost the same average effective projected beam area, regardless of BPH in consideration of the antenna structure characteristics in Figure 1. As for BPH baseline beam center pointing angle, if beamforming antennas mounted on the same BPH are arranged at the corresponding BPH baseline beam center pointing angle, beam centers of all the beamforming antennas mounted the same BPH are positioned in an arc (projected baseline beam center circle of Figure 2 (a)) with the same radius. If all the beamforming antennas have the BPH baseline beam width at the corresponding BPH baseline beam center pointing angle, the average effective projected beam areas formed by all the beamforiming antennas are the same. Additionally, beamforming antennas are designed to move the beam center within a limited range by enabling beamforming antennas to perform vertical or/and horizontal tilting in a limited range so that non-overlapping projected beam areas of all the beamforming antennas cannot be overlapped. In this paper, the diameter of the projected baseline beam center circle that corresponds to the BPH7 is 400m, and the arc gap for each BPH is designed to be 28.57m. Figure 2 (b) shows the formation of coverage of a single MWMSB base station by performing the re-positioning to prevent non-overlapping projected beam areas of all the beamforming antennas from being overlapped each other through vertical or/and horizontal tilting of 57 beamforming antennas mounted on the BPH based on the protected baseline beam center circle. To sum up, the antenna design information of the above MWMSB BS is used to define the average effective projected beam area and average non-overlapping projected beam area of beamforming antenna and the height of BS antenna in consideration of BS’s target coverage and performance of beamforming antenna, and to determine the number of BPH to be laminated accordingly, height (BPH-H: Height, BPH-AH: Antenna Height from the ground) and diameter by BPH (BPHx-ID: Inner Diameter, BPHx-OD: Outer Diameter), intervals between BPHs (IaBPHs: Interval among BPHs), BPH baseline beam center pointing angle, BPH baseline beam width and range of vertical/horizontal tilting angle of beamforming antenna. Table 1 shows the design example of overall MWMSB BS antenna in this paper.



(a)

(b)

Figure 1. Overall Antenna Architecture of MWMSB Base Station



(a)

(b)

Figure 2. The Projected Coverage and Beam Areas of Base Station (a) The Projected Circle Positioning Baseline Beam Center of Each BPH (b) The Projected Base Station Coverage Composed of Planned 57 Projected Beam Areas

Table 1. The Design Example of Overall MWMSB BS Antenna

	-AH (Antenna Height) [m]	-OD/-ID/-H [m]	IaBPHs [m]	Beamforming antenna number(real mounted for Figure 2 (b)/available mounted for Figure 1 (a))	Baseline beam width/baseline beam center pointing angle [degree]
BPH7	50.0	4.152/3.848/0.6	$0.2_{(6\text{-}7)}$	09/18	g 04.00/ n 75.83
BPH6	49.2	3.749/3.451/0.6	$0.2_{(5\text{-}6)}$	06/18	f 05.29/ m 73.83
BPH5	48.4	3.346/3.054/0.6	$0.2_{(4\text{-}5)}$	15/15	e 07.34/ l 71.09
BPH4	47.6	2.944/2.656/0.6	$0.2_{(3\text{-}4)}$	15/15	d 10.85/ k 67.14
BPH3	46.8	2.541/2.259/0.6	$0.2_{(2\text{-}3)}$	06/09	c 17.43/ j 61.02
BPH2	46.0	2.139/1.861/0.6	$0.2_{(1\text{-}2)}$	03/06	b 30.56/ i 50.67
BPH1	45.2	1.736/1.464/0.6	-	03/03	a 49.83/ h 31.57

2.2. Mobile Station

The Figure on the left side of Figure 3 shows a schematic diagram of the overall antenna structure of mobile station in the MWMSB cellular system, and this architecture is composed of three mobile station phases (hereafter, MPH (Mobile station PHase)) (MPH1, MPH2, MPH3), and the figure in the parentheses next to the MPH means the

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number of patch array antennas for transmitting and receiving. For example, MPH2(8) means that eight patch array antennas are mounted (MPH2-P1thru8) on the MPH2 as shown in the Figure on the right side of Figure 3, and MPH1(9) represents that additional patch array antenna (MPH1-P0) is mounted on the top of eight patch array antennas (MPH1-P1thru8) in the MPH1, and thus there are a total of nine patch array antennas. Accordingly, the terminal has a total of 25 patch array antennas, and all the patch array antennas of one MS can be discriminated by combining port numbering (-Px), along with the MPHx.

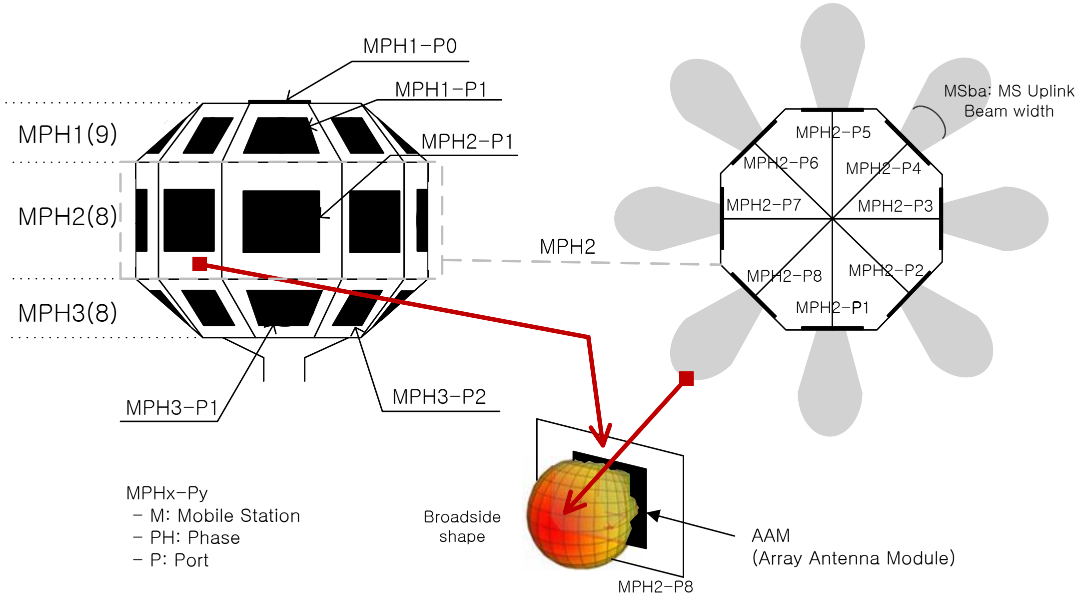

Figure 3. Overall Antenna Architecture of MWMSB Mobile Station

It is assumed that as for MS, it is possible to perform downlink soft combining up to three ports corresponding to the signal level that can be accepted in the order of the best MPH port by measuring downlink reference signals from 25 MPH ports according to the measurement method and criteria directed by the network, uplink transmission is done through only one MPH port, and uplink transmitting port becomes the MPH receiving port with the largest signal strength of downlink reference signal, which can still be changed by various factors, such as the movement of MS and appearance of obstacles. That is, the process for MS to find transmitting and receiving ports based on the measurement method and criteria directed by the network is defined as beam tracking in this paper. With respect to the entire antenna structure, the number of patch array antennas and uplink beam width, the related designs can be changed in consideration of the coverages of base station described in 2.1 and projected beam area within them, and the patch antenna can also can be mounted along its body surface, while maintaining the real body shape of the MS in actual commercial product.

3. Basic System Operation

MWMSB is very similar to the LTE or the LTE-A system in all respects. For example, system entities are the same as MS, BS and EPC(Evolved Packet Core), protocol structure is composed of PHY, MAC(Medium Access Control), RRC(Radio Resource Control), PDCP(Packet Data Convergence Protocol), GTP(GPRS Tunneling Protocol), NAS(Non-Access Stratum), S1AP(S1 Application Protocol) and X2AP(X2 Application Protocol), physical signal and channel, transport channel, logical channel and mutual channel mapping are the same except for MBMS(Multimedia Broadcast Multicast Service), and its system operation is very similar. The MWMSB differs from the LTE in that frame/subframe/slot duration is reduced to 1/10 of the LTE, and it uses high frequency that corresponds to A6. In addition, it has physical parameters as shown in Table 2, and major differences in a system operation are as follows.

Table 2. MWMSB Physical Layer Parameters

Parameters	Value
(1) Multiple access method	(DL) OFDMA, (UL) SC-FDMA
(2) Bandwidth	125 MHz, up to 1 GHz through CA
(3) Full duplex mode	TDD (similar to LTE Frame Structure Type 2)
(4) Frame duration	1 ms
(5) Subframe duration	0.1 ms
(6) Slot duration	0.05 ms
(7) Sampling rate	184.32 MHz
(8) Subcarrier spacing	180 kHz
(9) No. of subcarriers (total)	694
(10) No. of subcarriers (without guard band)	624
(11) OFDM sym. length (FFT size)	1,024
(12) OFDM sym. duration	5.56 us
(13) CP length	128
(14) CP duration	0.69 us
(15) No. of OFDM sym./slot	8

- If the specific FA of specific beam (hereafter, beam component carrier (BCC)) are defined into one group and CRS (cell specific reference signal) to all BCC within it is made to be the same, the corresponding BCC group is regarded as one cell.
- All BCCs belonging to the same FA in entire beams constituting the coverage of base station can be made into a single cell, or they can be made into multiple cells within one base station depending on different CRS position by grouping BCCs on specific FA belonging to the base station into several units (dynamic BCC clustering of Figure 4).
- Beam tracking is performed based on CRS measurements in receiving ports of the mobile station.

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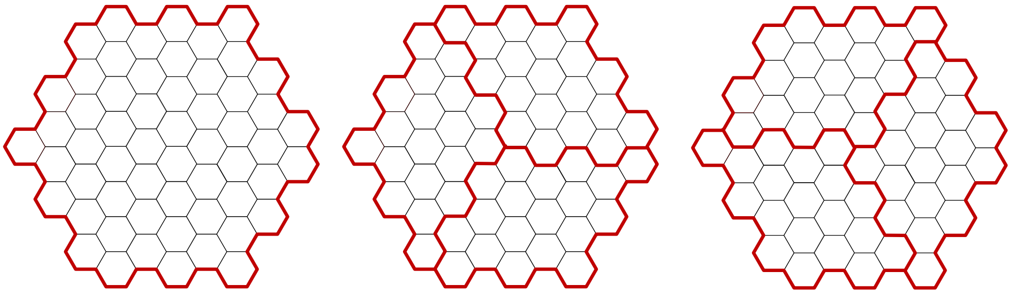
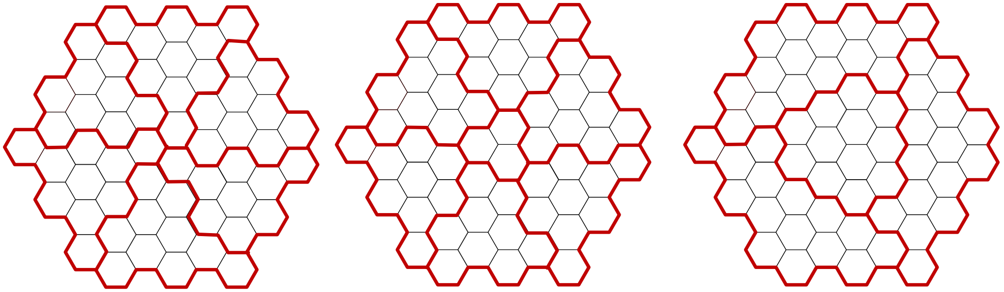


(a) 57 BCCs/1Cell

(b) 19 BCCs/3Cells – Type1

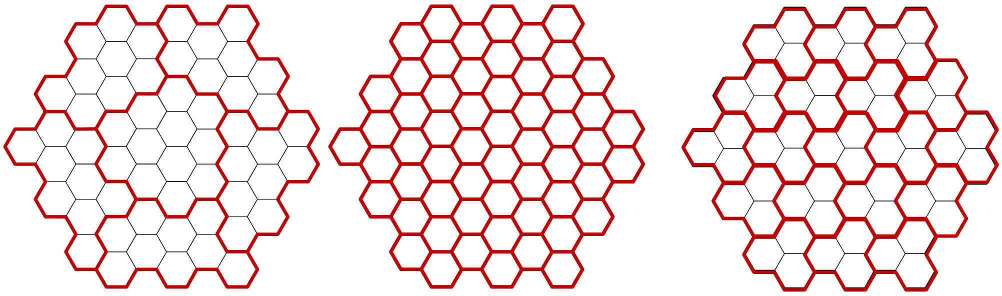
(c) 19 BCCs/3 Cells – Type2



(d) 9 BCCs/3 Cells plus 10 BCCs/3 Cells

(e) 9 BCCs/6 Cells plus 3 BCCs/1Cell

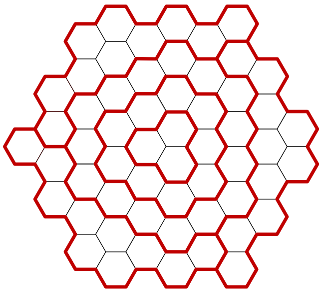
(f) 15 BCCs/3 Cells plus 12 BCCs/1 Cell



(g) 9 BCCs/5 Cells plus 12 BCCs/1 Cell

(h) 57 BCCs/1 Cell

(i) 3 BCCs/19 Cells

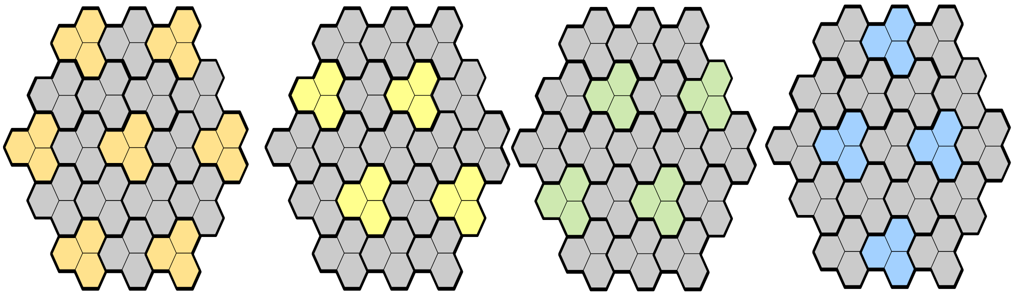


(j) 3 BCCs/1 Cell
plus 9 BCCs/1 Cell
Plus 15 BCCs/1 Cell
Plus 10 BCCs/1 Cell
(donut cells)

Figure 4. Dynamic Cell Configuration within the Same FA

- As for the same FA of all the beams defined as the same cell, PSS, SSS, PBCH, PCFICH, PDCCH, PHICH, PDCCH and PUCCH, PRACH are operated in common.
- With respect to the same FA of beams defined as the same cell, PDSCH and PUSCH are operated independently by each BCC.
    - ■ exception case1: paging, system information(SI), random access response
    - ■ exception case2: RRC signal (joint transmission and joint reception over the specific FA of all beams belonging to cell, or data allocation prohibition in the

  residual beams to avoid serving beam resource allocation region related RRC signal)
  - exception case3: with regard to all BCCs belonging to the dynamic clustered cell (Figure 4), PDSCH/PUSCH resource can be operated by regarding it as a common resource
- If there exist several operational component carriers of the cell, one of them is fixed as the primary component carrier (PCC) in terms of the network, and RRC signal, paging and initial random access for initial radio connection are done through this PCC, and the rest of the component carriers are mainly used only for naive data transmission and reception.
- In all BCCs, different BSI (Beam Status Information)-RS (Reference Signal) (the same concept as CSI-RS of LTE-A) is allocated, and as for UE, BSI feedback through BSI-RS measurement is transmitted to the network through PUCCH.
- As for BCC switching belonging to the same cell, BS MAC determines BCC switching by using BSI feedback information and performs BCC switching using DCI (Downlink Control Information) of PDCCH.

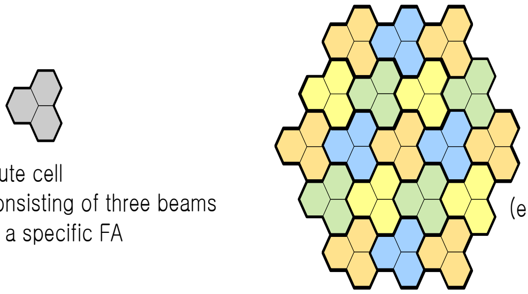


(a) Secondary FA3
- active cell 7 EA
- mute cell 12 EA

(b) Secondary FA4
- active cell 4 EA
- mute cell 15 EA

(c) Secondary FA5
- active cell 4 EA
- mute cell 15 EA

(d) Secondary FA6
- active cell 4 EA
- mute cell 15 EA



Mute cell
consisting of three beams
In a specific FA

(e) Secondary FA3~6
- (a)+(b)+(c)+(d)

Figure 5. The Example of Multi-FA Layered Dynamic Cell Deployment

When compared to the existing cellular systems, the MWMSB cellular system has the following advantages

- Under the assumption of the same coverage, it can further increase the average base station capacity compared to the existing cellular systems.
- Assuming Figure 2 (b), the MWMSB cell system has a reduction in OPEX, as compared to the case of the deployment of 57 small cells.
- It is possible to provide flexible network configuration, optimal system capacity and mobility through dynamic BCC clustering (Figure 4) according to changes in temporal and spatial user distribution. As shown in Figure 4, new cell shape like (j) (donut cell) which did not exist before is possible, and system gain can be obtained through a variety of dynamic BCC clustering per FA of beam. For example, one FA among 8 FAs is placed in the primary as BCC clustering of Figure 4 (a). This one primary cell corresponding to it is mainly used for reliable transmission and reception such as signaling, and other FAs are used for data offloading in the form

of (b), (c), (d), (e), (f), (g), (h), (i), (j) of Figure 4. For example, the data of stationary users may flow into the best cell of FA that corresponds to (h), the data of users in a low-speed state may flow into the best cell of FA that corresponds to (i), and the data of high-speed users may flow into the primary cell (a) or any cells of FA that corresponds to (b), (c). That is, data offloading can be attempted by finding cells and FA with the best signal quality for MS in consideration of changes in moving speed of the MS.

- Since the secondary FAs are for data offloading, a specific cell sparsely on them can be muted (status of sending only minimal control signals like almost blank subframe) and that achieves interference-reduced cell deployment through the association between FAs (Figure 5 shows the association between FAs in the BCC clustering that corresponds to Figure 4 (i)). They can change various cell deployments in real time from the perspective of load, mobility, user's distribution and interference reduction through the association between FAs or inside the FA if traffic load is not heavy.

Under the assumption of wired non-ideal backhaul between macro cell and small cells in SCE (Small Cell Enhancements) [5], MS has dual connectivity (one is macro cell for coverage, another is small cell for capacity) in the air and assumes that many small cells are distributed within macro cell coverage and installed as many as the required system capacity. The MWMSB assumes a standalone system. However, it can play two parts of small cell as well as macro cell like SCE architecture, simulate a variety of pseudo-small cells like Figure 4 (b), (c), (d), (e), (f), (g), (h) and pseudo-macro cell like Figure 4 (a) through dynamic cell configuration and perform real-time radio resource management between pseudo-macro cell and pseudo-small cells because of wired ideal backhaul.

4. Simulation

For capacity evaluation on the MWMSB system, four simulation categories are proposed as below. The simulations were performed based on the LOS (Line of Site), and it was assumed that all the categories have the same BS coverage, and three cells cover the coverage of BS depicted as LTE MC and LTE-A MC. In the case of LTE-A SCs and MWMSB, 57 small cells (LTE-A SCs) or 57 beams (MWMSB) were assumed to be positioned in the beam center as shown in Figure 2 (b). Parameters not mentioned in LTE MC, LTE-A MC, and LTE-A SCs are the same as those in MWMSB.

- LTE MC(Macro Cell)
  - ■ 3GPP Case 1 [6], TDD ul-dl configuration 5
  - ■ 2GHz center frequency, 20MHz, Antenna 4tx
  - ■ BS coverage diameter 400m, height 50m, Tx power 30 dBm, 3cells/BS
  - ■ MS distribution/BS coverage 100
- LTE-A MC(Macro Cell)
  - ■ 3GPP Case 1 [6], TDD ul-dl configuration 5
  - ■ 2GHz center frequency, 20MHz up to 100MHz via CA, Antenna 8tx
  - ■ BS coverage diameter 400m, height 50m, Tx power 30 dBm, 3cells/BS
  - ■ MS distribution/BS coverage 100
- LTE-A SCs (Small Cells)
  - ■ 3GPP Case1 [6], TDD ul-dl configuration 5
  - ■ 2GHz center frequency, 20MHz up to 100MHz via CA, Antenna 8tx
  - ■ Small cell coverage diameter 80m, height 15m, Tx power 23 dBm
  - ■ 57 LTE-A small cells at each beam center of Figure 2 (b)
  - ■ MS distribution/MWMSB coverage 25, 50, 75, 100, 125, 200, 300, 400
- MWMSB
  - ■ Refer to Table 2 and 3

Table 3. MWMSB Simulation Baseline Parameters

Parameters	Value
(1) Beam no./base station	57 spot beams/BS
(2) Base station coverage diameter	400 m
(3) Cell no./base station	3cells/BS (Fig 4(b))
(4) Base station antenna height	50 m
(4) Full duplex mode	TDD (similar to LTE Frame Structure Type 2, Uplink-downlink configuration 5)
(5) BPH baseline beam pointing angle	Refer to Table 1
(6) BPH baseline beam width	Refer to Table 1
(7) Base station Tx power	30 dBm/Beam, 1tx/Beam
(8) Center frequency	27 GHz
(9) Bandwidth	1GHz (125MHz x 8FA)
(9) Free space Loss (L)	92.4+20log f+20log R dB
(10) Path Loss (PL)	L + 10 dB
(11) MS antenna gain	12 dB
(12) PDCCH OFDM symbol no.	3
(13) UE distribution/BS	25, 50, 75, 100, 125, 200, 300, 400

Figure 6 shows the peak BS capacity of each category under the optimum condition. Based on 403Mbps of LTE MC, LTE-A MC displays 9.38(3.78Gbps) times the capacity, LTE-A SCs 178.13 times (72.82Gbps), and MWMSB 250.8 times (101.123Gbps). Assuming the optimum condition, the MWMSB has the highest Peak BS Capacity.

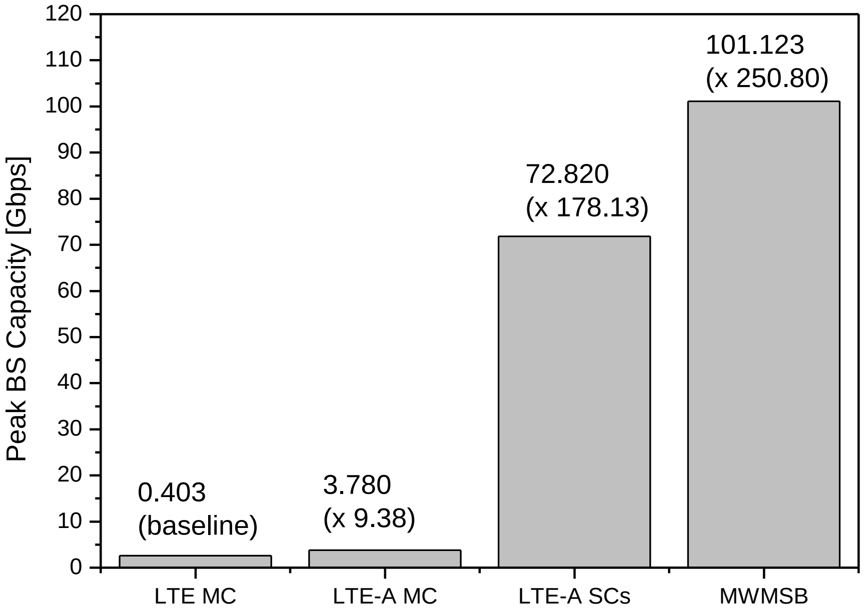


Figure 6. Peak and Average User Capacity and Base Station Capacity

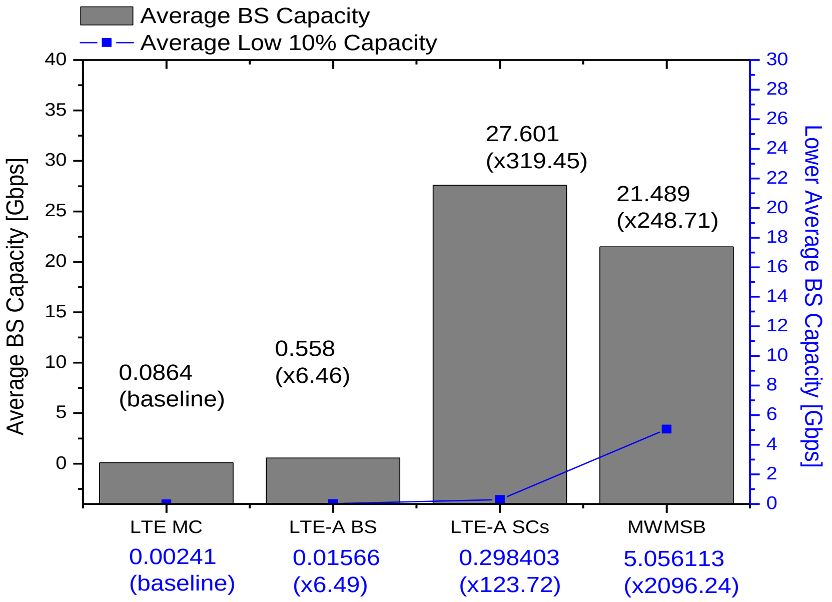


Figure 7. Average Base Station Capacity According to the Number of UEs

In Figure 7, when 100 MSs are uniformly distributed in the same BS coverage, the sum of user capacities that each MS experiences is defined as the Average BS Capacity, and that of user capacities of the MSs corresponding to the lower 10% among 100 MSs is Lower Average BS Capacity. Based on 86.4Mbps of LTE MC in terms of the Average BS Capacity, LTE-A MC is 6.46 (558Mbps) times the capacity, LTE-A SCs 319.45 times (27.601Gbps), and MWMSB 248.71 times (21.489Gbps). Based on 2.41Mbps of LTE MC In terms of Lower Average BS capacity, LTE-A MC is 6.49 (15.66Mbps) times the capacity, LTE-A SCs 123.72 times (298.403Mbps), and MWMSB 2096.24 times (5.056Gbps). When compared with the LTE-SCs, the MWMSB shows lower Average BS Capacity but higher Lower Average BS Capacity, which indicates that since in the distribution of 100 users, the MWMSB has lower system utilization compared to that of LTE-A SCs in terms of the Peak BS Capacity, but throughput imbalance between users is high in the MWMSB, it can be seen as a more fair system.

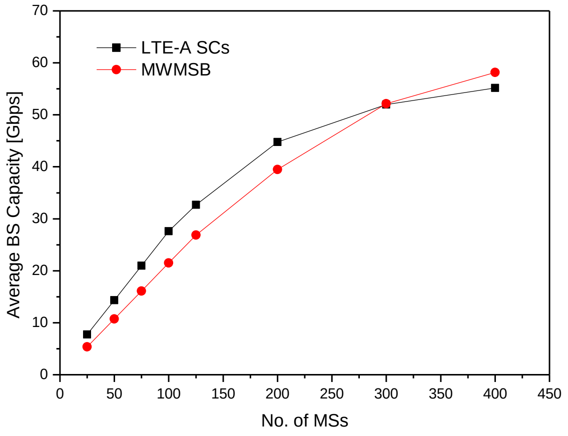


Figure 8. Average Base Station Capacity According to the Number of UEs

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Figure 8 shows the Average BS Capacity according to the number of users scheduling LTE-A SCs and MWSMB. In less than 300 users, the Average BS Capacity of LTE-A SCs is higher than that of MWMSB, but the Average BS capacity of MWMSB system is higher from the unit of 300 users, which means that when compared with the LTE-A SCs, the MWMSB is in closer proximity to the Peak BS Capacity as the number of users increase, but its system utilization becomes lower compared to that of LTE-A SCs in case there are fewer users.

5. Conclusion

In this paper, we designed base station, mobile station and basic system operation on the new standalone and centralized MWMSB cellular system and performed an evaluation under the LOS environment in terms of capacity. As MWMSB cellular system to ensure the 250-fold capacity increase compared to the LTE through simulation, it has higher system capacity utilization rate compared to the peak system capacity in a relatively high load mobile distribution and it is characterized by a smaller throughput imbalance between users, as compared to that of LTE-A SCs.

However, since mmWave has different characteristics [7] from those of existing cellular frequency (B6), its applicability as a pragmatic cellular system can be verified only when the NLOS environment where there are obstacles such as a building is taken into account, and the occurrence of coverage holes and mobility performance degradation according to the beam switching, cell change and BS change are investigated. For future work, there is a need to investigate the generation of spontaneous coverage hole and mobility performance based on the MWMSB cellular system design of this paper, and to proceed with the research on the system gains in the case of the organization of pseudo-small cells and pseudo-macro cell for MWMSB beam component carriers through multi-FA layered dynamic cell configuration, compared with the original SCE structure [5].

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