Cost/Revenue Performance in an IMT-Advanced Scenario with Spectrum Aggregation over Non-Contiguous Frequency Bands

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Abstract—**This paper determines the cost/revenue performance of a mobile communication system in an IMT-Advanced scenario with integrated Common Radio Resource Management (iCRRM). The iCRRM performs classic CRRM functionalities jointly with Spectrum Aggregation (SA), being able to switch users between non-contiguous frequency bands. The SA scheduling is obtained with an optimized General Multi-Band Scheduling (GMBS) algorithm with the aim of cell throughput maximization. In particular, we investigate the dependence of the throughput on the cell coverage distance for the allocation of users over the 2 and 5 GHz bands for a single operator scenario under a constant average Signal to Interference-plus-Noise Ratio (SINR), for the same type of Radio Access Technology and both frequency bands. The operator has the availability of a non-shared 2 GHz band and has access to part (or all) of a shared frequency band at 5 GHz. An almost constant gain near 30% was obtained with the proposed optimal solution compared to a system where users are first allocated in one of the two bands and later not able to handover between the bands. It is shown that the profit in percentage terms decreases as the cell radius increases. These results allow for evaluating the impact of the revenue from the channel in the total revenue and in the profit, defined as the difference between revenues and costs, in percentage. Maximum profits of about 1270, 585 and 240% have been obtained for prices of 0.10, 0.05 and 0.025 €/Mbyte, respectively, when iCRRM is employed, while profits of 990, 440, and 170% have been reached with no iCRRM, i.e., simple CRRM. Finally, an energy efficiency strategy is proposed and analyzed, showing that there is significant transmission power saving potential through the opportunistic reallocation scheme.**

Keywords-component; cost/revenue; spectrum management; energy efficiency, IMT-Advanced scenario.

I. INTRODUCTION

Dynamic spectrum access has thus far primarily been investigated in the context of different spectrum owners accessing each other's spectrum, or in other primary/secondary access paradigms such as "cognitive radio". However, given different spectrum bands being owned by the same entity but being designated for different usage purposes, the dynamic sharing of the spectrum among those purposes is also of considerable research interest.

Radio Resource Management (RRM) plays an important role in wireless system design, due to the scheduling algorithm which decides among packets that are ready for transmission, allowing certain quality of service (QoS) levels be achieved. Common RRM (CRRM) refers to the set of functions that are devoted to ensure an efficient and coordinated use of the available radio resources in heterogeneous networks scenarios.

Affordable high-bandwidth mobile access improves the quality of experience (QoE) for users, enabling them to get more out of existing services and opens up opportunities for new mobile broadband services. Supporting additional system capacity and higher data rates will improve the value of these services. Spectrum aggregation (SA) appears as a solution for the highly fragmented radio frequency spectrum. Therefore, mobile operators might apply SA of two or more separated sub-bands for downlink (DL) and uplink (UL) bands in order to determine the best user allocation for a single operator over two (or more) International Mobile Telecommunications – Advanced (IMT-Advanced) frequency bands in order to maximize the total network throughput.

This paper investigates spectrum aggregation of 2 and 5 GHz bands in an IMT-Advanced scenario, showing considerable throughput increase potential. The innovation from this work consists of considering the cost-benefit trade-off for such systems and deployment scenarios.

The remaining of the paper is organized as follows. Section II addresses aspects of throughput enhancement through SA employing multi-band scheduling, explaining the approach, developed technique and results. Section III describes the cost/revenue model and the resulting optimization results. Section IV presents the energy aspects with two important concepts in terms of power-saving. Finally, Section V presents the main conclusion of the economic trade-off study for SA in such IMT-Advanced scenario.

II. THROUGHPUT IMPROVEMENT THROUGH SPECTRUM AGGREGATION WITH A MULTI-BAND SCHEDULER

Supporting additional system capacity and higher data rates through high speed Radio Access Technologies (RAT), such as the IMT-Advanced, users can be granted universally accessible broadband services. One important enabling factor is the availability of bandwidth, which is also related to the assignment of frequency spectrum bands for IMT-Advanced and beyond technologies. This is impeded by the existing highly fragmented radio frequency spectrum that does not match the actual demand for transmission and network resources. Such fragmentation poses a challenge during dynamic spectrum use where multiple frequency bands can be assigned in support of the users and the mobile transmission system's ability to support a wide range of services across all elements of the network (i.e. core, distribution and access).

The idea of this Multiband Scheduler [2] is to explore the integration of spectrum and network resource management functionalities to the benefit of achieving higher performance and capacity gains in an IMT-Advanced scenario. In particular, we investigate the allocation of users over two frequency bands (i.e., 2 and 5 GHz) for a single operator scenario. High speed Packet Access (HSPA) was considered for the RAT for both frequency bands. It is assumed that the operator has gained access to a non-shared 2 GHz band and to part (or all) of the frequency pool band at 5 GHz, as shown in Fig. 1.

A. Approach

The fragmented available spectrum can be virtually joined through the SA technique suggested by IMT-Advanced and Long Term Evolution-Advanced (LTE-A), [3] and [4]. Information about how to aggregate contiguous and not contiguous parts of the highly fragmented spectrum to be used and how to allocate users over the dedicated and shared bands of an operator, can improve the overall system capacity.

SA can be performed in the same or in different bands and may occur when the operator's dedicated DL or UL band is not contiguous but is split into two or more parts. Enablers of SA are the advances in the area of smart antenna design, spread-spectrum technologies, software-defined radio (SDR), cooperative communications, and cognitive radio (CR) systems. Cognitive capabilities, such as sensing, access to database (in connection with geolocation), use of cognitive pilot channel (CPC), transmission power control, etc. can form a CR system capability toolbox and could facilitate coexistence/sharing in bands, where it was previously determined to be not feasible.

B. General Multiband Scheduling

A CRRM entity with spectrum management functionalities, supported by General Multi-Band Scheduling (GMBS) was proposed in [2]. By having information about how to aggregate contiguous and not contiguous parts of the spectrum to be used and how to optimally allocate users over the dedicated and shared bands, an operator can improve the overall system capacity. The optimization is based on signal quality that a mobile station (MS) is suffering and based on past frame receptions quality.

Depending on the capabilities at the MSs, each user may be allocated to a single frequency band or to both the frequency bands. In the latter case, the MSs have multi-radio transceivers and can transmit and receive data on both bands. Here, the focus is only on single-band MSs that need to be allocated over one of the two possible bands. Spectrum sharing mechanisms are beyond the scope of this work.

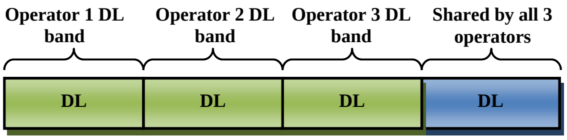

Fig. 1. Scenario of common frequency pool.

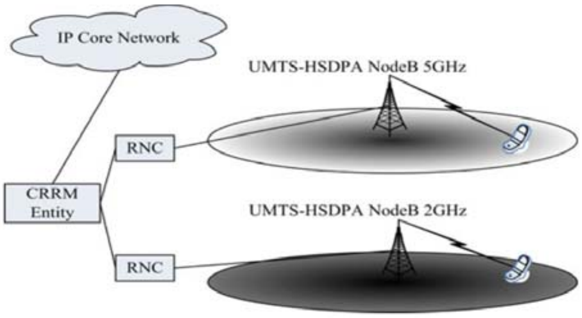

Fig. 2 CRRM in the context of SA with two separated frequency bands.

C. Results

Following the approach from [2], the performance of the algorithm is assessed by using the service throughput, i.e., the total number of bits that have been transmitted and correctly received by all users in the cell. Users are deployed in the cell with a uniform distribution within a distance of 900 m with overlapping 2 and 5 GHz coverage, as shown in Fig. 2.

The NRTV session generation is modeled by a Poisson distribution, and session duration is exponentially distributed with an average of 180 s.

The curves in Fig. 3 enable the comparison of the results between the presence and absence of GMBS. The enhancement provided by the GMBS algorithm is clear for overloaded systems (around 55-56 users). Without GMBS, the system reaches its full capacity around 2.47 Mbps. With GMBS, it reaches the maximum capacity around 3.15 Mbps. A gain up to about 650 kbps may thus be obtained, i.e., 28 % gain. The gain is achieved by dynamically allocating resources (2 or 5 GHz bands channels) to the MS that best suits the system. The achieved improvement is relative to a scenario where users are randomly deployed on the cell.

D. Summary

This work has proposed a resource allocation mechanism for users over two frequency bands accessed by a single operator. The proposal is valuable in the scope of currently on-going work within ITU-R towards IMT-Advanced, and in particular the use of SA. It assumes that SA can be successfully combined with RRM techniques to optimized performance. The GMBS performance was assessed in terms of the total throughput. A gain up to 28 % was obtained with the proposed optimal solution. Future work will include the QoS requirements into the GMBS formulation via a linear combination of multiple objectives ("scalarization"). The combined solution for the packet scheduler and the spectrum scheduler is foreseen to be able to greatly reduce delay and jitters, which are of paramount importance for real time services.

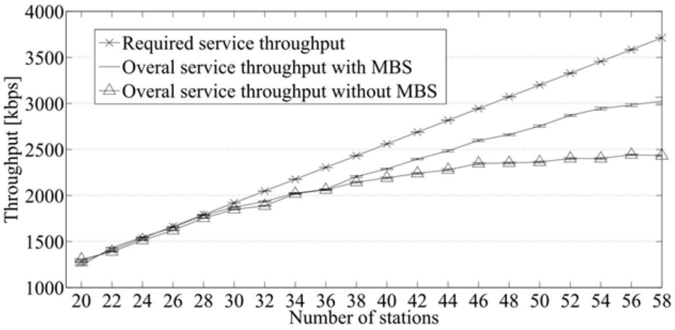

Figure 3 Service throughput with and without GMBS.

III. COST/ REVENUE OPTIMIZATION

The economics of cellular systems can be viewed from the points of view of the different entities: subscribers, network operators, service providers, the regulator, and equipment vendors [5]. In this research, we consider operator's/service provider's point of view, whose main goal is obtain the maximum profit from his business, i.e., to increase revenue, decreasing costs as much as possible.

Although project duration of five years is assumed, it is decided in this paper to analyse costs and revenues on an annual basis. Furthermore, our analysis is under the assumption of a null discount rate. By no means is it intended to perform a complete economic study in this paper, the aim is simply to present initial contributions that facilitate cellular planning optimisation. Appropriate refinements would be needed to perform a complete economic analysis based on discounted cash flows (e.g., to compute the net present value).

From a cellular planning and radio resource management perspective, the objective of the operator is to determine an optimal operating point that maximizes the expected revenue. Examples of major decisions affecting this include the type of technology to be used, the size of the cell, and the number of radio resources in use in each cell. It is therefore important to identify the main components of system's costs and revenues, in particular those that bear a direct relationship to either the maximum cell coverage distance or the reuse pattern.

As it is explained in [5], the cost per unit area is given by:

$$C_{[/km^2]} = C_{fi[€/km^2]} + C_b N_{[cell/km^2]} \qquad (1)$$

where C_{fi} is the fixed term of the costs (e.g. licensing and spectrum auctions or fees), and C_b is the cost per base station (BS) assuming that only one transceiver is used per cell/sector, which corresponds to the installation costs of BSs including the cost of obtaining cell sites, the normal backhaul, and the cost of hardware and core equipment common to all.

The number of cells per unit area is given by:

$$N_{[cell/km^2]} = \frac{2}{3\sqrt{3}R^2} \qquad (2)$$

and the cost per BS is given by:

$$C_b = \frac{C_{BS}+C_{bh}+C_{Inst}}{N_{year}} + C_{M\&O} \qquad (3)$$

where N_{year} is the project's lifetime, C_{BS} is the cost of the BS, C_{bh} is the cost for the normal backhaul, C_{Inst} is the cost of the installation of the BS, and $C_{M\&O}$ is the cost of operation and maintenance.

Assuming the following values for an IMT-Advanced system in Portugal, where C_{BS} is the resulting of summing 20000 € for both 2 GHz and 5 GHz frequency bands, and also considering C_{BSsite} = 7000 €, which is considered in the BS cost, $C_{bh} = 5000$ €, C_{Inst} = 2500 € for the radio installation, plus 20000 € for the total infrastructure (site acquisition, site design and site construction), and $C_{M\&O}$= 1500 € per year of operation, considering preventive and corrective infra maintenance, first-line maintenance and rental costs.

Assuming a period of time assumed here to be $N_{year} = 5$, and $C_{BS} = C_{BS2GHz} + C_{BS5GHz} - C_{BSsite} = 33000$, we replace these values in (3), and obtain $C_b = 13600$ € per BS; which is further considered in (2).

Regarding C_{fi}, if there is channel of 5 MHz available within each cell, assuming that the annual cost of a license, for 3x5MHz, is 100 000 000 € at 2 GHz, and considering a null cost for the 5 GHz band, both bands paired, for K = 1, and considering a total area of 91391.5 km^2 as the area of Portugal, the fixed cost per unit area is:

$$C_{fi2GHz[€/km^2]} = \frac{100000000}{91391.5 \text{ x } 5} = 218{,}8 \approx 220 \text{ €/km}^2$$

$$C_{fi5GHz[€/km^2]} = 0 \text{ €/km}^2$$

A recap of the costs is shown in Table I. The revenue per cell per year, $(R_v)_{cell}$, can be obtained as a function of the supported throughput per BS, $R_{b-\sup[kbps]}$, and the revenue of a channel with a data rate $R_{b[kbps]}$, $R_{R_b[€/min]}$, is given by:

$$(R_v)_{cell[€]} = \frac{N_{sec} R_{b-\sup[kbps]} * T_{bh} * R_{R_b[€/min]}}{R_{b-ch[kbps]}} \qquad (4)$$

where N_{sec} is the number of sectors, which in our case, using an omnidirectional antenna, is 1, T_{bh} is the equivalente duration of busy hours per day (6 busy hours per day, 240 busy days per year, per minute), and $R_{b-ch[kbps]}$ is the bit rate of the basic "channel".

As in [5], we assume that project duration is of 5 years and there is a null discount rate; costs and revenues are taken on an annual basis. We also consider and a revenue/price of a 144 kbps "channel" per minute (approximately corresponding to the price of 1 MByte, as 144 × 60 = 8640 kb ≈ 1 MByte), R_{144}[€/min]. The revenue per cell can be obtained as:

$$(R_v)_{cell[€]} = \frac{1 * R_{b-\sup[kbps]} * 60 * 6 * 240 * R_{144[€/min]}}{144_{[kbps]}} \qquad (5)$$

The (absolute) profit is given by:

$$P_{[€/km^2]} = R_v + C \qquad (6)$$

from which, the profit in percentage terms is given by:

$$P_{[\%]} = \frac{R_v - C}{C} \times 100 \qquad (7)$$

In order to obtain profit optimization, revenues should be maximized with respect to cost. The revenue curves from Fig. 4 were obtained for different values of $R_{144[\,€/min]}$, i.e. 0.025, 0.05 and 0.10 €/MByte (which corresponds to the assumptions for the price per MByte in Table VI of [7]).). Figure 4 shows, as it was envisaged, that increasing the price per MByte, increases the revenue. The total cost is fixed and lower than the revenues for every radius; however, cost and revenues decrease significantly for $R > 600$m.

Figure 5 shows the results for the profit, in percentage, as a function of R for different values of price/MByte with/without iCRRM. It is evident that profit increases as the price increases; nevertheless, the curves keep the same shape and behaviour; that is, slightly decreasing as the radius increases. Maximum profits of about 1270, 585 and 240% for 0.10, 0.05 and 0.025 €/MByte, respectively, were obtained when iCRRM was employed, whilst 990, 440, and 170% were reached without iCRRM. It is important to note that the profits obtained were high because of the relatively high values of $R_{144[\,€/min]}$. When prices lower than 0.01€ were considered, the profits were even negative; thus, the significance of analysing the trade-off between price and profit.

TABLE I COSTS ASSUMPTIONS FOR ONMINIRECTIONAL BS ANTENNA ($K = 1$).

Costs	Omnidirectional $K = 3$
$C_{fi800MHz[\,€/km^2]}$ $C_{fi2GHz[\,€/km^2]}$	≈ 220 $= 0$
$C_{BS}\,[€]$	33000
$C_{Inst}[€]$	22500
$C_{bh}[€]$	5000
$C_{M\&O}[\,€/year]$	1500

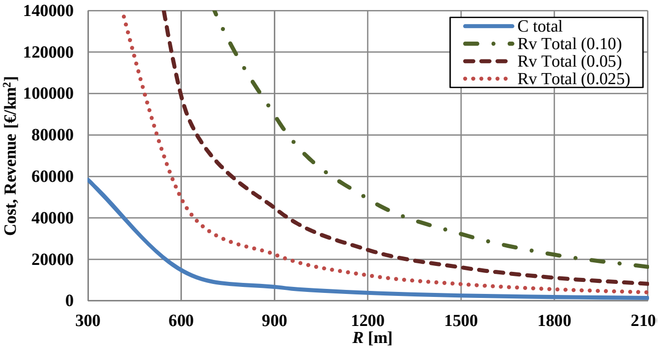

Fig. 4 Total cost and revenue versus R with different $R_{R_b[\,€/min]}$ with iCRRM

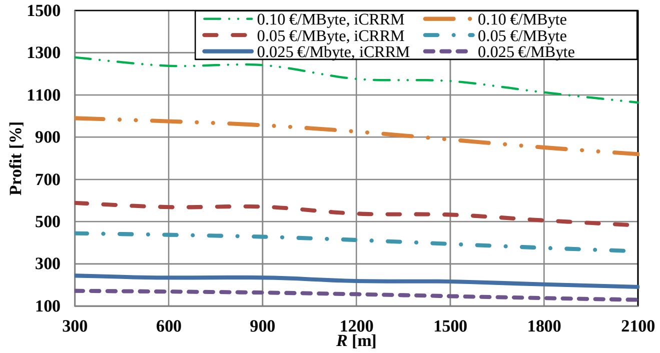

Fig. 5 Profit in percentage terms versus R with different $R_{R_b[\,€/min]}$ with and without iCRRM.

IV. ENERGY EFFICIENCY THROUGH OPPORTUNISTIC LOAD AND SPECTRUM MANAGEMENT

Nowadays, there is an increasing concern in sustaining the planet by significantly reducing the energy consumption. In wireless communication systems, power consumption usually reaches high levels, mainly in the BSs. Therefore, reducing transmission power and/or enabling sleep modes in the BS allow lowering operation power consumptions, as it is presented in [6].

A. Power- saving spectrum management concepts

1) Power Saving by Dynamically Powering Down Radio Equipment

The first concept, illustrated in Fig. 6(a), is the switching off of radio equipment through reallocating load to other bands at times of low load. This is extremely promising as it implies a guaranteed power saving through radio equipment being virtually “switched off at the socket”.

There are two possibilities: (i) turning off cells entirely in one network or spectrum band at that time/location, through traffic being sufficiently carried by a single network or spectrum band; (ii) using spare capacity of one network/band to cover the required drop in load of another network/band in order to enable that other network/band operate in omnidirectional instead of tri-sectored mode. The power saving assessments of this proposal reallocates users between bands whenever possible to achieve one or both of these objectives.

2) Power Saving by Propagation Improvement

The concept, illustrated in Fig. 6(b), is the opportunistic reallocation of links or users to more appropriate propagation bands at times when that spectrum becomes available. This decreases necessary transmission power due to improved propagation, or alternatively in a frequency reuse scenario, reallocation based on the necessary deployed cell density/radius and the given local propagation environment can be used to reduce inter-cell interference through minimizing power “leaking” into co-channel cells. Both power saving concepts might be employed together, yielding further improvement in power efficiency.

To simulate this second approach in the context of IMT-A, it is assumed that a separate ON/OFF traffic flow to each user, either parameterized as FTP traffic or HTTP (web browsing) traffic, whereby the number of users receiving flows varies throughout the 24 hour period according to the average load at that time of day (Fig. 3 in [6]). The chosen FTP and HTTP ON/OFF model parameterizations are widely used in literature, taken from [2]. In this second approach, a separate simulation is performed for each hour in the 24 hour period for a given number of users being present (obtained in Fig. 3 from [6], scaled by the *BusyLoad*), where, at each second in the simulation duration, the simulation tallies the number of users present in each band according to the ON/OFF model being applied to each user. It then performs the power saving solution according to this number of users being present, and ascertains the power required in the before and after power saving solution cases. Results are then averaged over results achieved at each second in the simulation duration, where all such simulations are typically performed over tens of millions of seconds.

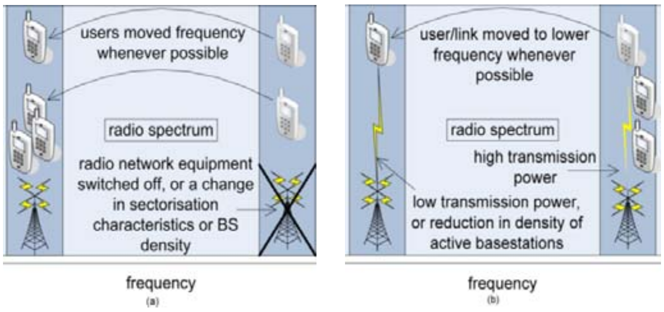

Fig. 6 Power saving concepts: Reallocating (a) traffic to enable radio network equipment to be switched off, or (b) users/links to improve propagation.

Finally, results are averaged over all simulations performed at each hour in the 24 hour period. Configuration parameters applicable to the simulation are given in Table 1 from [6].

In assessing the power saving of reallocating users/links to improve propagation, our option has been to study HSDPA. This is because an HSDPA BS was the most modern specification BS for which detailed data was available on from-the-socket power consumption against transmission power. Internal documentation indicates power consumption for an HSDPA BS at 100% transmission power to be 857W, and at 20% transmission power to be 561 W. It is widely observed that from-the-socket power consumption against transmission power broadly varies with an $m \cdot p + c$ relationship, comprising a fixed term c that is independent of transmission power p, and a term that varies with transmission power, $m \cdot p$. The above figures regress to give 487 W, as the fixed part from-the-socket power consumption c, and the gradient of variation with transmission power m as 9.25 Watts per transmission Watt.

To analyze the necessary transmission power, we consider values in Table 3 from reference [2], with 80% of the power budget scaled by the number of users present in the system and 20% allocated to pilot transmission. The comparison in [2] is between full HSDPA networks operating at 2 GHz, and at 5 GHz. A 600m cell radius is chosen, where again we assume the FTP ON/OFF traffic model. Figure 7 shows that there is significant transmission power saving potential through the opportunistic reallocation scheme. Power saving initially increases to some 58% as the busy hour load is increased to 30; this is because it is always possible to reallocate users to power down radio equipment. However, as the traffic load is increased further power saving decreases.

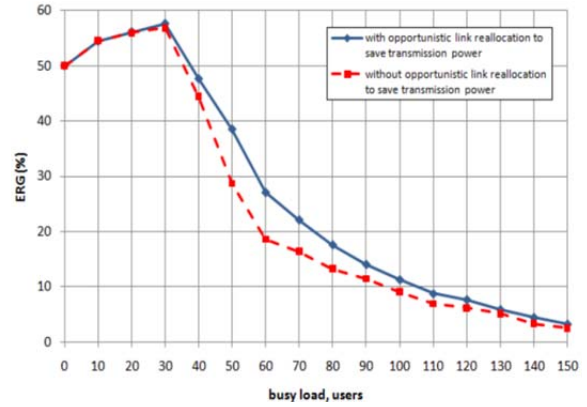

Fig. 7 Power saving against busy hour load through opportunistic link reallocation to use better propagation bands (FTP ON/OFF traffic).

A difference begins to emerge in performance for the solutions with and without opportunistic reallocation to save transmission power.

V. CONCLUSIONS

This work evaluates the cost/revenue performance of a mobile communication IMT-Advanced system, which comprises an iCRRM entity, as presented in [2], whose General Multi-band Scheduling allows for switching users between non-contiguous 2 and 5 GHz frequency bands. With the proposed optimal solution, a gain up to 28 % has been obtained in the throughput. The results for throughput are considered as an input to the cost/revenue optimization analysis and allow for evaluating the impact of the revenue from the channel in the total revenue; hence in the profit (the difference between revenues and costs, in percentage). It is shown that the profit in percentage terms decreases as the cell radius increases. Maximum profit of about 1270, 585 and 240% for 0.10, 0.05 and 0.025 €/Mbyte has been obtained, respectively, when iCRRM is employed, while profits of 990, 440, and 170% have been reached with simple CRRM. These values directly depend on the price of the basic channel. Finally, an energy efficiency strategy is proposed and analyzed; showing that there is significant transmission power saving potential through the opportunistic reallocation scheme; nonetheless, as the traffic load is increased further power saving decreases.

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