Cambium Networks™

TECHNICAL ADVANTAGES AND INNOVATION

PMP 450m and cnMedusa™ Technology

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Introduction

Networks today are at a crossroads. Outdoor fixed wireless access networks support highly cost-effective deployment and bring high-speed connectivity to hard-to-reach areas, but not without challenges. Network operators need to enable denser subscriber network deployments per sector and provide higher bandwidth to their subscribers – including support for media-rich services such as IPTV or streaming video – with the goals of growing their average revenue per user (ARPU) and future-proofing their networks.

Network operators already deploying PMP 450 devices face the obstacles of not only increasing network capacity without using more wireless spectrum, but also protecting their existing investments by avoiding wholesale replacements of the networking equipment already deployed (e.g. a “forklift upgrade”).

Network operators planning Greenfield deployments aim to build durable, scalable networks with the expectation that both the number of subscribers and the usage per subscriber will increase significantly over time.

The Cambium Networks PMP 450 platform, deployed worldwide as the basis for some of the largest fixed wireless access service provider networks in the world, has evolved to overcome these challenges with PMP 450m, powered by cnMedusa technology – the industry’s first commercially deployed massive multi-user multiple-input multiple-output (MU-MIMO) platform.

This white paper is an overview of the general technologies used in massive MU-MIMO, followed by specific details on Cambium Networks’ cnMedusa massive MU-MIMO technology as implemented in the PMP 450m product.

The Road to Massive MU-MIMO

MIMO Evolution MIMO is a range of technologies used to multiply the capacity of a wireless connection without requiring additional spectrum. At their most basic level, wireless communication systems can use a single antenna element to communicate with each other – known as a single polarization system.

Adding another antenna element to each wireless node creates a dual polarization system, which doubles network capacity without requiring more spectrum by using the horizontal and vertical polarity of the radio wave, each carrying a separate data stream to transmit and receive data. PMP 450 is an example of a dual polarization system.

This is also referred to as a 2x2 MIMO system; both wireless nodes, which are communicating with each other, have two antenna elements. The first “2” refers to the number of transmit antennas; the second to the number of receive antennas used to communicate over the radio channel at any moment. Through the use of dual polarization antennas at each end of the link, a 2x2 MIMO system can typically support two streams in the same radio spectrum.

Beyond dual polarization systems, implementation of MIMO techniques becomes more intricate. By adding more antenna elements, the potential capacity gains increase, but so does the complexity of signal processing and antenna design.

Towards Massive MIMO Networks exceeding 8x8 MIMO systems are typically considered massive MIMO systems, which require a highly complex active antenna array and advanced signal processing to realize the benefit of massive MIMO capacity in real world conditions.

Presently, the vast majority of massive MIMO systems are experiments in academic laboratories. It has proven very difficult for wireless equipment manufacturers to create working, real world massive MIMO solutions. Current LTE and Wi-Fi standards include increased use of MIMO techniques, but have not yet achieved massive MIMO.

Benefitting Multiple Subscribers Historically, MIMO technologies have been used to increase capacity between two wireless nodes. This benefits one subscriber at a time, but if a subscriber is not able to use all the capacity enabled by MIMO, that capacity is not utilized. Also, the increased capacity can only be achieved if the subscriber matches the capability of the AP, meaning the same number of transmit and receive antennas. Because network operators aim for the highest utilization of their network possible, this is not ideal. A recent development is to use these technologies to allow an access point (AP) to communicate to several subscribers at once.

In traditional systems, each subscriber transmits or receives in sequence. If more than one subscriber were to transmit or receive at the same time, interference would occur between them, drastically limiting network performance. MU-MIMO divides the capacity of the antenna array used for MIMO between multiple subscribers, allowing them to transmit and receive data concurrently. This allows the network operator to both increase and better utilize network capacity.

Spatial Multiplexing The benefits of MU-MIMO rely on highly intelligent AP antenna arrays. The access point allocates resources to different subscribers by electrically tuning the antenna elements to different phases in a technique is known as beamforming, wherein the antennas used to communicate to a particular subscriber are tuned such that their radio beam is targeted (or 'formed') to overlap a specific subscriber.

The goal of beamforming is to allow spatial multiplexing, which refers to making concurrent transmissions possible in the same wireless spectrum by using physically separated radio beams.

Each beam targeted to a specific subscriber,is much narrower than the beam from an AP (in a conventional system, sectors are typically 90 or 120 degrees), enabling multiple beams to be used concurrently without overlapping sufficiently to cause significant interference.

Beamforming can be applied in both the uplink and downlink directions, relative to the AP, and has significant benefit to overall network interference mitigation as well. Because PMP 450 subscribers already use directional (i.e. narrow) antennas to communicate to the AP, this functionality only requires changes at the AP, not the subscribers.

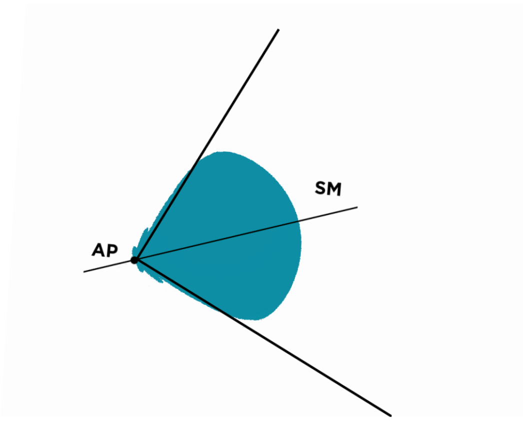

Figure 1 - Antenna Pattern for Sector Mode Operation

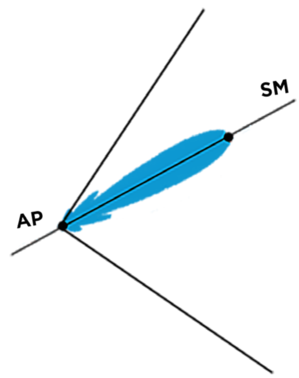

Figure 2 - Beamforming to a single user

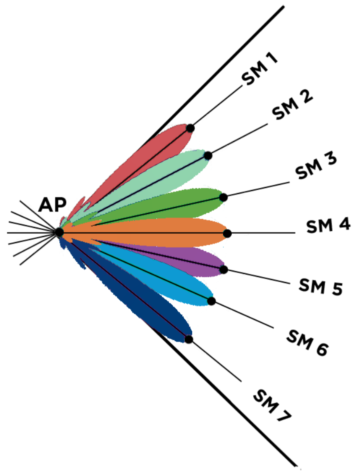

Figure 3 - Beamforming to 7 users simultaneously

Channel Sounding The access point must also be able to determine the state of the radio channel between it and each subscriber, known as channel state information (CSI). A complex channel sounding mechanism between the AP and subscribers, occurring rapidly and continuously, must be used to ensure optimal performance.

The AP estimates a property of the channel associated with each SM called spatial frequency, used by the spatial multiplexing and beamforming algorithms. The spatial frequency is related to the azimuth angle of the subscriber, although the relationship is not unique (one-to-one).

CSI is collected at a basic level when the AP generates a test signal that transmits to a subscriber. The subscriber returns the test signal, and the AP is able to estimate what other transmissions from that subscriber will 'sound like' by measuring the changes to the test signal from its original form. By using this information, the AP is able to distinguish between subscribers.

Putting it all Together Enabled by the combination of MIMO (H+V polarization), spatial multiplexing through beamforming, and highly efficient channel sounding, massive MU-MIMO systems offer powerful solutions to some of today's networking challenges. Cambium Networks cnMedusa technology, first implemented in the PMP 450m solution, is the first commercially available massive MU-MIMO platform.

PMP 450m Overview

PMP 450m with cnMedusa technology is an outdoor point-to-multipoint (PMP) AP with a seven-element adaptive dual-polarity array smart antenna and massive MU-MIMO capabilities. The antenna array is composed of fourteen chains, connected to seven vertical and seven horizontal antennas, covering 90 degrees in the azimuth.

Each PMP 450 SM operates in 2x2 MIMO mode. PMP 450m is capable of communicating with up to 7 subscribers simultaneously and supporting a total of up to 14 streams, making PMP 450m a 14x14 massive MU-MIMO system. All PMP 450 series subscribers (PMP 450, PMP 450i and PMP 450b) are interoperable.

Operating Modes PMP 450m supports multiple communication modes, which will be described in detail in the rest of this document:

- Downlink Sector mode: used when transmitting broadcast data to all subscribers, or unicast data to an SM that did not provide channel state information. Functionally equivalent to the mode used by PMP 450 and PMP 450i APs.
- Downlink Beamforming mode: used when transmitting to one subscriber that provided channel state information.
- Downlink MU-MIMO mode: used when transmitting to multiple subscribers that provided channel state information.
- Uplink Beamforming mode: used when receiving from one subscriber that provided channel state information.
- Uplink MU-MIMO mode: used when receiving from multiple subscribers that provided channel state information.
- Multiple fixed Uplink Beamforming mode: used when receiving in contention (non-scheduled) symbols, and when receiving from a subscriber that did not provide channel state information.

All communication modes are currently supported, except for UL MU-MIMO, which will be available later this year.

Advantages of PMP 450m powered by cnMedusa

Higher sector throughput The most important of several key advantages of PMP 450m versus traditional 2x2-MIMO based APs is the support of MU-MIMO mode, which multiplies the sector throughput.

Using the channel state information each subscriber reports through the sounding mechanism, PMP 450m creates groups of up to 7 subscribers under ideal conditions Subscribers are selected for one of these groups based on their azimuth spacing and amount of traffic, and their channel information is used to create up to seven spatially distinct beams. Each beam points to one SM in the group, and its nulls are aligned with the directions of the other subscribers in the group, limiting interference between subscribers.

Groups are continuously and rapidly re-evaluated and re-created depending on the RF conditions and the traffic demand. Subscribers within a group communicate with the PMP 450m AP simultaneously, then (in the next symbol or in the next frame) the PMP 450m will move to the next group and perform simultaneous communication with those subscribers.

Communicating with multiple subscribers in the same channel concurrently provides much higher sector capacity without requiring more wireless spectrum, dramatically increasing spectral efficiency. Network operators can either support more subscribers per sector in the same spectrum, or offer existing subscribers higher average throughput. The PMP 450m AP supports a sector capacity of more than 600 Mbps in a 20 MHz channel and more than 1.3 Gbps in a 40 MHz channel

Range of sector throughput improvement cnMedusa technology enables PMP 450m to communicate with up to seven subscribers in a group, for an expected throughput improvement of 3-4 times that of PMP 450 or 450i, depending on the specific deployment. Factors that affect the actual sector throughput improvement are:

- The modulation level: the modulation level used for each subscriber in a group may be lower than that used when communicating to one subscriber only. This is due to residual interference between subscribers when forming beams in MU-MIMO mode.
- Only lower priority traffic is grouped. Traffic on the higher priority data channels is transmitted to one subscriber at a time in sector or beamforming mode, because typically the amount of information transmitted at higher priority is small. This gives preference to group users that need a large amount of data, resulting in a group that spans more symbols and uses resources more efficiently.
- Subscribers can be grouped if they are sufficiently spaced in the azimuth. Wider sectors with a large number of subscribers have a higher probability of creating large groups. This translates into a higher probability of transmitting multiple streams, and therefore into a higher sector throughput. The azimuth separation necessary to group users is around 6-7 degrees.
- Subscribers can be grouped if they have traffic to send/receive. Sectors that are very active have a higher probability of finding subscribers that can be grouped. It is common for a sector to have a larger average number of subscribers per group during busy hours and a smaller average number of subscribers per group during non-busy hours.
- Subscribers below peak of beam may be ineligible for MU-MIMO grouping if their channel distortion is too large. These subscribers are very close to the access point and can typically support a high modulation mode in non-MU-MIMO mode. However, when MU-MIMO mode cannot be used, the sector throughput doesn't increase.

The best candidate for using cnMedusa with MU-MIMO mode enabled is a wide sector, with a large number of fairly active subscribers dispersed across the azimuth, and only a moderate amount of high priority traffic. cnMedusa technology has been optimized for simultaneously streaming downlink data to many users, such as video. The spectral efficiency that can be achieved is the highest in any commercially available system, with field data confirming an excess of 40 bps/Hz *per sector* in some cases. Because cnMedusa employs the same frequency reuse benefits as other PMP 450 series APs, this can yield *site* spectral efficiency of over 80 bps/Hz.

Given that spectrum is scarce in many deployments, being able to increase capacity without having to increase the channel bandwidth is a significant advantage for the network operator. That these gains are achieved by only changing the AP hardware is another significant benefit.

Examples of MU-MIMO patterns MU-MIMO patterns are generated frame by frame according to the SMs the PMP 450m AP needs to communicate with.

Figure 4 shows three examples of MU-MIMO composite patterns. The composite pattern is the overlap of the individual beamforming patterns, each with a peak in the direction of one of the SMs in the group, and nulls in the direction of the other SMs. Having nulls in the direction of the other SMs in the group minimizes interference between concurrent transmissions. The overlapping beams are calculated using information on the Spatial Frequency (azimuth) of the SM, and the channel state information of the channel between the AP and each SM.

The overlapping beams are calculated using information on the Spatial Frequency (azimuth) of the SM, and the channel

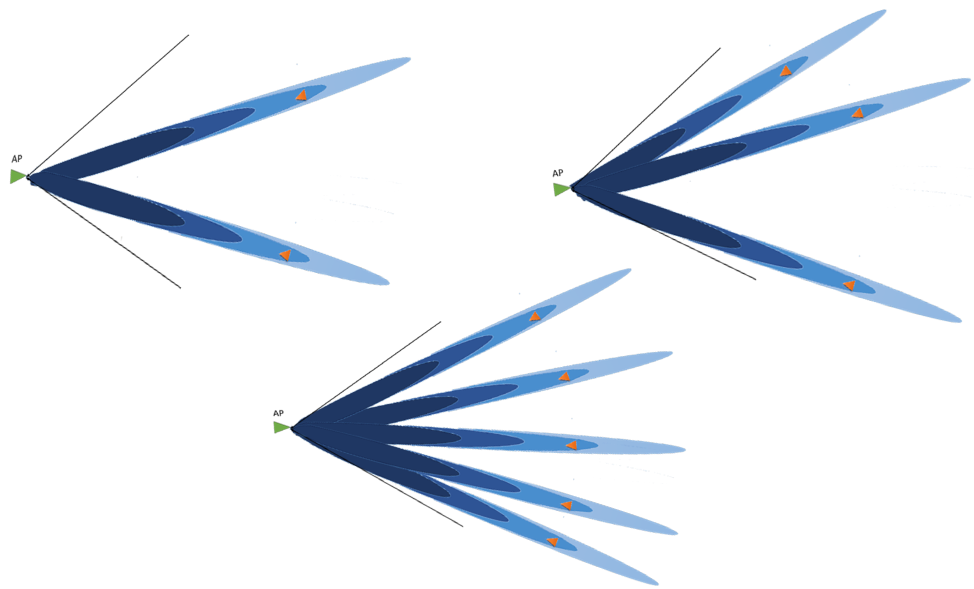

Figure 4. Examples of MU-MIMO patterns

state information of the channel between the AP and each SM.

There are also numerous benefits in using PMP 450m versus PMP 450 or PMP 450i AP, even if MU-MIMO is not enabled.

Beamforming array gain If the MU-MIMO feature is not enabled, PMP 450m communicates to each individual SM in beamforming mode. Using the channel state information provided by the subscriber through the sounding mechanism, PMP 450m forms a narrow beam in the direction of the intended subscriber, limiting interference to nearby sectors.

For the downlink direction In EIRP-limited regions, the transmit power must be decreased as the array gain increases, so that the total EIRP – given by the sum of the transmit power, the array gain, and the antenna gain – does not exceed the regulatory limit. In these regions, with or without array gain (meaning in sector mode or in beamforming mode) the EIRP, and therefore the link budget, is the same as that of the PMP 450 or 450i.

There is one advantage to operating at reduced transmit power, however: when the radio operates in a more linear region far from the saturation point of the power amplifier, it is less subject to distortion and can more easily operate at higher modulation levels.

A software upgrade available later this year will enable EIRP (and correspondingly link budget) to be increased by both the array gain and the antenna gain in non EIRP-limited regions. The results of this are:

- Increasing the range.
- Increasing the average modulation level achieved by the subscribers, which increases the sector throughput in the

downlink direction.

In the uplink direction, the array gain associated with the narrow beam increases the link budget, allowing each subscriber to achieve a higher average modulation level. This translates to better sensitivity and increases the sector throughput in the uplink direction.

Reduced interference The narrow beams created in the downlink and uplink beamforming mode, as well as MU-MIMO mode, not only increase link budget and therefore coverage and throughput, but also reduce the system's interference.

When transmitting in the downlink beamforming mode, interference is only created in the direction of the intended subscribers. Any other device operating on the same frequency in the same area will not suffer from interference due to this transmission unless it is located in the same direction. This significantly reduces the interference generated by the PMP 450m compared to an AP that transmits in all directions in the sector, as in a conventional system.

In the uplink direction, when receiving in beamforming mode, PMP 450m is only receiving (or 'listening') in a narrow beam directed toward the intended subscriber. Any transmissions outside this beam are not received and cannot interfere with the desired signal. Keeping the interference level low using these techniques means that on average the subscribers can achieve higher modulation levels, which increases the uplink sector capacity and overall system efficiency.

Figure 5 shows an example of increased uplink throughput and reduced uplink interference using beamforming mode.

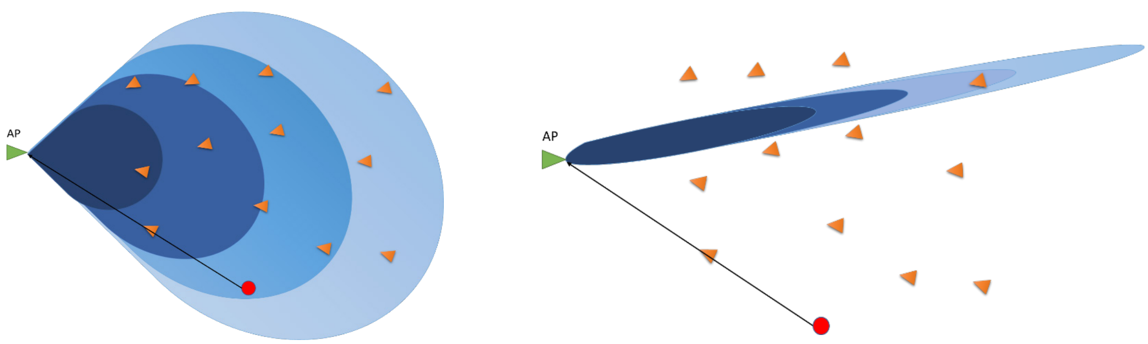

Figure 5. Examples of Uplink throughput and interference rejection improvement

The figure to the left shows a typical sector deployment, in which the AP receives transmissions from one SM at a time. The modulation each SM uses for transmission depends on the SM's distance to the AP. The four shades of blue show areas where SMs operate at progressively reduced modulation: 256-QAM, 64-QAM, 16-QAM and QPSK. The three SMs in the light blue ring operate at the lowest modulation (QPSK).

The figure to the right shows the same deployment, but with the AP operating in uplink beamforming mode. The signal is now directed only in the direction of the intended subscriber. As the array gain of the antenna increases the link budget, the areas covered by higher modulation operation are extended. The SM at the edge of the coverage area, which was originally operating at QPSK modulation, can now operate at 16-QAM modulation, doubling its throughput. The overall sector capacity is also improved when one SM's link improves, as SMs are served faster, and resources can be allocated to other SMs.

In addition to the benefit of link budget improvement, and therefore increased throughput, the interference rejection capability of the AP also improves with uplink beamforming. Because APs are typically installed in high locations, with visibility of a large area and possibly a large number of interfering devices, they are more susceptible to interference.

In the figure to the left, an interfering signal in the coverage area (red device) may corrupt the received signal coming from any of the SMs in the coverage area. This results in the SM having to operate at a lower modulation, therefore achieving a lower throughput.

In the figure to the right, only the signal coming from the direction of the transmitting SM is received at the AP. Any interfering signal outside the narrow beam is rejected, and therefore does not affect reception of the signal. In this case, the modulation at which the SM operates is not degraded, enabling higher throughput and overall sector capacity.

Additional antenna technology advantages The PMP 450m AP is integrated with a sophisticated antenna array, which in addition to supporting beamforming, beam steering, and MU-MIMO functionalities, has additional features that improve coverage and performance.

The integrated antenna has a built-in 2-degree electrical down-tilt. Down-tilting the sector antenna is a common practice because typically the AP is installed at higher elevation than the SMs. By down-tilting the antenna, more SMs are closer to the peak of beam, which decreases interference to neighbouring sectors using the same frequency.

Any antenna can be mechanically down-tilted, but electrical down-tilt provides more control and better performance. The difference is that with mechanical down-tilt the tilting angle is higher at boresight, but lower at the edge of the sector (at +/- 45 degrees for a 90-degree sector). This means that the positive effect of down-tilting peaks in front of the antenna but decreases on the sides. On the other hand, electrical down-tilting allows the tilt to be uniform across the sector, and therefore achieves better performance over the whole sector beam-width.

Additionally, the PMP 450m antenna uses null-filling to improve performance for SMs located closer to the AP. A typical sector antenna that does not provide null-fill may have a pattern with deep nulls at close range. If SMs located close to the AP fall into a null, the received signal strength is greatly attenuated, causing the device to switch to a lower modulation level, or drop the link if the attenuation is too high. This is not a general concern in mobile applications because the mobile device can move around, so as soon as it leaves the location of the null, the signal strength is significantly higher. However, the subscriber is always in the same location in a fixed deployment; if the location happens to coincide with a null, the reception would always be poor. This is why it is important for sector antennas in fixed deployment to have good null-fill properties, like the PMP 450m AP antenna.

Both of these antenna features benefit not only the single subscriber, which can receive a stronger signal and therefore on average operate at a higher rate, but also all the other subscribers in the sector. Every device that can transfer data faster gets off the channel faster, leaving resources available for other devices. The whole sector capacity is therefore improved by increasing performance in specific directions.

Packet Per Second (PPS) processing capability PMP 450m is an advanced platform with powerful processing capabilities. This reflects directly on the PPS, which measures the number of packets the device can process in a second. High PPS values allow an AP to sustain a very high sector throughput, even when processing a large number of small packets such as those found in voice over IP (VoIP) and gaming applications. Correspondingly, smaller PPS values limits sector throughput when a large number of small packets must be processed, because the AP would not be able to process them fast enough.

The PMP 450 AP has a PPS processing capability of about 12k packets. The PMP 450i AP improved on that, with a capability of about 45k packets. Currently, the PMP 450m has a PPS processing capability of over 120k, with potential software improvements that can push that number higher.

Regardless of the communication mode (sector, beamforming or MU-MIMO), PMP 450m can sustain much higher throughput when traffic is composed of a large number of small packets.

PMP 450m Limited The PMP 450m is available in two versions – the full version with all the capabilities of cnMedusa, or a Limited version that restricts operation of MU-MIMO. The simple application of a software license key can enable MU-MIMO operation at any time., allowing network operators to deploy the PMP 450m hardware at a lower cost when needed, then update to MU-MIMO operation at a later time. What are the advantages of purchasing a PMP 450m AP without the MU-MIMO feature enabled?

PMP 450m is designed for sectors with very high capacity. However, some sectors may start with a small number of users, with the potential of growth over time, so if there is no need for very high capacity at deployment, the PMP 450m can be installed without the MU-MIMO feature enabled. As the sector grows in subscriber density, the MU-MIMO feature can be enabled, allowing the AP to support a much higher throughput without having to change the hardware. This is a future-proof investment for sectors that are expected to grow, and especially useful if the AP deployment location is difficult or expensive to access.

Another benefit of the PMP 450m is in the interference reduction due to receive beamforming, as described earlier – functionality inherent in the cnMedusa technology that is also available in the Limited version.

PMP 450m Limited is ideal for smaller sectors that will benefit from high performance MU-MIMO functionality when their sector has scaled to an appropriate size, while offering a lower entry point cost than the full PMP 450m AP.

Summary

PMP 450m is an AP powered by cnMedusa technology that allows network operators to vastly increase sector capacity – without requiring more wireless spectrum, and while protecting existing investments in PMP 450 subscribers.

MU-MIMO mode provides a large boost in sector capacity by incorporating highly advanced signal processing, antenna array control, and channel sounding techniques – all of which are aspects of innovative radio design in their own right. Even if the operator does not operate PMP 450m in MU-MIMO mode, the 450m's bi-directional beamforming and higher packet processing capability provide a considerable performance benefit over alternative equipment.

PMP 450m represents a significant technical leap over proposed commercial fixed wireless access systems, allowing network operators to future-proof their networks with confidence.

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