Improving Communication Performance in High-mobility Environments by Millimeter-wave Base Station Cooperation for 5G evolution

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Abstract

Although the 5th-generation mobile communications system (5G) commercial services are now being provided, further evolution of 5G is needed to meet a variety of future demands. As part of these studies, we consider the provision of millimeter-wave high-speed communications over a wide area to multiple mobile stations traveling at high speed. In a high-mobility environment, area construction must be performed over a wide area through the cooperation of multiple base stations. Additionally, to achieve simultaneous communications with multiple mobile stations, interference must be suppressed so that signals transmitted to each mobile station do not interfere with each other. To deal with these issues, we developed millimeter-wave base station cooperation technology to enable multiple base stations to cooperate with each other while suppressing inter-mobile-station interference by applying digital beamforming to base stations to generate and control beams by digital signal processing. We showed through outdoor experimental trials that high communication speeds could be achieved over a wide area.

Keywords: digital beamforming, base station cooperation, outdoor experimental trials

1. Introduction

In the 5th-generation mobile communications system (5G), high-speed communications is being pursued using frequency bands below 6 GHz and the so-called 28 GHz millimeter-wave*1 band. Here, to compensate for the large path loss*2 of high-frequency bands such as the millimeter-wave band, beamforming (BF)*3 technology using Massive multiple-input multiple-output (Massive MIMO)*4 has come to be researched as a 5G radio access technology.

NTT DOCOMO is rolling out 5G commercial services using the 3.7, 4.5, and 28 GHz bands. Here, the available bandwidth in the 28 GHz band is wider than that in the 3.7 and 4.5 GHz bands, so high-speed communications can be expected. On the other hand, strong straight-line propagation and large path loss of

*1 Millimeter waves: Radio signals in the frequency band from 30 GHz to 300 GHz as well as the 28 GHz band targeted by 5G all of which are customarily called "millimeter waves."

*2 Path loss: The amount of attenuation in the power of a signal emitted from a transmitting station until it arrives at a reception point.

*3 BF: Technology for increasing/decreasing signal power in a particular direction by giving directionality to the transmission signal. It includes analog beamforming that forms directionality by phase control of multiple antenna elements (radio-frequency equipment) and digital BF that performs phase control in the baseband section.

millimeter waves means that technical issues still remain in the provision of stable high-speed communications over a wide area. Nevertheless, the use of the millimeter-wave band is essential to further the evolution of 5G [1].

In this article, we show by outdoor experimental trials that high-speed communications can be provided over a wide area by (1) using multiple 28 GHz band experimental base stations equipped with digital BF to perform BF by digital signal processing and (2) having those base stations cooperate with each other while suppressing the interference generated between multiple mobile stations traveling at high speed. We present and discuss the experimental results.

2. Overview of experimental equipment equipped with millimeter-wave base station cooperation technology by digital BF

2.1 Effects of applying digital BF and base station cooperation to high-mobility environments

The following problems must be solved to achieve even higher communication speeds using millimeter waves:

(1) While higher communication speeds can be expected for each base station through simultaneous communications with multiple mobile stations (by achieving multi-user MIMO), interference generated between mobile stations must be suppressed.

(2) For example, when a base station is communicating with mobile stations within vehicles traveling on an expressway at 100 km/h, cooperation among multiple base stations is necessary to provide wide-area communications.

A variety of methods have been proposed to suppress inter-mobile-station interference such as transmitting signals to mobile stations using a different beam for each. Nevertheless, interference can still occur between beams, so this method is not necessarily able to sufficiently suppress interference. Furthermore, given the large path loss of millimeter waves, the service area of each base station cannot be easily expanded. In environments with mobile stations traveling at high speeds, this means that the time during which a mobile station is present in that area is short, which in turn means frequent switching between base stations.

Based on the above, an important requirement for providing high-speed communications for multiple mobile stations traveling at high speeds is to maintain stable high-speed communications even during a switchover between base stations while suppressing inter-mobile-station interference. To this end, we here report on the development of Massive MIMO experimental equipment using digital BF in the millimeter-wave band as opposed to implementing BF using analog circuits (hereinafter referred to as "analog BF") as a base station function.

In general, analog BF operates by having the base station select the beam to be used from a set of beam candidates determined beforehand. The advantage here is that information only on beam direction is sufficient thereby simplifying equipment structure. On the other hand, the beam is not optimized to radio wave propagation conditions.

In contrast, digital BF performs communication by calculating the optimal beam shape (number of individual beams and directions) according to radio wave propagation conditions. In this way, an improvement in communication quality can be expected, but other problems arise; that is, information on the propagation channel must be estimated, but tracking of wildly fluctuating radio wave propagation conditions in an environment with mobile stations traveling at high speeds is difficult. However, the fact that digital BF is achieved by digital signal processing means that suppression of inter-mobile-station interference can be incorporated in beam generation and control and that optimal BF can be performed even in an environment with multiple mobile stations, all of which make digital BF a key technology for enhancing communication performance in the future. Additionally, as examples of base station cooperation, information (received power, degree of spatial multiplexing available for transmission, etc.) obtained from channel information used for digital BF can be used for instantaneous switching to the base station best suited for communication, or multiple base stations can be controlled to perform simultaneous transmissions. Such base station cooperation can achieve stable and high-speed communications within an area.

2.2 Overview of digital BF

In contrast to analog BF, digital BF generates and controls beams by digital signal processing. Analog

*4 Massive MIMO: MIMO systems transmit radio signals overlapping in space by using multiple antenna elements for transmission and reception. Massive MIMO systems aim to achieve high-speed data communications with greater numbers of simultaneous streaming transmissions while securing service areas. They achieve that aim by using antenna elements consisting of super multi-element arrays to create sharply formed radio beams to compensate for the radio path losses that accompany high-frequency band usage.

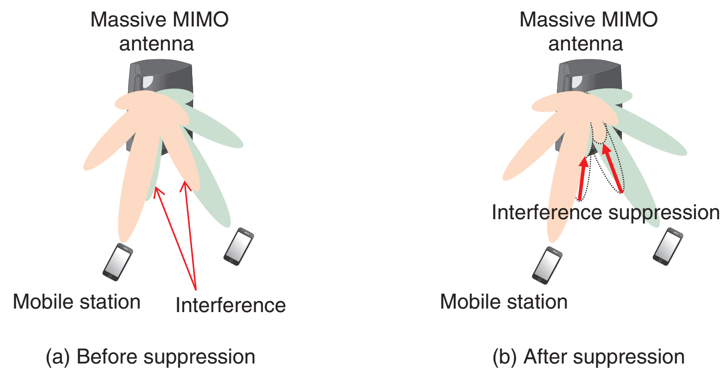


Fig. 1. Conceptual diagram of interference suppression by digital BF.

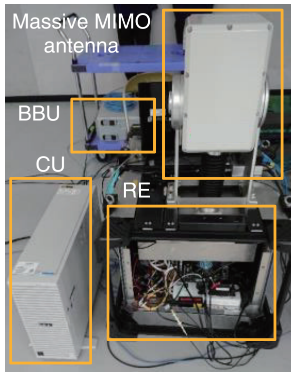
BF uses a phase shifter*5 and amplifier*6 connected to each antenna element to achieve strong radio wave directionality in a particular direction by superimposing radio waves emitted from each of those elements. The problem here, however, is that the superimposing of radio waves always results in the same beam shape in whatever the direction. Digital BF, on the other hand, generates beams by using channel information between the base station and mobile station, calculating the weighting factors to obtain maximum received power, and multiplying the transmission signal by those factors by digital signal processing. In this way, digital BF can deal with a situation in which the mobile station's peripheral environment is fluctuating though the mobile station itself may be stationary by reforming an optimal beam according to that fluctuation. Digital signal processing also enables high-accuracy MIMO multiplexing of multiple signals and suppression of inter-mobile-station interference. A conceptual diagram of interference suppression is shown in **Fig. 1**. In analog BF, when a beam faces a particular direction as shown in Fig. 1(a), the shape of that beam always has a fixed pattern. As a result, interference can occur between mobile stations depending on the environment and communication performance can greatly deteriorate if the effect of that interference is large. Digital BF, though, can perform beam shaping correctly according to the peripheral environment. In Fig. 1(b), the beam shape is formed so as to suppress inter-mobile-station interference, which can improve communication quality compared with no interference suppression.

However, channel information between the base station and mobile station must be determined in detail to achieve digital BF. This channel information is estimated from the channel matrix, whose number of rows is equal to the number of antenna elements and number of columns is equal to the number of base stations. In 5G, a base station turns out to be a massive-element antenna, so it is necessary to estimate a matrix of enormous size. Additionally, if the temporal fluctuation of the mobile station and peripheral environment is gentle, it should be possible to estimate channel information, but if this temporal fluctuation is intense as in a high-mobility environment, a discrepancy will emerge in channel information between the time of estimation and the time at which the signal is actually transmitted. As a result, an optimal beam cannot necessarily be formed.

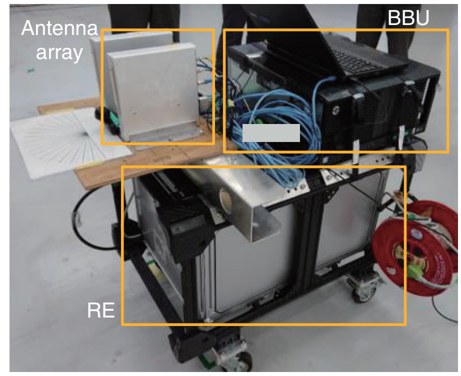
With the aim, therefore, of exploiting the benefits of digital BF while contracting the size of the matrix to be estimated, we adopted technology that first forms multiple beams in predetermined directions using a many-element antenna and then estimates channel information between those multiple beams and the mobile station [2]. With this approach, the size of the matrix to be estimated can be reduced from number of mobile station elements × number of base station elements to number of mobile station elements × number of beams. In this way, by performing digital signal processing using a matrix of a size equal to number of mobile station elements × number of beams, it becomes possible to estimate channel information in a relatively short time while minimizing quality degradation from the use of all elements. With this approach, digital signal processing as in forming and controlling beams and suppressing inter-mobile-station interference can still be performed thereby

*5 Phase shifter: A circuit that can change the phase going to each antenna element.

*6 Amplifier: A circuit that amplifies the signal.



(a) Base station



(b) Mobile station

Fig. 2. Experimental equipment.

enabling transmission by digital BF even in a high-mobility environment.

2.3 Overview of experimental equipment

External views of base-station and mobile-station experimental equipment that we developed are shown in **Fig. 2**. The base station features a 240-element Massive MIMO antenna connected to a baseband unit (BBU)*7 that performs digital BF weight calculations. In addition, the central unit (CU)*8 connects to multiple BBUs with the role of performing a control function in multi-base-station cooperation.

The mobile station, meanwhile, features four antenna arrays*9 each having 15 vertical elements. Among these four arrays, only two panels for a total of 30 elements are used for transmitting a reference signal*10, but in reception, all four panels are used to increase receive gain. These antenna arrays connect to the BBU via radio equipment (RE)*11.

With this experimental equipment, the base station uses the reference signal periodically transmitted by the mobile station to estimate channel information. It then generates digital BF weights based on the results of that estimation and transmits a maximum to two streams per mobile station. A mobile station can achieve a maximum throughput of 705 Mbit/s with a total of two streams. Additionally, once the mobile station begins to receive signal streams, it calculates a receive filter*12 at its BBU, detects transmitted signals, and measures throughput.

3. Overview and results of millimeter-wave outdoor experimental trials

3.1 Experimental environment

In outdoor experimental trials targeting multiple mobile stations traveling at high speeds, we performed transmission experiments to evaluate throughput under base station cooperation [3]. The experimental setup is shown in **Fig. 3**. In these experiments, we used three base stations each temporarily installed in the bed of a truck. We also used two mobile stations each installed in a vehicle and had them travel at high speed. At this time, antenna height was set at 2.2 m for both the base stations and mobile stations.

Experimental configuration is shown in **Fig. 4**. In the experiments, two mobile stations each pass by three base stations while traveling at a uniform speed of 90 km/h. These three base stations are positioned

*7 BBU: One component of base station equipment performing digital signal processing of transmit/receive information when communicating with a mobile station.

*8 CU: Equipment that connects to a baseband unit and performs radio resource control.

*9 Antenna array: An arrangement of multiple antenna elements or panels forming an antenna group.

*10 Reference signal: A known signal from base stations, configured in user equipment.

*11 RE: The equipment that connects with the baseband processor via the fronthaul.

*12 Receive filter: In MIMO communications, transmitting/receiving by multiple antennas enables the transmission of multiple streams and an improvement in received power of the desired signal. On the other hand, the information in multiple streams through transmitting/receiving by multiple antennas is received in a complicated overlapping state, so a filter is used to mitigate that overlapping and make it easier to estimate the desired signal.

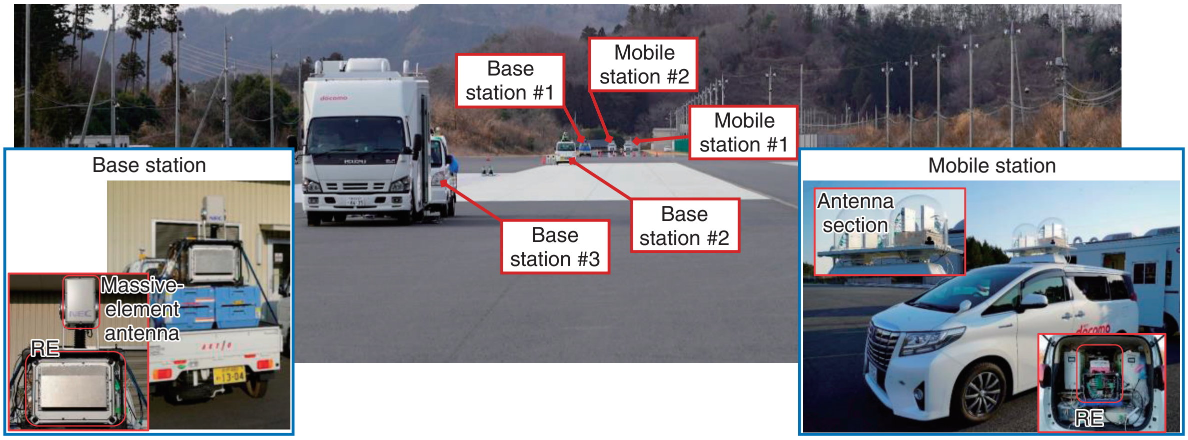


Fig. 3. Experimental setup.

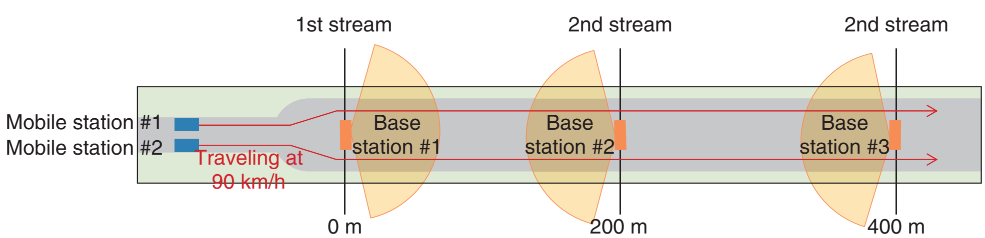


Fig. 4. Experimental configuration.

at distances of 0, 200, and 400 m, respectively. At this time, it is assumed that two streams are transmitted to each mobile station and that distributed MIMO technology is applied to transmit each stream from a different base station. Specifically, base station #1 transmits the 1st stream of each mobile station continuously while base station #2 and base station #3 transmit the 2nd stream. Transmitting different streams from multiple base stations in this way causes the correlation of channel information from each base station to drop making it easy to separate MIMO spatially multiplexed streams. In addition, two methods of base station cooperation were implemented here: high-speed switching to base station #2 and base station #3 and simultaneous transmission from base station #2 and base station #3. In these experiments, we evaluated downlink throughput for mobile stations traveling at a high speed of 90 km/h.

3.2 Experimental results

3.2.1 Base station cooperation experiment

To test the effects of base station cooperation, we compared the case of not using base station #2 in Fig. 4 (no base station cooperation) and the case of using all base stations (cooperation between base station #2 and base station #3). To examine only the effects of base station cooperation, we used only mobile station #2 in this experiment traveling at a speed of 90 km/h. Here, base station #1 transmits the 1st stream while base station #2 or base station #3 transmits the 2nd stream, and when performing base station cooperation, the base station from among base station #2 and base station #3 that CU judges most capable of improving communication quality based on channel information will transmit the 2nd stream.

Throughput versus mobile station position from 0 to 400 m is shown in **Fig. 5**. It can be seen from these results that throughput deteriorated at the 100 m position when not performing base station cooperation. However, communications could be achieved without this drop in throughput when performing base station cooperation. This was the effect of installing base station #2 at the 200 m position and performing base station cooperation (base station high-speed switching)

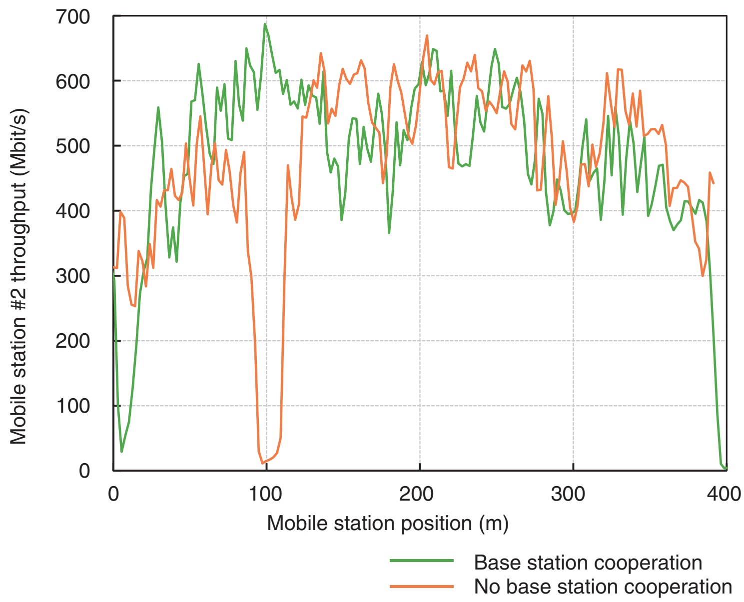


Fig. 5. Effects of base station cooperation.

so that communications could be continued from a different base station even in an environment or at a mobile station position where the communication performance of a certain base station had deteriorated. This result demonstrates that base station cooperation can achieve high-speed communications over a wide area within the coverage area.

3.2.2 Base station cooperation experiment (base station high-speed switching) during two-mobile-station multiplexing

Figure 6 shows throughput for a total of two streams transmitted to each of two mobile stations during high-speed switching between base station #2 and base station #3 depending on communication quality. Since the antenna array of base station #2 is facing to the left in Fig. 4, we consider that a mobile station will switch from base station #2 to base station #3 near the 200 m position. Consequently, on checking throughput near 200 m, no major deterioration in throughput can be observed for either mobile station #1 or mobile station #2 showing that base station switching could be achieved in a relatively stable manner.

From these results, it can be seen that stable and high throughput can be achieved within the coverage area through base station switching while achieving simultaneous communications with two mobile stations by suppressing inter-mobile-station interference through digital BF. This holds even in an environment in which two mobile stations are traveling at a high speed of 90 km/h.

3.2.3 Base station cooperation experiment (base station simultaneous transmission) during two-mobile-station multiplexing

Throughput when having base station #2 and base station #3 perform simultaneous transmission is shown in **Fig. 7**. Basic conditions are the same as those of Fig. 6, but with respect to the 2nd stream, base station #2 and base station #3 transmit the same signal simultaneously, so an improvement in received power can be expected at the mobile stations.

Examining throughput in the range of 0–200 m, it can be seen that simultaneous transmission operated without a problem. Furthermore, on comparing these results with those of Fig. 6, it can be seen that throughput was improved if only slightly in the range, for example, of 0–50 m. We offer two reasons for this, one that received power increased by simultaneous transmission, and another that deterioration in communication quality could be suppressed overall even if the quality of the signal from one of the base stations deteriorated due to the peripheral environment since there was also a signal from the other base station. However, at positions from 50 to 200 m, throughput in Fig. 7 could not necessarily maintain higher values than throughput in Fig. 6. This is

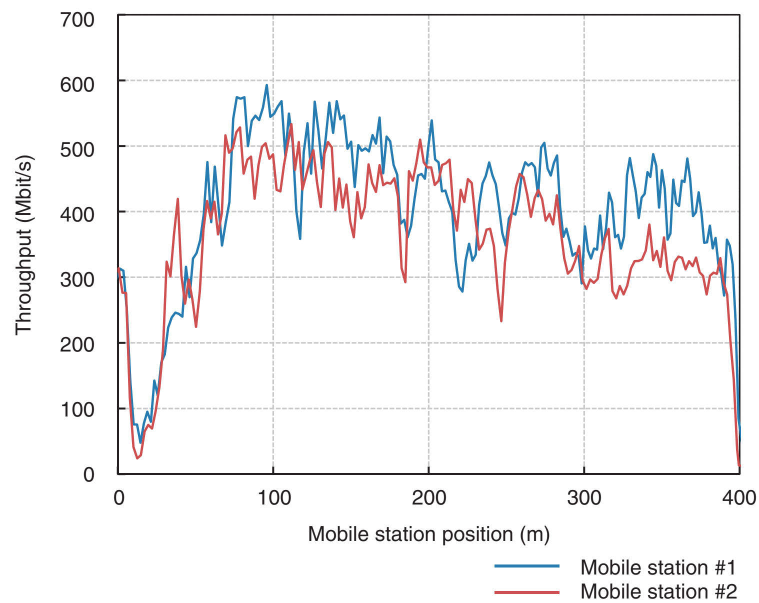


Fig. 6. User throughput for base station switching at 90 km/h.

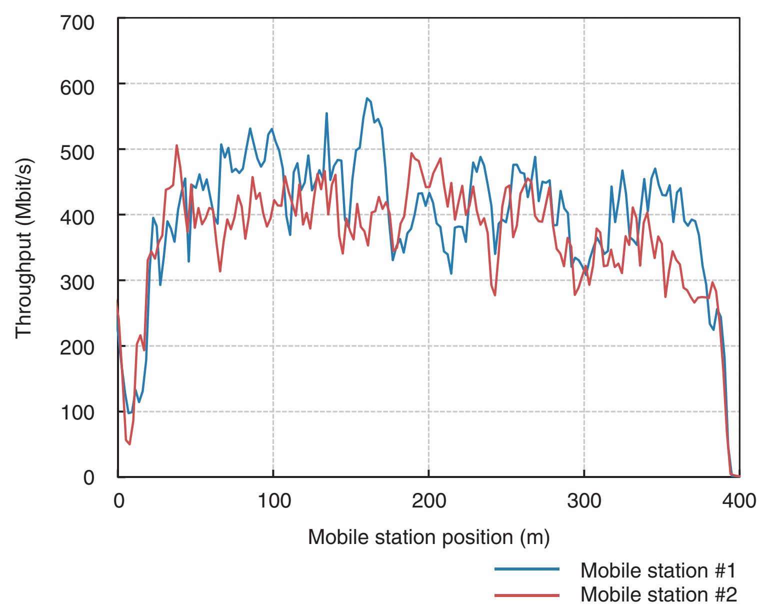


Fig. 7. User throughput for simultaneous base station transmission at 90 km/h.

because, in this experimental environment, line-of-sight waves are dominant and radio waves on which signals of base station #2 and base station #3 are superimposed cancel each other out at some positions. Nevertheless, we consider that throughput in a high-mobility environment can be made stable through simultaneous transmission.

The results of this experiment demonstrate the effectiveness of simultaneous transmission as a form of base station cooperation.

4. Conclusion

This article described research and development for 5G evolution with the aim of providing stable throughput with wide coverage by applying base station cooperation technology while suppressing interference between multiple mobile stations by applying digital BF in the millimeter-wave band. On developing millimeter-wave band experimental equipment incorporating base station cooperation technology by digital BF and performing outdoor experimental trials, it was shown that high-speed switching among three base stations could be achieved while suppressing interference between two mobile stations moving at a high speed of 90 km/h. It was also shown that stable and high throughput could be provided over a wide area by performing simultaneous base-station transmissions through base station cooperation. In future research, we plan to test the effects of base station cooperation technology with a variety of base-station arrangement methods.

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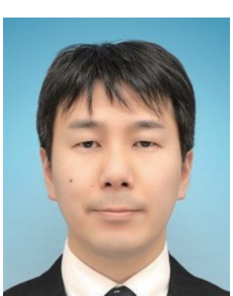

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