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# Performance Analysis of Downlink Inter-band Carrier Aggregation in LTE-Advanced

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**Abstract**— Carrier aggregation (CA) is one of the most distinct features for LTE-Advanced systems, which can support a much wider transmission bandwidth up to 100 MHz by aggregating two or more individual component carriers (CCs) belonging to the same (intra-band) or different (inter-band) frequency bands. With CA, it is possible to schedule a user equipment (UE) on multiple CCs simultaneously. From radio resource management (RRM) perspective, CC selection plays an important role in optimizing the system performance, especially in the case of inter-band CA where the radio propagation characteristics of each CC can be different. In this paper, we investigate the downlink resource allocation for inter-band CA, i.e., how to assign carrier(s) to different UEs. A simple yet effective G-factor based carrier selection algorithm, which takes both traffic load and radio channel characteristics into considerations, is proposed with the objective to guarantee good coverage for Rel'8 UEs and robustness for Rel'10 UEs. Simulation results show that our proposed G-factor based carrier selection algorithm can achieve much better coverage performance compared to the least-load carrier selection in scenarios with relatively high inter-site distance and relatively high frequency separation between carriers, at the expense of some marginal average user throughput loss.

## I. INTRODUCTION

UMTS Long Term Evolution (LTE) Release 8 is one of the primary broadband technologies based on OFDM, which is currently being commercialized. LTE Release 8 can provide peak data rates up to 300 Mbps in downlink and 75 Mbps in uplink for a 20 MHz bandwidth. Studies of further enhancements have been carried out to provide substantial improvements to LTE Release 8, allowing it to meet or exceed International Mobile Telecommunications-Advanced (IMT-A) requirements, which targets to achieve peak data rates up to 1 Gbps in downlink and 500 Mbps in uplink respectively [1]. These enhancements have been considered in 3GPP as part of LTE-Advanced (also known as LTE-A or LTE Release 10) specifications.

Carrier aggregation (CA) is one of the key features in LTE-A. This feature allows for scalable bandwidth expansion through aggregation of multiple component carriers (CCs). These carriers can be configured with different bandwidths, and can be in the same (contiguous) or different (non-contiguous) frequency bands to provide maximum flexibility in utilizing the scarce radio resources to operators, while maintaining backward compatibility to legacy LTE Release 8 users. With carrier aggregation, users can access a much wider transmission bandwidth up to 100 MHz [1] compared

with LTE Release 8 standard.

Carrier aggregation enables a user to be scheduled on multiple CCs simultaneously, each of which may exhibit different radio channel characteristics. This introduces some new challenging issues related to modifications and design of new functionalities in radio resource management (RRM) framework for LTE-A systems, thus is an area of research interests. The different load balancing schemes and performance analysis of CA in uplink (UL) and downlink (DL) are investigated in [2]-[4], respectively. To the authors' knowledge, most of the work on CA are concentrated in the scenario that the CCs are configured in the same frequency band and the radio propagation characteristics of each CC is more or less the same. However, from the operator's perspective, there also exists other scenarios that the operators might have to aggregate two or more separated carriers belonging to different frequency bands, according to the existing spectrum allocation policies and the fact that the allocated spectrum is highly fragmented [5]. With inter-band CA, the radio channel characteristics of each carrier can be relatively different. Therefore, the allocation of carrier(s) to a user equipment (UE) should not only take the Quality-of-Service (QoS) requirements, UE capability, cell load, but also the radio channel characteristics into considerations. In this paper, the focus is on how to assign CC(s) to different UEs with the objective to achieve better performance in terms of coverage and robustness compared to the least-load carrier selection for LTE-A systems.

The rest of the paper is organized as follows. Section II provides an overview of different types of CA, with the main focus on the considerations in carrier selection for inter-band non-contiguous CA. Section III outlines the simulation methodology and main parameter settings. Simulation results and performance analysis are presented in Section IV. Finally, some conclusions are drawn in Section V.

## II. CARRIER AGGREGATION AND CARRIER SELECTION

Since LTE-A systems should be backward compatible to legacy Rel'8 users, support for wider transmission bandwidth in LTE-A is provided via aggregation of multiple CCs. Legacy Rel'8 users see each CC as an LTE carrier and can only transmit and receive over one of the CCs, while LTE-A users have the capability to transmit and receive on several CCs simultaneously. As shown in Fig. 1, three types of CA techniques have been proposed for LTE-A systems [7]:

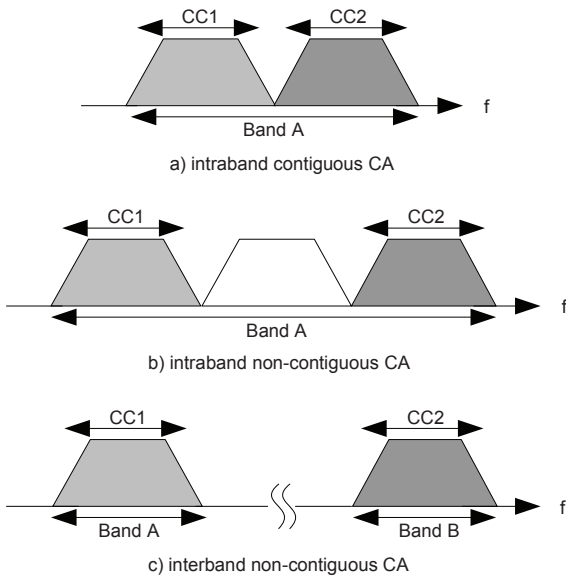


Fig. 1. Three types of CA for LTE-A

- Intra-band Contiguous CA: when multiple CCs are adjacent to each other within the same band
- Intra-band Non-Contiguous CA: when multiple CCs within the same band are used in a non-contiguous manner
- Inter-band Non-Contiguous CA: when multiple CCs are separated along the frequency band

Considering the UE complexity, cost, and power consumption for supporting simultaneous transmission over multiple CCs, it is easier to implement contiguous CA without making many changes to the RF design of LTE systems. In 3GPP standardization, specifications for both uplink and downlink intra-band contiguous CA have been completed. Downlink inter-band non-contiguous CA is current under discussion. In this study, we concentrate our effort on downlink inter-band non-contiguous CA.

With CA being defined in Release 10, system bandwidth of up to 100 MHz can be supported, subject to spectrum availability and UE's capability. In practice, spectrum allocation for an operator is often dispersed along the frequency bands with large frequency separation. According to the current spectrum allocation policies and the fact that the spectrum availability in low frequency band ( $< 4$  GHz) is scarce [5], it is difficult to support large transmission bandwidth with contiguous CA for an operator. Therefore, inter-band non-contiguous CA provides a practical approach for the operators to fully utilize the current spectrum resources including the frequency bands already allocated for some legacy systems such as GSM and UMTS systems, and the unused scattered frequency bands. An example of 40 MHz transmission bandwidth for DL with inter-band non-contiguous CA is aggregating either 20 MHz (800MHz) + 20 MHz (2.1GHz) or 20 MHz (1.8GHz) + 20 MHz (2.6GHz) component carriers. But for non-contiguous CA, it may require

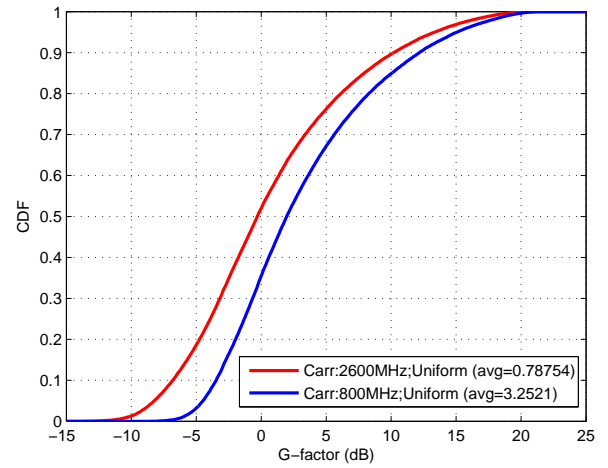


Fig. 2. G-factor distribution at different frequency carriers with macro scenario in real sub-urban environment [6]

additional complexity in the radio frequency front-end of LTE-A terminals, e.g., multiple RF receiving units.

With non-contiguous CA, data transmission occurs over multiple separated carriers across a large frequency range. As a result, the radio channel characteristics, such as propagation path loss and geometry (G-) factor, may be different at different frequency bands. The G-factor is generally defined as the expected value of the ratio between received signal power to all other cell interference in downlink. In the design of CC selection algorithms, the radio channel characteristics should be carefully investigated and considered. Since the user experienced throughput is mainly determined by the received signal to interference plus noise ratio (SINR), which has a close correlation with G-factor distribution, the study of G-factor distribution at different frequency bands is of great interest. Fig. 2 shows the G-factor distribution at different frequency carriers with macro scenario from a real measured sub-urban environment. It is shown that 800MHz frequency carrier exhibits better G-factor distribution than 2.6GHz frequency carrier, especially at cell edge (approximately 4 dB difference in G-factor at 5-percentile CDF curve). Generally speaking, the G-factor distribution is different at different frequency carriers, and the difference mainly depends on the inter-site distance (ISD) between cells and the frequency separation between carriers. Specifically, increase the inter-site distance or increase the frequency separation will increase the difference in G-factor, and lower-frequency carrier exhibits better G-factor distribution than higher-frequency carrier. Therefore, with inter-band CA, coverage and supportable modulation and coding schemes can be different across the aggregated CCs (a low-frequency carrier can provide larger coverage). In order to optimize the performance for inter-band CA, the CC selection algorithm should not only take the traffic load, but also the radio channel characteristics into considerations.

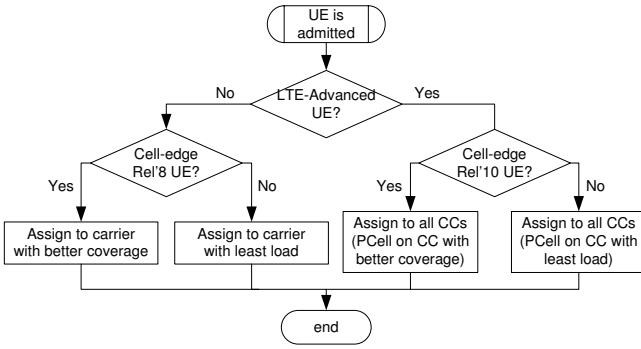


Fig. 3. Proposed G-factor based CC selection algorithm for downlink interband CA

The main difference of LTE-A RRM framework compared to Rel'8 is the CC-selection functionality which is responsible for configuring a CC set for each user based on their Quality-of-Service (QoS) requirements, UE capability, etc. In a multi-CC LTE-A system, both Rel'8 and LTE-A users may co-exist. The CC-selection algorithm is important to perform load balancing among CCs, as well as to optimize the system performance.

For Rel'8 users, the coverage performance can potentially be improved by assigning cell-edge (5-percentile in G-factor distribution) users to the carrier with better coverage (low-frequency carrier), while the rest of users are assigned to the carrier with the least number of users to guarantee that all carriers are equally loaded.

When an LTE-A user establishes a connection with eNodeB (eNB), only one serving cell is configured which is called the primary serving cell (PCell). The corresponding CC is designated as primary CC (PCC). One or more additional serving cells may be configured for LTE-A users, which are called secondary serving cells (SCells). The corresponding CCs are designated as secondary CCs (SCCs). In downlink, allocating more CCs to an LTE-A user generally results in a higher throughput thanks to the larger transmission bandwidth and higher transmission power. However, the selection of PCell has to be carefully considered. The PCell designation is user specific and can be different for different LTE-A users served by the same eNB [7]. The PCell of UE can not be deactivated and can only be changed via handover. One of the main considerations for selecting a proper PCell is the reliable transmission and reception of control channel signalings, e.g., physical downlink control channel (PDCCH) and physical uplink control channel (PUCCH) on the PCell. The PDCCH is used to schedule UL grants or DL resource allocation corresponding to physical uplink shared channel (PUSCH) or physical downlink shared channel (PDSCH) transmissions, respectively. The PDCCH messages transmitted on PCell can schedule resources on PCell or on SCells. In uplink, UE can only transmits PUCCH via PCell to the eNB. Therefore, the PCell should be robust. In our proposed scheme, LTE-A users are assigned on all CCs with the PCell selection

| Parameters                        | Settings   |
|-----------------------------------|--|
| Layout                            | 7 sites - 3 sectors/site - wrap around                                     |
| Inter-site distance               | 0.5 km, 1.7 km, and 3.0 km   |
| Penetration loss                  | 20 dB  |
| Component carriers                | $2 \times 20$ MHz non-contiguous CCs @ {800MHz, 2.1GHz} & {1.8GHz, 2.6GHz} |
| Number of PRBs                    | 92 PRBs per CC (12 subcarriers per PRB)                                    |
| Transmit pattern                  | $1 \times 2$ SIMO  |
| UE receiver                       | 2-Rx Interference Rejection Combining                                      |
| Time domain PS                    | Round Robin  |
| Frequency domain PS               | Cross-CC Proportional Fair   |
| Admission control                 | Max 50 users per cell  |
| Traffic model 1                   | Finite buffer with Poisson UE arrival                                      |
| Traffic model 2                   | Fixed number of UEs with full buffer                                       |
| Available MCSs                    | QPSK (R=1/5 to 3/4)<br>16QAM (R=2/5 to 5/6)<br>64QAM (R=3/5 to 9/10)       |
| HARQ modeling                     | Ideal chase combining  |
| Max number of retrans.            | 4  |
| 1 <sup>st</sup> tran. BLER target | 10%  |
| CQI freq resolution               | 1 CQI per 3 PRBs   |
| CQI reporting resolution          | 1 dB   |
| CQI reporting error               | Log normal ( $\mu = 0$ dB and $\sigma = 1$ dB)                             |

TABLE I  
SUMMARY OF MAIN SIMULATION PARAMETERS

similar to carrier selection scheme as for Rel'8 users. A detailed description of the proposed CC selection algorithm for downlink interband CA is illustrated in Fig. 3.

### III. SIMULATION ASSUMPTIONS

The performance evaluation is based on a detailed multi-cell system level simulator which follows the guidelines in [8]. The simulation scenario is 3GPP Macro-cell case with 7 sites and 3 sectors per site using the wrap-around technique. The inter-site distance is configured to be 0.5km, 1.7km, and 3.0km with penetration loss of 20 dB. Two sets of interband non-contiguous CA scenarios with two CCs, each of which has 20 MHz bandwidth, are configured to form a wide band of 40 MHz. Both Rel'8 and Rel'10 UEs, are supported in the system. Rel'8 UEs are only assigned on one CC with the proposed G-based carrier selection algorithm, while Rel'10 UEs are assigned on both CCs. Separate RRM blocks, such as Link Adaptation (LA) and Hybrid ARQ (HARQ), operate independently on each CC. The link to system level mapping is based on the actual value interface (AVI) method [9]. UEs are randomly placed in each cell. It is assumed that distance-dependent path loss and shadowing are maintained constant for each UE, but fast fading is updated every TTI independently on each CC based on the ITU Typical Urban power delay profile. In each cell, we simulate both fixed number of UEs with full buffer and Poisson UE arrival with finite buffer of 4 Mbits payload. For bursty traffic model, the offered load per cell can be obtained by multiplying the user arrival rate with the payload size. In frequency domain, joint proportional fair scheduling across multiple CCs is used to achieve better performance in terms of user fairness and cell coverage. Control channel signalings PDCCH and PUCCH are not explicitly simulated. Table I summarizes the main parameters used in the system-level simulations.

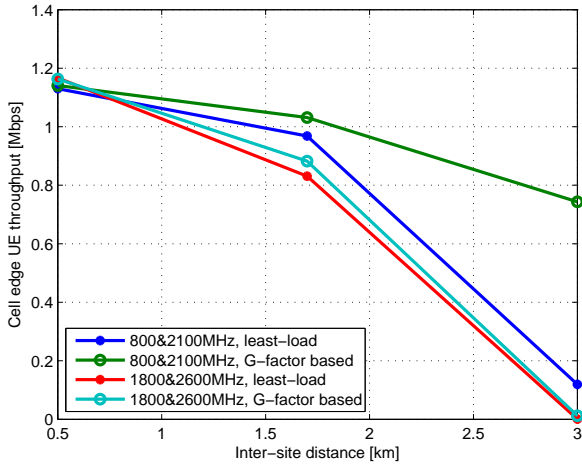


Fig. 4. Cell edge user throughput for Rel'8 UEs with different inter-site distance and frequency carriers

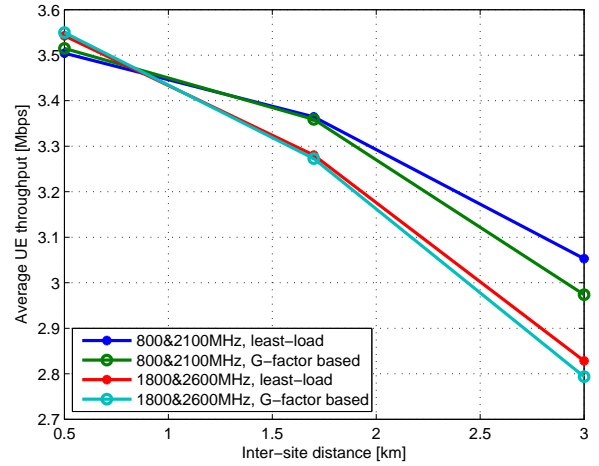


Fig. 5. Average user throughput for Rel'8 UEs with different inter-site distance and frequency carriers

#### IV. SIMULATION RESULTS

In this section, we evaluate and compare the performance of proposed G-factor based carrier selection algorithm with least-load carrier selection algorithm, i.e., Rel'8 UEs are always assigned on the carrier with the least number of users, in DL inter-band CA.

Fig. 4 and 5 show the cell edge user throughput (worst 5-percentile user throughput) and average user throughput with different inter-site distance and frequency carriers. We assume a fixed number of 16 UEs per sector with full buffer traffic. It is shown in the figures that when the inter-site distance is small, e.g., 0.5km, the cell edge and average user throughput performance of the proposed G-factor based carrier selection scheme is almost the same with the least-load scheme. However, as the inter-site distance increases, the cell edge throughput gain by applying the G-factor based scheme increases compared to the least-load scheme, and the gain can be very high with 3km ISD and 800&2100MHz frequency carriers. The user throughput is mainly determined by the received SINR, which is highly correlated with G-factor distribution. From simulations we know that the difference in G-factor distribution between carriers is dependent on the inter-site distance and frequency separation between carriers. Specifically, increase the inter-site distance or increase the frequency separation will increase the difference in G-factor distribution, especially at the lower end of the curve (cell-edge). Therefore the cell edge throughput gain by assigning cell-edge UEs to the carrier with better coverage increases as the inter-site distance increases. It is worth mentioning that in Fig. 4 with 3km ISD and 1800&2600MHz frequency carriers, there is no cell edge throughput in both carrier selection schemes due to bad channel conditions. From Fig. 5, it is shown that the average user throughput loss by applying the G-factor based carrier selection scheme is marginal (e.g., 2.6% loss with 3km ISD and 800&2100MHz frequency carriers)

compared to the significant gain we got. So in scenarios with relatively high inter-site distance and relatively high frequency separation between the carriers, the proposed G-factor based carrier selection scheme can achieve better cell edge performance compared to the least-load scheme, at the expense of marginal average user throughput loss. Otherwise the simple least-load scheme seems to be quite "robust".

Fig. 6 shows the cell-edge user throughput versus the offered load in different scenarios. We assume users arrive following Poisson process with a fixed payload size. For Rel'8 UEs, the G-factor based carrier selection can always achieve better cell edge performance compared to the least-load carrier selection. That is because the least-load carrier selection only takes the traffic load into consideration when selecting a carrier. As a result, the cell-edge users might be assigned on a carrier with less favorable channel conditions and experience performance loss. On the other hand, the proposed G-factor based carrier selection always assigns cell-edge users on the carrier with favorable channel conditions, thus improving the coverage. For a given offered load, the cell edge throughput gain in 3km inter-site distance scenario is higher than in 1.7km scenario, due to the reason that the difference in G-factor is higher for larger inter-site distance. For Rel'10 UEs, they are assigned on both CCs and the gain mechanism is the same as for intra-band CA. The cross-CC scheduling (joint scheduling) designed for Rel'10 UEs [3] can automatically compensate for potential differences in the experienced G-factor on different frequency carriers, i.e., schedule cell-edge UEs on low frequency carrier. So in general there is no big difference between performance of intra- and inter-band DL CA, except that the gain from inter-band CA is less than 100% since one of the two carriers has lower G-factor than the other. However, though not simulated, the PCell for Rel'10 UEs should be assigned to CC with better coverage to ensure reliable transmission and reception of control channel signalings, especially when there is noticeable

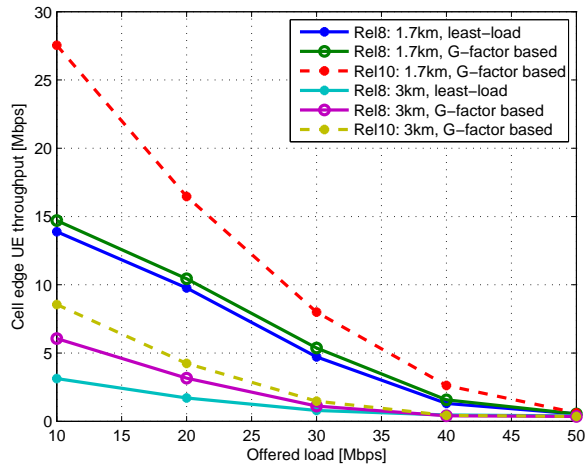


Fig. 6. Cell edge user throughput under different traffic loads in different scenarios, with 800&2100MHz frequency carriers

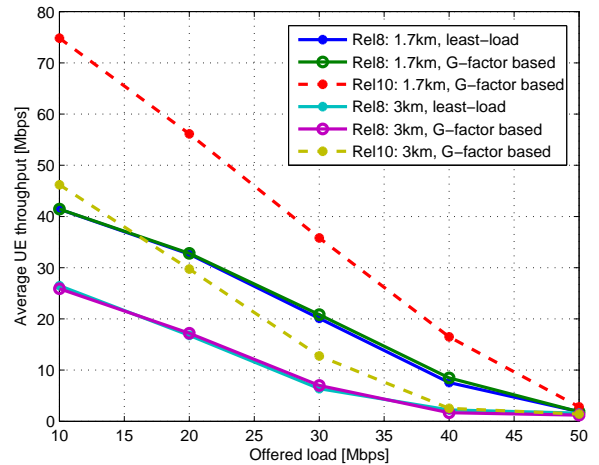


Fig. 7. Average user throughput under different traffic loads in different scenarios, with 800&2100MHz frequency carriers

difference in G-factor between CCs.

Fig. 7 shows the average user throughput versus the offered load in different scenarios. For Rel'8 UEs, the average user throughput of the G-factor based carrier selection is almost the same as the least-load carrier selection, in both 1.7km and 3km inter-site distance scenarios. The proposed scheme assigns the cell-edge UEs to the carrier with better coverage, while the rest of users are assigned to the carrier with the least number of users. By doing so, the load on each carrier is equally distributed, which results in a similar average user throughput performance with the least-load scheme. Again, the average user throughput gain in Rel'10 is less than 100% compared with Rel'8 due to the difference in G-factor distribution between carriers.

## V. CONCLUSIONS

In this paper, we have investigated the performance of downlink inter-band carrier aggregation in LTE-A systems. With inter-band CA, the radio channel characteristics can be different at different frequency carriers, and the difference mainly depends on the inter-site distance between cells and the frequency separation between carriers. Specifically, increase the inter-site distance or increase the frequency separation will increase the difference in G-factor, and lower-frequency carrier exhibits better G-factor distribution than higher-frequency carrier. The CC selection algorithm therefore should take both traffic load and radio channel characteristics into considerations. We proposed a G-factor based carrier selection algorithm. For Rel'8 users, cell-edge users are assigned to the carrier with better coverage (low-frequency carrier) to improve the coverage performance, while other users are assigned to the carrier with the least number of users to balance the load on each carrier. Rel'10 users are assigned on all CCs with the PCell selection following the same procedure as for Rel'8 users to ensure reliable transmission and reception

of control channel signalling. Simulation results show that the proposed G-factor based carrier selection algorithm can significantly improve the coverage performance at the expense of marginal average user throughput loss compared to pure least-load scheme in scenarios when there is large difference in G-factor distribution between carriers, i.e., scenarios with relatively high inter-site distance ( $ISD \geq 1.7$  km) and relatively high frequency separation between carriers (both 800MHz+2.1GHz and 1.8GHz+2.6GHz scenarios with 20 dB penetration loss). Otherwise, the performance of the two carrier selection schemes is almost the same.

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