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Analysis of Carrier Aggregation as a Diversity Technique for Improved Spectral Efficiency and Secrecy Performance in Mobile Communications

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Abstract: Carrier aggregation (CA) was introduced in mobile communication systems in response to the demand for higher network capacity. CA was conceived as a technique to achieve higher data rates by aggregating multiple blocks of spectrum from the same or different frequency bands. This work explores a different point of view, where CA is employed not as a way to increase capacity through using more bandwidth, but as a diversity technique in order to increase the spectral efficiency of the existing spectrum, and therefore, achieve higher capacity without needing additional spectrum. A mathematical model and set of closed-form expressions are provided, which can be used to characterise the performance of CA as a diversity technique (in terms of both ergodic capacity and secrecy capacity) and determine the impact of various relevant configuration parameters. The numerical results obtained by evaluating the mathematical expressions derived in this work are in line with our previous simulation studies and demonstrate that CA can be effectively exploited as a diversity technique to improve the capacity and performance of mobile communication systems compared to the case of single-carrier transmission over the same amount of bandwidth.

Keywords: mobile communications; carrier aggregation; diversity techniques; performance analysis

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1. Introduction

In an increasingly connected world, where information flows at unprecedented speeds, the demand for seamless and lightning-fast mobile communications has become paramount. Mobile networks have evolved from being simple voice communication platforms to sophisticated data networks that can be employed to deliver a wide and heterogeneous range of services, from video streaming and online gaming to remote healthcare and autonomous vehicles [1–5]. Since the introduction of the first data services in mobile networks, the evolution of mobile communication technologies has been mainly characterised by an exponential growth in data-intensive applications and the emergence of transformative technologies for achieving higher data rates in mobile communication systems [6]. The advent of 5G/6G introduced a paradigm shift in the way service requirements are perceived and prioritised, by means of encompassing a broader vision beyond mere data throughput and recognising that different applications have diverse needs that extend beyond raw data speed. Nevertheless, achieving higher data rates in mobile communication systems undoubtedly continues to be crucial for future services [7].

Carrier aggregation (CA), a key technology in modern mobile communication systems, emerged as a response to the ever-increasing demand for higher data rates and improved network capacity. Initially introduced as part of the 3GPP specifications for 4G LTE-Advanced [8–10], CA has become an integral part of subsequent mobile communication standards, including 5G/6G and beyond [11–20]. CA allows mobile devices to simultaneously use multiple frequency bands, or component carriers (CCs) in 3GPP terminology, effectively combining the available bandwidth and boosting the overall data throughput. By aggregating multiple carriers, mobile operators can efficiently utilise their spectrum resources, enhance the user experience by enabling faster download and upload speeds as well as reduced latency, seamlessly support bandwidth-intensive applications by providing the necessary data rates, and improve the overall network performance. Despite being introduced over a decade ago, CA continues to be a relevant technique in mobile communications and an active area of research. Several aspects of CA have recently been explored such as its delay performance [12], energy efficiency [12–15], spectrum orchestration [16], integration with O-RAN [17], integrated sensing and communications [18], sidelink communications [19], and THz communications [20].

The classical definition of the CA concept assumes that higher data rates are enabled through the aggregation of additional spectrum. In this work, a different approach is considered, where CA is employed to increase the data rates without requiring additional spectrum (the gain is obtained from a higher spectral efficiency). To this end, the proposed approach is to artificially divide an available block of spectrum (that would otherwise be used as a single carrier) into a number of sub-blocks, each of which is treated as a separate CC. The set of CCs into which the available spectrum is divided is then aggregated via regular CA. The motivation for this approach is to benefit from the frequency diversity available in frequency-selective channels with a sufficiently large bandwidth. Such frequency diversity can be exploited via CA because the data transmitted through each CC undergoes an individual instance of the MAC and PHY layers and their associated processes, which are individually adapted and optimised for each CC. Thus, CA can be effectively utilised as a diversity technique.

Frequency diversity has traditionally been exploited by means of PHY-layer techniques, mainly through diversity receivers such as maximum-ratio combining or selection combining [21]. PHY-layer diversity receivers are designed based on the fact that the same data symbols at the PHY layer are transmitted in parallel through different physical channel paths and the replicas of the same data symbols are combined coherently at the PHY layer of the receiver. On the other hand, with CA usually a different data stream is transmitted in each CC and all data streams are reorganised at the MAC layer of the receiver in order to recover the original data sequence. Therefore, existing PHY-layer diversity techniques are based on different operating principles and can be employed in conjunction with the method proposed in this work given that CA is fundamentally a MAC-layer technique. The MAC layer can effectively be seen as an additional dimension to exploit the channel frequency diversity through CA with the method proposed in this work and obtain further performance improvements in addition to those achieved through PHY-layer diversity techniques.

The performance of CA as a diversity technique was preliminarily evaluated in [22] by means of simulations carried out with the ns-3 simulator, where it was shown that CA can be exploited as a diversity technique to enhance the system performance and increase the network capacity without increasing the total amount of spectrum. While simulations can be valuable to explore the performance of a particular technique, an analytical study is also necessary to provide a comprehensive understanding of the technique being investigated. In this context, this work presents an analytical study that complements the simulation study presented in [22] by developing a mathematical model and a corresponding set of closed-form expressions can characterise the operation of CA as a diversity technique, thus providing a theoretic basis that supports and explains the findings of the simulation study reported in [22].

The following contributions are provided in this work:

- A novel approach for the use of CA as a diversity technique is proposed. The proposed approach is discussed in detail, including its motivation, relevant design aspects and impact at various layers of the protocol stack. Some example configurations compatible with 3GPP frequency ranges and channels are presented as well.

- In order to investigate the performance of CA as a diversity technique, the concept of *effective SNR* is introduced, which is defined as the equivalent SNR at which a single channel achieves the same performance as the considered CA scenario with the same total bandwidth. This concept provides a simple yet powerful tool for the mathematical analysis of CA. Two models for the effective SNR are considered (an ideal model and an average model). For both models two scenarios are considered, where the SNR is distributed homogeneously and heterogeneously across the aggregated CCs. Closed-form expressions for the statistical distribution of the effective SNR are then derived for the four possible cases considered in this work.
- Capitalising on the model of effective SNR, the ergodic capacity of a system with CA as a diversity technique is analysed and mathematical expressions are derived for both homogeneous and heterogeneous SNR scenarios.
- Similarly, the secrecy capacity of a system using CA as a diversity technique is also investigated and mathematical expressions are derived as well for the homogeneous and heterogeneous SNR scenarios. By considering both the ergodic and secrecy capacities, a robust communication system design can be achieved.

The remainder of this work is organised as follows. First, Section 2 discusses the concept of CA being used as a diversity technique. The motivation and objectives of this work are then formulated in Section 3. The considered system model is described in Section 4. Afterwards, Section 5 introduces and provides a formal definition of the concept of effective SNR along with mathematical expressions for its statistical distribution under both homogeneous and heterogeneous SNR scenarios, considering an ideal modelling approach as well as an average modelling approach. Based on the developed effective SNR model, analytical results for the performance of CA as a diversity technique in terms of the ergodic and secrecy capacities are presented in Sections 6 and 7, respectively. Numerical results are then presented and discussed in Section 8. A summarised discussion of the main results and findings of this study is presented in Section 9. Finally, Section 10 summarises and concludes this work.

2. Carrier Aggregation as a Diversity Technique

When CA is utilised, the data stream from the user application layer is divided into a number of sub-streams at the medium access control (MAC) layer and each sub-stream is transmitted through a different CC at the physical (PHY) layer. In this process, the PHY layer divides and maps higher-layer data onto physical resources while the MAC layer is in charge of the scheduling and resource management processes, with the radio resource control (RRC) layer controlling and configuring the aggregated CCs. At the receiver side, the data of the different sub-streams are recombined (aggregated) at the MAC layer and passed forward to the higher layers, as illustrated in Figure 1. Thus, multiple chunks of (possibly non-contiguous) spectrum can be combined in a transparent manner so that they are effectively perceived as a single (larger) block of spectrum by the higher layers of the protocol stack. This enables the network to simultaneously transmit and receive data across multiple CCs, thereby enhancing data rates, increasing capacity, and optimising network performance.

Since the user's main data stream is split into sub-streams at the MAC layer, the sub-streams transmitted through each CC will run a separate instance of the MAC and PHY layers and their associated processes. Consequently, each sub-stream will run an individual, dedicated instance of packet scheduler, HARQ retransmission process, transmission power control, dynamic adaptation of the modulation and coding scheme, and so on. As a result, these processes are dynamically adapted and optimised individually to the instantaneous channel quality conditions experienced in each CC. This observation suggests the possibility of utilising CA as a way to exploit the frequency diversity obtained through the use of different CCs. In general, the transmission through each CC will experience different propagation conditions due to frequency diversity, and each CC can, therefore, be seen as a different diversity path. By transmitting the user data through multiple CCs, frequency diversity can be exploited.

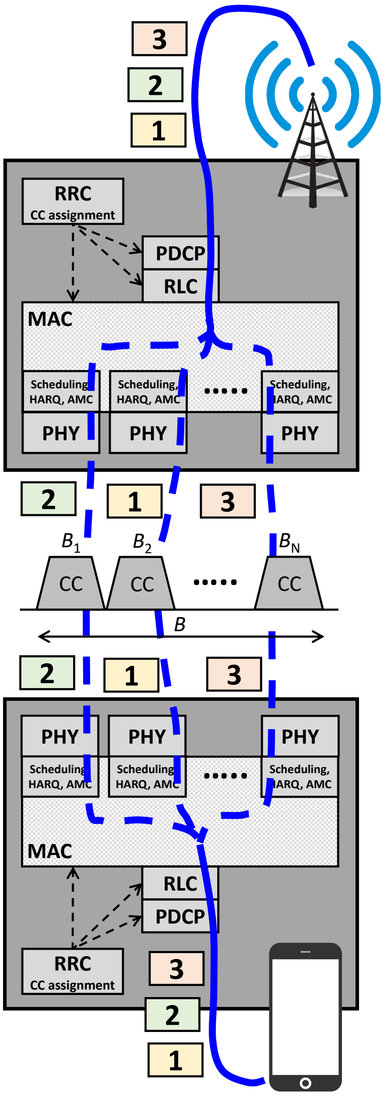

Figure 1. Transmission and reception with carrier aggregation. The data stream from the user application layer is represented by the solid blue line, while the sub-streams into which it is divided are represented by the dashed blue lines. PHY: physical layer; MAC: medium access control; RLC: radio link control; PDCP: Packet Data Convergence Protocol; RRC: radio resource control; HARQ: hybrid automatic repeat request; AMC: adaptive modulation and coding.

In order to employ CA as a diversity technique, a sufficiently large block of spectrum is divided into a number of sub-blocks, each of which is employed as a CC and combined via CA. The user data stream is then divided into the same number of data sub-streams when transmitted through the set of spectrum sub-blocks (CCs) via CA. For instance, a mobile operator with a spectrum block of 20 MHz could exploit the existing block of 20 MHz, not as a single carrier of 20 MHz, but instead as two CCs of 10 MHz each, or four CCs of 5 MHz each, which would then be combined via CA. The number of possibilities is actually much larger, in particular if the new bands introduced for 5G are considered. In Frequency Range 1 (FR1) [23], a block of 100 MHz could be exploited based on the proposed framework as 2 CCs $\times$ 50 MHz, 4 CCs $\times$ 25 MHz, 5 CCs $\times$ 20 MHz, or 10 CCs $\times$ 10 MHz (the option of 20 CCs $\times$ 5 MHz is not allowed by the standard given that up to 16 CCs can be aggregated). In Frequency Range 2 (FR2) [24], a block of 400 MHz could be exploited as

2 CCs $\times$ 200 MHz, 4 CCs $\times$ 100 MHz, or 8 CCs $\times$ 50 MHz. Many other combinations are also possible following a similar principle.

Note that this is different from the use of CA in classical sense. The traditional definition of the CA concept is to enable the incorporation of new additional frequency bands as a way to increase the data rate. On the other hand, the idea of CA as a diversity technique considered in this work does not require the addition of new spectrum; instead, it simply divides an existing block of contiguous spectrum into sub-blocks, treating each sub-block as a CC with a separate data sub-stream, and recombines the data sub-streams transmitted through each CC via CA. Note that in the proposed approach the use of CA would in principle not be needed; the operator could choose to transmit using the available block of spectrum as a single channel but, instead, artificially divides the available spectrum into a number of CCs that are recombined via CA in order to benefit from the frequency diversity that would normally be expected in channels with a sufficiently large bandwidth. Such frequency diversity can be exploited via CA because, as stated above, the data transmitted through each CC undergoes an individual instance of the MAC and PHY layers and their associated processes. Consequently, the parameters of the packet scheduler, HARQ retransmission process, transmission power control, dynamic adaptation of the modulation and coding scheme, etc., can be adapted and optimised individually for the instantaneous channel quality conditions of each CC. This individual adaptation and optimisation results in an improved capacity. Conversely, if the available spectrum is exploited as a single channel, then a single instance of the MAC/PHY layers and their processes is run and the selected operation parameters are unlikely to be optimum for the various instantaneous conditions experienced through the whole range of frequencies within the bandwidth of a frequency-selective channel, and as a result a lower capacity is obtained in this case. Thus, by artificially forcing separate data streams via different CCs in the available spectrum, the aim is to exploit the diversity in each frequency interval. As a result, in this context, CA can be effectively employed as a diversity technique to improve the overall performance without requiring additional spectrum. This performance improvement can be obtained regardless of any other diversity techniques that may be implemented in a mobile communication system, for example, at the physical layer.

Note that CA was originally proposed by 3GPP as a technique to increase data rates by incorporating additional bandwidth [8–10]. On the other hand, the framework proposed in this work as discussed above does not require additional bandwidth since it simply splits the existing spectrum into smaller blocks in order to benefit from frequency diversity, thus effectively exploiting CA as a diversity technique. Therefore, while traditional CA aims to increase the capacity by increasing the available bandwidth (i.e., Hz), the proposed approach aims to increase the capacity by increasing the spectrum efficiency within the available spectrum (i.e., bit/s/Hz). This is a novel point of view for CA that, to the best of the authors' knowledge, has not been considered by other authors before.

It is worth noting that the CA-based transmission scheme considered in this work does not involve a higher level of complexity compared to the traditional use of CA, both from the hardware and software points of view. The hardware complexity of CA is determined by the type of frequency deployment of CA, namely (in increasing order of complexity), intra-band contiguous CA, intra-band non-contiguous CA, or inter-band CA. The proposed CA-based scheme falls within the category of intra-band contiguous CA, which is the simplest form of CA with the lowest level of hardware complexity in the radio frequency front-end since all CCs are contiguous and belong to the same band, so they use the same numerology and transmission configuration. From the software point of view, the method considered in this work does not involve additional complexity compared to the traditional use of CA. The use of CA is certainly more complex than single-carrier transmission as it requires appropriate mechanisms to correctly execute the packet scheduling function, including the distribution of the user data across different CCs and the synchronisation of the scheduling information among CCs in a timely and efficient manner. However, commercial network equipment that supports CA must implement appropriate algorithms to address these issues. Such algorithms are usually vendor-specific and do not need to be modified to implement the CA-based scheme considered in this work. A mobile operator willing to implement the CA-based scheme presented in this work would only need to reconfigure the transmission in a broad channel from single-carrier mode to CA mode to benefit from the performance improvements offered by the proposed CA-based scheme.

3. Motivation and Objectives

The performance of CA as a diversity technique was evaluated in [22] by means of simulations carried out with the ns-3 simulator [25,26]. The simulation results presented in [22] demonstrated that CA can be exploited as a diversity technique to enhance the overall system performance and increase the network capacity without increasing the total amount of spectrum. Moreover, it was also observed in [22] that there exists an optimum number of CCs that maximises the throughput for each propagation scenario (depending on the radio propagation distance among other parameters). As a result, the system performance cannot be improved indefinitely by making the number of employed CCs arbitrarily large. On the one hand, a higher number of CCs enables the proposed approach to exploit frequency diversity with a finer granularity, thus increasing the data rate. On the other hand, a higher number of CCs also reduces the total amount of bandwidth available for data transmission because a higher amount of spectrum needs to be reserved for the guard bands between adjacent spectrum sub-blocks (see, for example, table 5.4.2A-1 in [27]) and to accommodate a higher amount of signalling traffic given that each CC runs its own dedicated instance of the MAC- and PHY-layer protocols (see, for example, section 7.6.1 in [28]). For CA to be beneficial as a diversity technique, the gain in spectrum efficiency obtained from frequency diversity needs to overcome the bandwidth penalty incurred by the required guard bands and signalling overhead, thus determining an optimum number of CCs for each propagation scenario.

Simulation studies can be valuable tools for exploring the performance of a particular technique. In fact, the simulation study presented in [22] was instrumental in understanding and demonstrating the effectiveness of CA when used as a diversity technique. However, an analytical study is also necessary to provide a comprehensive understanding of the technique being investigated. In this context, this work fills such an existing gap. The main objective is to develop a mathematical model and a corresponding set of closed-form expressions that can characterise the operation of CA as a diversity technique and support, from a theoretical point of view, the conclusions obtained in the simulation study presented in [22].

4. System Model

Let B denote the total bandwidth of a contiguous block of spectrum whose size is appropriate to be exploited as a single 4G LTE or 5G NR carrier. The mobile operator divides the bandwidth B into N adjacent sub-blocks, each of which is physically exploited as a separate CC and combined with the rest of sub-blocks at the receiver by means of CA. (Note that an operator may divide the total bandwidth into CCs with the same or different bandwidths. This work does not make any specific assumptions on the bandwidth allocated to each individual CC and the analytical results here presented do not take this aspect into account. The study of the impact of equal/unequal CC bandwidth allocations and the optimum configuration that maximises the total aggregated capacity is out of the scope of this work and is left as future work. However, the simulation results in [26] suggest that a homogeneous bandwidth allocation where the total bandwidth is equally divided across the used CCs may maximise the total aggregated capacity.) The transmitter's MAC layer splits the sequence of data packets generated at higher layers into N data flows, each of which is transmitted over one of the N available CCs, as shown in Figure 1. Each CC in general carries a different data stream. The CA-enabled receiver reorders the recovered packets at the MAC layer so that the process is transparent to the higher layers. The total data rate observed at higher layers is the sum of the individual rates experienced in each CC.

When CA is employed, each CC runs its own instance of the MAC and PHY layers and their associated processes, which are dynamically adapted to the instantaneous channel quality conditions experienced in each CC. This requires the use of L1/L2 control signalling to exchange control and feedback information for each CC. The signalling overhead introduced by each CC together with the guard bands required between adjacent CCs can both be jointly characterised by a fraction α ($0 < \alpha \ll 1$) of the total bandwidth. As a result, a bandwidth αB needs to be sacrificed for each employed CC and the total bandwidth W available for data transmission when N CCs are used is $W = B(1 - \alpha N)$. Note that the overhead parameter α refers to the fraction of total available bandwidth B and not to the bandwidth allocated to each individual CC. In order to obtain a positive data rate, the requirement $B(1 - \alpha N) > 0$ must be met, which implies that the number of CCs that can be used is constrained by the upper bound $N \leq N_{max} = \lfloor 1/\alpha \rfloor$.

The data transmitted through each CC experience an independent Rayleigh fading process. The probability density function (PDF) of the instantaneous SNR at the receiver is, therefore, given by equation (2.7) in [29]:

$$f_{\gamma_n}(x) = \frac{1}{\overline{\gamma}_n} \exp\left(-\frac{x}{\overline{\gamma}_n}\right), \quad \text{for } n = 1, \ldots, N \tag{1}$$

and its cumulative distribution function (CDF) is obtained by integrating (1), which yields

$$F_{\gamma_n}(x) = 1 - \exp\left(-\frac{x}{\overline{\gamma}_n}\right), \quad \text{for } n = 1, \ldots, N \tag{2}$$

where $\overline{\gamma}_n$ is the average SNR in the nth CC. Two frequency diversity scenarios are considered, namely, a homogeneous SNR scenario, where all CCs experience the same average SNR ($\overline{\gamma}_n = \overline{\gamma}$ for $n = 1, \ldots, N$), and a heterogeneous SNR scenario, where each CC experiences a different SNR ($\overline{\gamma}_n \neq \overline{\gamma}_k$ for $n \neq k$), with an overall average SNR $\overline{\gamma} = (1/N) \sum_{n=1}^{N} \overline{\gamma}_n$. The main motivation to consider these two scenarios regarding the SNR observed in different CCs is to provide a more comprehensive evaluation of the performance of CA as a diversity technique in scenarios with varying levels of frequency diversity.

5. Models for the Effective SNR

The capacity of CA has usually been investigated in the literature by characterising the capacity of each CC individually as an independent channel and then adding up the individual capacity of each CC. This approach may be suitable to calculate numerically the aggregate sum-rate in optimisation-based studies (e.g., [30,31]); however, the involved mathematical expressions provide little insight into how the total capacity depends on each relevant parameter. In order to investigate the capacity of CA as a diversity technique, the analysis carried out in this work considers a different approach based on the concept of *effective SNR*, which is defined in this study as the equivalent SNR at which a single channel with bandwidth B achieves the same performance as the considered CA scenario with a total aggregated bandwidth B divided across N CCs and instantaneous channel quality conditions represented by the set $\{\gamma_n\}_{n=1}^{N}$ of SNR values in each CC.

The introduction of this definition of effective SNR provides a convenient and useful new tool for the analysis of CA in general, and as a diversity technique in particular. However, this concept also raises the question of how to map a set $\{\gamma_n\}_{n=1}^{N}$ of N SNR values in each CC into a single effective SNR γ_{CA} that results in the same performance in the case of a single channel. This is an extremely challenging problem given the broad range of processes at the MAC and PHY layers that determine the performance of CA (packet scheduler, HARQ retransmission process, transmission power control, dynamic adaptation of the modulation and coding scheme, etc.) and the many different algorithms that can be implemented for each such MAC/PHY process. For this reason, an exact mapping of the individual SNR in each CC into a single effective SNR, while highly desirable, seems unfeasible. To overcome this limitation, this work considers two models for the effective SNR, which are presented below. These models are sufficient for the purposes of this study, and the development of more accurate models is proposed as future work.

5.1. Ideal Model for the Effective SNR

The maximum effective SNR that would be achievable in an ideal scenario would be equal to the sum of the SNR of all the individual CCs, $\gamma_{\text{CA}}^{\text{ideal}} = \sum_{n=1}^{N} \gamma_n$. This model characterises the maximum possible diversity gain across the N available CCs that could hypothetically be achieved in an ideal diversity propagation scenario and can, thus, be used to derive theoretical upper bounds on the performance of CA. This model has been commonly considered in the existing literature (e.g., see equation (10) in [32] and equations (1)–(3) in [33]).

Proposition 1. *Ideal SNR model for CA with homogeneous SNR*

The PDF and CDF of the instantaneous effective SNR under an ideal CA scenario with homogeneous SNR are given, respectively, by

$$f_{\gamma_{\text{CA}}}(x) = \frac{1}{(N-1)!} \frac{x^{N-1}}{\overline{\gamma}^N} \exp\left(-\frac{x}{\overline{\gamma}}\right) \tag{3}$$

$$F_{\gamma_{\text{CA}}}(x) = \frac{\gamma(N, x/\overline{\gamma})}{\Gamma(N)} \tag{4}$$

where $\Gamma(\cdot)$ and $\gamma(\cdot,\cdot)$ in (4) represent the gamma function (equation (8.310.1) in [34]) and the lower incomplete gamma function (equation (8.350.1) in [34]), respectively.

Proof. The effective SNR in this case is calculated as the sum of N i.i.d. exponential random variables, therefore it follows an Erlang distribution (i.e., a gamma distribution with integer shape parameter). Refer to chapter 12 in [35] for the PDF; the CDF follows from the direct integration of the PDF with the help of equation (3.351.1) in [34], noting that $(N-1)! = \Gamma(N)$. □

Proposition 2. *Ideal SNR model for CA with heterogeneous SNR*

The PDF and CDF of the instantaneous effective SNR under an ideal CA scenario with heterogeneous SNR are given, respectively, by

$$f_{\gamma_{\text{CA}}}(x) = \sum_{n=1}^{N} \frac{\Omega_n}{\overline{\gamma}_n} \exp\left(-\frac{x}{\overline{\gamma}_n}\right) \tag{5}$$

$$F_{\gamma_{\text{CA}}}(x) = 1 - \sum_{n=1}^{N} \Omega_n \exp\left(-\frac{x}{\overline{\gamma}_n}\right) \tag{6}$$

where

$$\Omega_n = \prod_{\substack{j=1 \\ j\neq n}}^{N} \frac{1}{1 - \overline{\gamma}_j/\overline{\gamma}_n}. \tag{7}$$

Proof. The effective SNR in this case is calculated as the sum of N i.n.i.d. exponential random variables, therefore it follows a generalised Erlang (hypoexponential) distribution. Refer to equation (7) in [36] for the PDF; the CDF readily follows from the direct integration of the PDF, noting that $\sum_{n=1}^{N} \Omega_n = 1$. □

5.2. Average Model for the Effective SNR

The ideal model for the effective SNR proposed in Section 5.1 assumes an optimistic, best-case scenario and, as such, the expressions provided in Propositions 1 and 2 represent upper bounds to the actual performance of CA. A model that can provide a closer approximation to the actual performance would be desirable. However, as discussed in Section 5, an exact mathematical model for the effective SNR in such a case is unlikely to be feasible. Thus, this section proposes a simple approximation, where the effective SNR is obtained as the average of the SNR in each CC, $\gamma_{\text{CA}}^{\text{avg}} = \frac{1}{N}\sum_{n=1}^{N}\gamma_n$. The average is commonly employed as an approximation due to its ability to provide a representative value that reflects the overall trend or central tendency of a set of values. This approach allows us to summarise the set of SNR values in each CC in a concise and meaningful way, making it possible to obtain results that can be expected to be closer to the actual effective SNR than the ideal model of Section 5.1. While this approach may not capture accurately the impact of all the MAC/PHY processes that determine the performance of CA, the average is in general a widely accepted measure that offers a reliable estimation in many practical scenarios. Moreover, it provides a simple yet powerful model that can be conveniently employed in subsequent analytical manipulations.

Proposition 3. *Average SNR model for CA with homogeneous SNR*

The PDF and CDF of the instantaneous effective SNR under an average CA scenario with homogeneous SNR are given, respectively, by

$$f_{\gamma_{\text{CA}}}(x) = \frac{N^N}{(N-1)!}\frac{x^{N-1}}{\overline{\gamma}^N}\exp\left(-N\frac{x}{\overline{\gamma}}\right) \tag{8}$$

$$F_{\gamma_{\text{CA}}}(x) = \frac{\gamma(N, Nx/\overline{\gamma})}{\Gamma(N)}. \tag{9}$$

Proof. Note that $\gamma_{\text{CA}}^{\text{avg}} = \gamma_{\text{CA}}^{\text{ideal}}/N$. If X and Y are random variables related as $Y = X/N$, then their PDFs are related as $f_Y(z) = Nf_X(Nz)$, which yields (8) from (3). The CDF in (9) follows from the direct integration of the PDF in (8), following the same steps as in the proof of Proposition 1. □

Proposition 4. *Average SNR model for CA with heterogeneous SNR*

The PDF and CDF of the instantaneous effective SNR under an average CA scenario with heterogeneous SNR are given, respectively, by

$$f_{\gamma_{\text{CA}}}(x) = N\sum_{n=1}^{N}\frac{\Omega_n}{\overline{\gamma}_n}\exp\left(-N\frac{x}{\overline{\gamma}_n}\right) \tag{10}$$

$$F_{\gamma_{\text{CA}}}(x) = 1 - \sum_{n=1}^{N}\Omega_n\exp\left(-N\frac{x}{\overline{\gamma}_n}\right) \tag{11}$$

with Ω_n defined in (7).

Proof. The same as for Proposition 3, applied to (5) and (6). □

Remark 1. *Note that if $N = 1$, then (3)–(4), (5)–(6), (8)–(9), and (10)–(11) reduce to (1)–(2), respectively.*

Proof. By substitution, noting where appropriate that $\Omega_1 = 1$ and $\gamma(1, x) = 1 - \exp(-x)$ (equation (8.350.1) in [34]). □

6. Ergodic Capacity Analysis

The concept of channel capacity is a fundamental concept in communication theory, particularly in wireless communication systems. The capacity of a communication channel represents the maximum rate at which information can be transmitted reliably over that channel. The instantaneous capacity of a channel (in bits per second) is given by $W\log_2(1+\gamma)$, where W is the channel bandwidth and γ is its instantaneous SNR. Since the instantaneous SNR of a wireless communication channel fluctuates randomly, the instantaneous channel capacity will fluctuate accordingly. The concept of ergodic capacity extends the notion of channel capacity to account for the statistical variations in channel conditions over time. Instead of considering the capacity of the channel at a specific time instant, the ergodic capacity evaluates the average capacity of the channel over an extended period, assuming that the channel conditions vary randomly according to certain statistical distributions. Therefore, the ergodic channel capacity is a measure of the achievable data rate or capacity of a communication channel in the long term, considering statistical variations in the channel conditions, such as those caused by the presence of fading.

Based on the concept of effective SNR, the ergodic capacity of a CA scenario can be obtained in bits per second as

$$C = W \int_0^{\infty} \log_2(1+x) f_{\gamma_{\mathrm{CA}}}(x) dx \tag{12}$$

where W is the total aggregated bandwidth effectively available for data transmission and $f_{\gamma_{\mathrm{CA}}}(x)$ is the effective SNR PDF. In this section, analytical results will be provided only for the average SNR model presented in Section 5.2. The counterparts for the ideal model of Section 5.1 can be obtained by simply replacing $\overline{\gamma}/N$ with $\overline{\gamma}$ (homogeneous SNR scenario) and $\overline{\gamma}_n/N$ with $\overline{\gamma}_n$ (heterogeneous SNR scenario).

Theorem 1. *Ergodic capacity of single carrier scenario*

The ergodic capacity of the single carrier scenario is given by

$$C = B(1-\alpha) \log_2(e) \exp\left(\frac{1}{\overline{\gamma}}\right) E_1\left(\frac{1}{\overline{\gamma}}\right) \tag{13}$$

where $E_1(x) = \int_x^{\infty} e^{-t} t^{-1} dt$ denotes the exponential integral function, equation (5.1.1) in [37].

Proof. Since the signalling overhead introduced by a single carrier requires a capacity equivalent to a bandwidth αB, the bandwidth effectively available for data is $W = B(1-\alpha)$. Introducing (1) in (12) and noting that $\log_2(x) = \log_2(e)\ln(x)$, the resulting integral can be solved with the help of equation (4.337.2) in [34] and equation (5.1.7) in [37]. □

Theorem 2. *Ergodic capacity of CA with homogeneous SNR*

The ergodic capacity of CA with homogeneous SNR is

$$C = B(1-\alpha N) \log_2(e) \exp\left(\frac{N}{\overline{\gamma}}\right) \sum_{n=1}^{N} \frac{\Gamma\left(n-N, \frac{N}{\overline{\gamma}}\right)}{\left(\frac{N}{\overline{\gamma}}\right)^{n-N}} \tag{14}$$

where $\Gamma(\cdot,\cdot)$ represents the upper incomplete gamma function defined in equation (8.350.2) in [34].

Proof. The control signalling overhead introduced by N CCs requires a capacity equivalent to a bandwidth αNB, thus $W = B(1-\alpha N)$. Introducing (8) in (12) and noting that $\log_2(x) = \log_2(e)\ln(x)$, an integral of the form of equation (15.24) in [29] is obtained, which can be resolved with the help of equation (15B.7) in [29] to obtain the expression shown in (14). □

Theorem 3. *Ergodic capacity of CA with heterogeneous SNR*

The ergodic capacity of CA with heterogeneous SNR is

$$C = B(1-\alpha N) \log_2(e) \sum_{n=1}^{N} \Omega_n \exp\left(\frac{N}{\overline{\gamma}_n}\right) E_1\left(\frac{N}{\overline{\gamma}_n}\right). \tag{15}$$

Proof. For N CCs, $W = B(1-\alpha N)$. Introducing (10) in (12) yields a sum of integrals, each of which can be resolved as discussed in the proof of Theorem 1. □

Remark 2. *Note that if $N = 1$, then both (14) and (15) reduce to the single-carrier expression in (13).*

Proof. By substitution, noting where appropriate that $\Omega_1 = 1$ and $\Gamma(0, x) = E_1(x)$ (equation (5.1.1) in [37]; equation (8.350.2) in [34]). □

7. Secrecy Capacity Analysis

The ergodic capacity analysed in Section 6 represents the maximum theoretical achievable data rate over a wireless channel, which is an important aspect to achieve efficient data transmission and optimise the system performance. However, in practical scenarios, the communication security is also extremely relevant, and therefore, analysing the secrecy capacity becomes equally important. The secrecy capacity or secrecy rate is a concept primarily used in information theory and communication systems to quantify the amount of secrecy or confidentiality achieved when transmitting digital information over a communication channel, particularly in the presence of potential eavesdroppers. The secrecy capacity represents the maximum theoretical achievable data rate at which information can be transmitted reliably over a wireless channel while maintaining the confidentiality of communication against attackers (commonly referred to as eavesdroppers). The secrecy capacity is essentially a measure of the amount of information that can be transmitted securely over a communication channel and can, therefore, be employed to characterise the level of security of a communication system from a physical-layer point of view. The secrecy capacity is a critical metric in assessing the security and confidentiality of communication systems. A high secrecy rate indicates that a significant amount of information can be transmitted securely, reducing the risk of sensitive data being compromised by unauthorised parties. By considering both the ergodic and secrecy capacities, a robust communication system design can be accomplished. The analysis presented for the ergodic capacity in Section 6 is here complemented by analysing the secrecy capacity.

The instantaneous secrecy capacity of a wiretap channel [38] is defined as the difference between the instantaneous channel capacity for the legitimate receiver (i.e., the intended recipient) and the instantaneous channel capacity for the eavesdropper (i.e., the potential attacker). Mathematically, it is defined as $C_s(\gamma_m, \gamma_e) = C_m - C_e$ if $C_m > C_e$ and zero otherwise, where γ_m and γ_e represent the instantaneous SNR of the main and eavesdropper links, respectively, and their instantaneous capacities are given by $C_m = W \log_2(1 + \gamma_m)$ and $C_e = W \log_2(1 + \gamma_e)$, respectively. Note that the eavesdropper needs to use the same configuration as the main link in order to attempt to successfully decode its information. If the main link transmits over a bandwidth B using CA with N CCs, then the eavesdropper must do exactly the same. As a result, the bandwidth penalty parameter α will be the same for both links as will the net bandwidth available for data transmission, hence the presence of the same bandwidth W in the expressions of both C_m and C_e.

The characteristics of the communication channel, such as bandwidth, noise, and fading effects, influence both the legitimate receiver's channel capacity and the eavesdropper's channel capacity. As a result, the instantaneous secrecy capacity will fluctuate randomly. In this context, a meaningful metric for the secrecy capacity is its average value, which can be calculated by averaging the instantaneous secrecy capacity over the fading statistics of the main and eavesdropper links. Thus, the average secrecy capacity (in bits per second) can be obtained as equations (38)–(41) in [39]:

$$\begin{aligned} C_s &= \int_0^\infty \int_0^\infty C_s(x, y) f_{\gamma_m}(x) f_{\gamma_e}(y) dx dy \\ &= W \log_2(e) [\mathcal{I}_1 + \mathcal{I}_2 - \mathcal{I}_3], \end{aligned} \tag{16}$$

where $f_{\gamma_m}(\cdot)$ and $f_{\gamma_e}(\cdot)$ denote the PDF of the instantaneous SNR in the main and eavesdropper links, respectively, and

$$\mathcal{I}_1 = \int_0^\infty \ln(1+x) F_{\gamma_e}(x) f_{\gamma_m}(x) dx \tag{17}$$

$$\mathcal{I}_2 = \int_0^\infty \ln(1+x) F_{\gamma_m}(x) f_{\gamma_e}(x) dx \tag{18}$$

$$\mathcal{I}_3 = \int_0^\infty \ln(1+x) f_{\gamma_e}(x) dx \tag{19}$$

with $F_{\gamma_m}(\cdot)$ and $F_{\gamma_e}(\cdot)$ denoting the CDF of the instantaneous SNR in the main and eavesdropper links, respectively.

Based on the expressions shown above and capitalising on the effective SNR models proposed in Section 5, this section analyses the secrecy capacity of CA when used as a diversity technique. Similar to Section 6, analytical results will be provided for the average model of the effective SNR. The equivalent expressions for the ideal effective SNR model can be obtained by simply replacing $\overline{\gamma}_m/N$ and $\overline{\gamma}_e/N$ with $\overline{\gamma}_m$ and $\overline{\gamma}_e$, respectively (for the homogeneous SNR scenario), and by replacing $\overline{\gamma}_{m,n}/N$ and $\overline{\gamma}_{e,n}/N$ with $\overline{\gamma}_{m,n}$ and $\overline{\gamma}_{e,n}$, respectively (for the heterogeneous SNR scenario).

Theorem 4. *Secrecy capacity of single carrier scenario*

The secrecy capacity of the single carrier scenario is given by

$$C_s = B(1-\alpha)\log_2(e)\left\{\exp\left(\frac{1}{\overline{\gamma}_m}\right)E_1\left(\frac{1}{\overline{\gamma}_m}\right) - \exp\left(\frac{1}{\overline{\gamma}_m}+\frac{1}{\overline{\gamma}_e}\right)E_1\left(\frac{1}{\overline{\gamma}_m}+\frac{1}{\overline{\gamma}_e}\right)\right\} \tag{20}$$

where $E_1(\cdot)$ is the exponential integral function.

Proof. Since the control signalling overhead introduced by a single carrier requires a capacity equivalent to a bandwidth αB, the bandwidth effectively available for data transmission is $W = B(1-\alpha)$. Introducing (1)–(2) in (16)–(19) and noting that $\log_2(x) = \log_2(e)\ln(x)$, the resulting integrals can be solved with the help of equation (4.337.2) in [34] and equation (5.1.7) in [37]. □

Theorem 5. *Secrecy capacity of CA with homogeneous SNR*

The secrecy capacity of CA with homogeneous SNR is

$$\begin{aligned} C_s = B(1-\alpha N)\log_2(e)\Bigg\{ &\exp\left(\frac{N}{\overline{\gamma}_m}\right)\sum_{n=1}^{N}\frac{\Gamma\left(n-N,\frac{N}{\overline{\gamma}_m}\right)}{\left(\frac{N}{\overline{\gamma}_m}\right)^{n-N}} \\ &- \exp\left(N\left[\frac{1}{\overline{\gamma}_m}+\frac{1}{\overline{\gamma}_e}\right]\right)\sum_{n=1}^{N}\frac{(n+N-2)!}{(n-1)!(N-1)!} \\ &\times\left(\frac{N}{\overline{\gamma}_m\overline{\gamma}_e}\right)^{n+N-1}\left(\overline{\gamma}_m^{n-1}\overline{\gamma}_e^{N}+\overline{\gamma}_e^{n-1}\overline{\gamma}_m^{N}\right) \\ &\times\sum_{k=1}^{n+N-1}\frac{\Gamma\left(k-n-N+1,N\left[\frac{1}{\overline{\gamma}_m}+\frac{1}{\overline{\gamma}_e}\right]\right)}{\left(N\left[\frac{1}{\overline{\gamma}_m}+\frac{1}{\overline{\gamma}_e}\right]\right)^{k}}\Bigg\} \end{aligned} \tag{21}$$

where $\Gamma(\cdot,\cdot)$ represents the upper incomplete gamma function.

Proof. The overhead introduced by N CCs requires a capacity equivalent to a bandwidth αNB, thus $W = B(1-\alpha N)$. Introducing (8)–(9) in (16)–(19), substituting the lower incomplete gamma function with its equivalent form in equation (8.352.1) in [34] and noting that $\log_2(x) = \log_2(e)\ln(x)$, integrals of the form of equation (15.24) in [29] are obtained, which can be resolved with the help of equation (15B.7) in [29]. After reorganising and grouping terms, the expression shown in (21) is obtained. □

Theorem 6. *Secrecy capacity of CA with heterogeneous SNR*
The secrecy capacity of CA with heterogeneous SNR is

$$
\begin{aligned}
C_s = B(1-\alpha N)\log_2(e)\Bigg\{ & \sum_{n=1}^{N} \Omega_{m,n} \exp\left(\frac{N}{\overline{\gamma}_{m,n}}\right) E_1\left(\frac{N}{\overline{\gamma}_{m,n}}\right) \\
& - \sum_{i=1}^{N}\sum_{j=1}^{N} \Omega_{m,i}\Omega_{e,j} \exp\left(N\left[\frac{1}{\overline{\gamma}_{m,i}} + \frac{1}{\overline{\gamma}_{e,j}}\right]\right) \\
& \times E_1\left(N\left[\frac{1}{\overline{\gamma}_{m,i}} + \frac{1}{\overline{\gamma}_{e,j}}\right]\right)\Bigg\}
\end{aligned} \tag{22}
$$

Proof. For N CCs, $W = B(1-\alpha N)$. Introducing (10)–(11) in (16)–(19) yields a sum of integrals, each of which can be resolved as discussed in the proof of Theorem 1. □

Remark 3. *By comparing (20), (21) and (22) to (13), (14) and (15), respectively, it can be noted that the secrecy capacity is equivalent to the ergodic capacity minus a term that quantifies the amount of information that can be transmitted through the channel, but not in a confidential manner due to the presence of an eavesdropper (i.e., the secrecy capacity is lower than the ergodic capacity, as expected).*

8. Results

The performance of CA as a diversity technique is evaluated numerically in this section based on the analytical results obtained in Sections 6 and 7, considering as a benchmark the case of single-carrier transmission over the same amount of bandwidth used by the considered CA-based transmission scheme. The main aim is to determine whether the mathematical model and closed-form expressions derived in this work can correctly predict the trends observed by simulations in [22] and to determine the impact of various relevant parameters on the system performance. Note that a direct quantitative comparison of the numerical results obtained in this section with those obtained from simulations in [22] would not be meaningful, not only because of the approximated nature of the effective SNR models considered in this work but also the practical limitations of the simulator employed in [22], which is based on 4G LTE, and therefore, supports up to five CCs only. For this reason, the comparison with [22] is carried out in a qualitative manner by verifying that the main conclusions derived from the study presented in [22], which are summarised in Section 3, are also reached when evaluating the mathematical modelling framework developed in this work. This approach is sufficient for the main objective of this section, which is to demonstrate that the developed mathematical model can characterise the operation of CA as a diversity technique and provide a theoretic basis that supports and explains the findings of the simulation study presented in [22].

As discussed in Section 4, two frequency diversity scenarios are considered, namely, a homogeneous SNR scenario, where all CCs experience the same average SNR ($\overline{\gamma}_n = \overline{\gamma}$ for $n = 1, \ldots, N$), and a heterogeneous SNR scenario, where each CC experiences a different average SNR ($\overline{\gamma}_n \neq \overline{\gamma}_k$ for $n \neq k$), with an overall average SNR $\overline{\gamma} = (1/N)\sum_{n=1}^{N}\overline{\gamma}_n$. In the heterogeneous SNR scenario, the average SNR of each individual CC is selected from the interval $10\log_{10}\overline{\gamma}_n \in [10\log_{10}\overline{\gamma} - \varepsilon, 10\log_{10}\overline{\gamma} + \varepsilon]$, where ε (in dB) is a spread parameter that determines the level of potential frequency diversity (the larger the value of ε, the higher the level of diversity in the propagation scenario). For simplicity, the performance is mainly investigated for the ideal model of effective SNR. The numerical results obtained for such a model show more pronounced trends that illustrate more clearly the impact of different relevant parameters. Some examples illustrating the impact of considering the average model of effective SNR are also shown, corroborating that the same trends are observed (just with different numerical values) and the same conclusions are therefore obtained. For convenience, all the capacity performance results presented in this section are given in terms of the ratio C/B, which represents the capacity per unit bandwidth (in bit/s/Hz), and therefore, does not require the consideration of a specific channel bandwidth for numerical evaluation.

8.1. Ergodic Capacity Results

Figure 2 shows the ergodic capacity of CA (in terms of the spectral efficiency, i.e., bit/s/Hz) as a function of the number of CCs for various values of the bandwidth overhead parameter α. The capacity obtained for single-carrier transmission (i.e., $N = 1$) is plotted as a horizontal solid black line along the width of the figure to provide a reference threshold that determines the range of CCs for which the considered CA-based transmission scheme outperforms the benchmark (i.e., the case of single-carrier transmission). Note that this threshold is different for each case plotted in this figure and, as is the case in this figure and other figures that will be shown later on, the reference lines may be very close to each other. The first relevant observation is that these results corroborate that CA can be effectively employed as a diversity technique to increase the data rate of the system without increasing the available bandwidth, which can be confirmed by noting that the curves for CA can lead to a higher spectral efficiency than the single carrier scenario (in certain regions of the figure if the number of CCs is correctly configured, which will be discussed later on). It can also be noted that the performance of CA tends to be slightly higher in the heterogeneous SNR scenario than in the homogeneous counterpart. This can be explained by the fact that the level of frequency diversity in the heterogeneous scenario is higher and in such a case the proposed method, based on the use of CA as a diversity technique, can benefit from it to a greater extent. The bandwidth overhead parameter α is also observed to have a significant impact on the resulting performance. As expected, if the use of CA incurs a higher bandwidth penalty (i.e., higher value of α), a lower amount of net bandwidth is available for data transmission, which leads to lower data rates. Note that in the hypothetical case of $\alpha = 0$ (i.e., if no bandwidth penalty is incurred by using CA), then the capacity would monotonically increase indefinitely with the number of CCs, as this would increase the frequency diversity gain without any bandwidth penalties. However, in a realistic case with $\alpha > 0$, the curves in Figure 2 become convex. This indicates the existence of an optimum number of CCs that maximises the data rate for each value of α. As explained in Section 3, increasing the number of CCs will initially increase the data rate as a result of increasing the frequency diversity in the system. However, this also increases the total amount of signalling traffic and bandwidth reserved for guard bands (i.e., bandwidth penalty), which reduces the total amount of bandwidth available for data transmission and contributes to reducing the data rate. If the number of CCs is sufficiently high, the bandwidth penalty incurred by a high number of CCs will exceed the gain obtained from the frequency diversity, thus effectively reducing the data rate. In fact, if the number of CCs is made arbitrarily large, it can be seen in Figure 2 that the data rate of CA can indeed fall below that of the single carrier scenario, and this will occur sooner (i.e., for a lower number of CCs) when the bandwidth penalty α is higher. In the extreme case where the number of CCs is set equal to $N = N_{max} = \lfloor 1/\alpha \rfloor$ (e.g., see the case α = 0.05 and N = 20), then all the available bandwidth is employed to accommodate signalling traffic and guard bands, which effectively reduces the total capacity available for data transmission to zero. The optimum number of CCs, thus, depends on the bandwidth penalty parameter. From Figure 2 it can be determined that the optimum number of CCs that maximises the data rate for $\alpha = \{0.01, 0.02, 0.03, 0.04, 0.05\}$ is 16, 9, 7, 5 and 4, respectively, which is in line with the observations above.

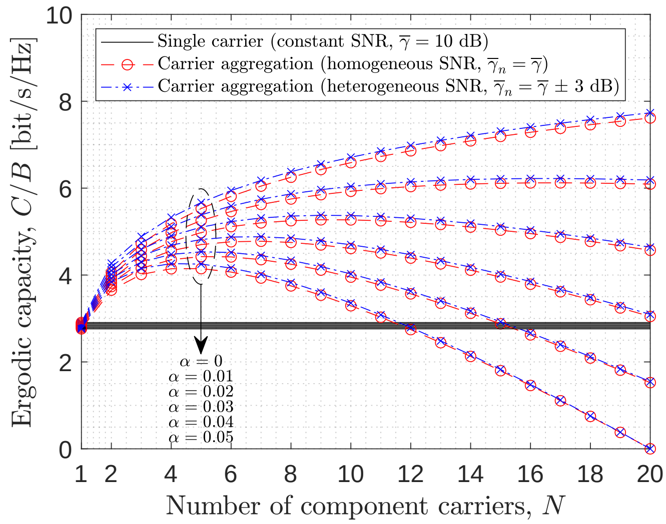

Figure 2. Ergodic capacity as a function of number of CCs for various values of bandwidth overhead parameter α (average SNR = 10 dB, ε = 3 dB).

The impact of the bandwidth penalty α on the optimum number of CCs and the resulting capacity is more clearly illustrated in Figure 3, where three scenarios are considered, namely, a 4G LTE scenario with a maximum of 5 CCs, a 5G NR scenario with a maximum of 16 CCs, and an ideal scenario where the number of CCs that can be aggregated is unconstrained (i.e., unlimited). Table 1 shows the capacity achieved by CA for various levels of bandwidth penalty (α) and the improvement with respect to the single carrier scenario, where no CA is used. Notice that, according to Figure 3, 4G LTE and 5G NR can achieve the same performance as the unconstrained CA scenario as long as the bandwidth penalty does not exceed the limits $\alpha < 0.04$ and $\alpha < 0.01$, respectively, in which cases the capacity improvement with respect to the single carrier scenario is equal to 64% for 4G LTE and 120% for 5G NR. Nevertheless, even if the bandwidth penalty exceeds these limits and the maximum number of CCs permitted by the 3GPP standard is taken into account, the use of CA as a diversity technique can still provide substantial capacity improvements with respect to the single carrier scenario, as evidenced by the results shown in Table 1.

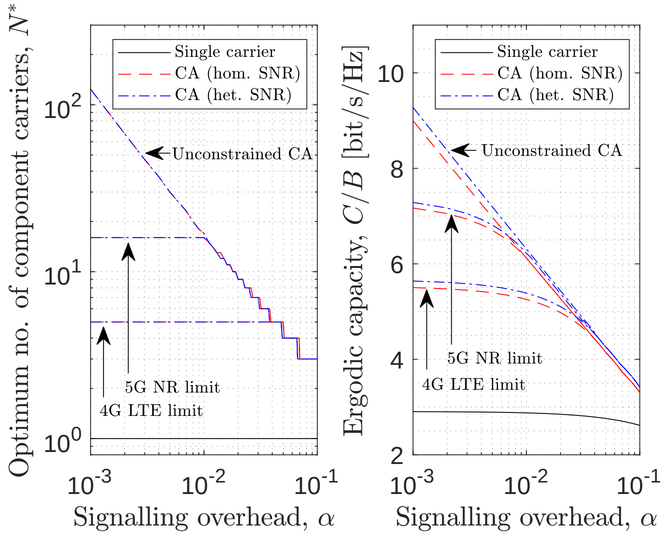

Figure 3. Optimum number of component carriers as a function of the bandwidth overhead parameter α (**left**) and the resulting ergodic capacity (**right**).

Table 1. Best attainable ergodic capacity for various scenarios and levels of bandwidth penalty (α) according to Figure 3.

	$\alpha = 10^{-3}$		$\alpha = 10^{-2}$	
Scenario	**Capacity**	**Improvement**	**Capacity**	**Improvement**
No CA	2.90 bit/s/Hz	—	2.88 bit/s/Hz	—
4G LTE CA	5.64 bit/s/Hz	94%	5.41 bit/s/Hz	88%
5G NR CA	7.29 bit/s/Hz	151%	6.34 bit/s/Hz	120%
Unconst. CA	9.28 bit/s/Hz	220%	6.45 bit/s/Hz	124%

Figure 4 shows the ergodic capacity of CA as a function of the number of CCs for various values of the average SNR experienced in the different considered scenarios. As expected, the capacity performance improves when the SNR increases and degrades when the SNR decreases, thus indicating that the dependency on the SNR is adequately captured. This figure also corroborates the main observations made when discussing Figure 2, namely, that (i) CA can be effectively employed as a diversity technique in order to improve the spectral efficiency with respect to the traditional single carrier scenario based on the same communication bandwidth (provided that the number of CCs is correctly configured); (ii) the performance of CA as a diversity technique tends to increase in the heterogeneous SNR scenario compared to the homogeneous SNR counterpart as a result of a richer diversity; and (iii) there exists an optimum number of CCs that maximises the total capacity, in this case, for each considered average SNR, for the same reasons discussed for Figure 2. Regarding the last observation, it can be seen in Figure 4 that the optimum number of CCs decreases as the average SNR increases. More concretely, for the numerical example shown in Figure 4, the data rate is maximised with 6, 4, and 3 CCs when the average SNR is 0, 10, and 20 dB, respectively. This trend can be explained intuitively based on the fact that a higher average SNR can be associated with a shorter communication distance, where the level of diversity can be expected to be lower than in a longer distance link (where the signal can find a larger number of diverse paths between the transmitter and receiver). Thus, a lower diversity gain means that a lower number of CCs can be used while guaranteeing that the bandwidth penalty associated with the number of CCs does not exceed the diversity gain. The optimum number of CCs as a function of the average SNR for a broader range of average SNR values is illustrated in Figure 5 along with the capacity obtained when the optimum number of CCs is used for every average SNR. This figure shows clearly how the use of CA as a diversity technique can significantly improve the spectral efficiency in order to increase the system capacity without increasing the amount of spectrum employed. Taking an average SNR of 10 dB as a reference, the results in Figure 5 indicate that the spectral efficiency of 2.74 bit/s/Hz in the single carrier scenario can be improved to around 4 bit/s/Hz with the use of CA as a diversity technique (in all cases, namely, 4G LTE, 5G NR and unconstrained CA), which represents a 55% increase in the system capacity without increasing the available bandwidth.

The results presented above indicate that CA can provide a slightly better performance in the heterogeneous SNR scenario than in the homogeneous SNR scenario as a result of a higher level of diversity. To illustrate this aspect more clearly, Figure 6 shows the impact of the spread parameter ε, which determines the width of the interval of SNR values in each individual CC, on the capacity as a function of the number of CCs. The results show that the capacity gain of using CA increases with the spread of SNR values over the different CCs. This means that for the same average SNR across the different CCs, the higher the standard deviation of the SNR in the individual CCs, the higher the capacity gain obtained by using CA (with respect to the single carrier scenario). A higher SNR spread can somehow be seen as an additional form of channel diversity that benefits the use of CA as a diversity technique.

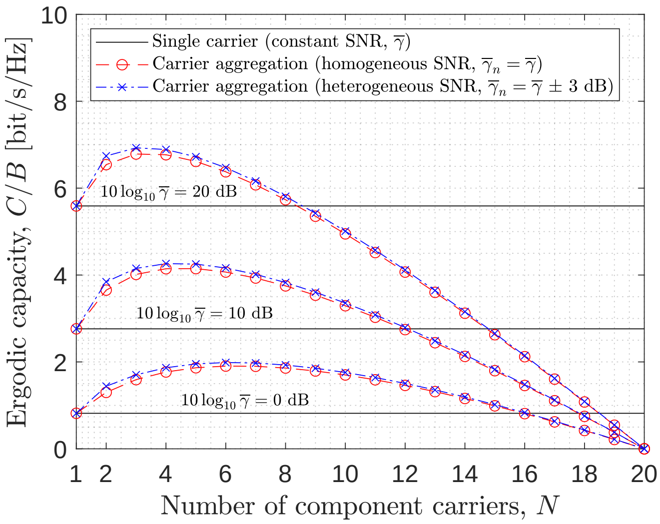

Figure 4. Ergodic capacity as a function of the number of CCs for various values of the average SNR (α = 0.05, ϵ = 3 dB).

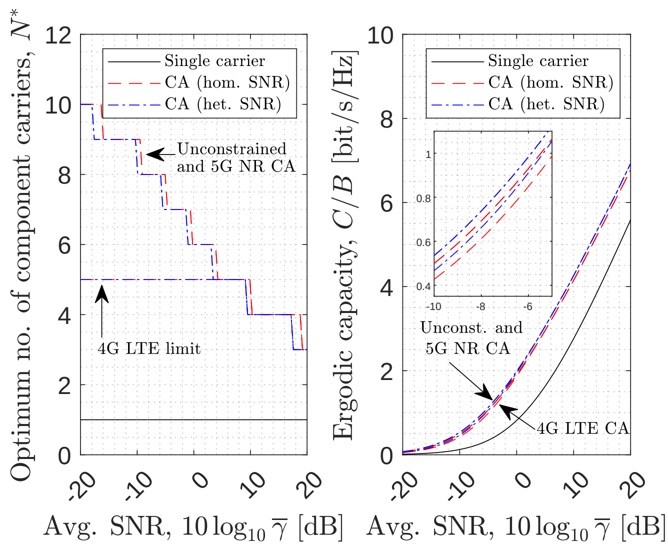

Figure 5. Optimum number of component carriers as a function of the average SNR (**left**) and the resulting ergodic capacity (**right**).

The results presented so far have been obtained based on the ideal model of effective SNR presented in Section 5.1. As discussed at the beginning of Section 8, this choice is preferred because the numerical results obtained from such a model show more pronounced trends that illustrate more clearly the impact of different relevant parameters on the performance of CA as a diversity technique. However, the ideal model for effective SNR assumes an optimistic best-case scenario and the results obtained from that model should be interpreted as performance upper bounds. The reader may naturally wonder whether the main conclusions obtained from the results presented in this section are also valid under a more realistic SNR model. To corroborate this, some illustrative results based on the average model of effective SNR proposed in Section 5.2 are presented here as well. Figures 7 and 8 show the counterparts to Figures 2 and 4, respectively, based on the average model of effective SNR. Taking into account that the average effective SNR model is more conservative and provides a scaled version of the ideal effective SNR model, the effective SNR value obtained under the former model will always be lower than the latter. This explains the lower numerical values of capacity obtained in Figures 7 and 8 (average model) compared to Figures 2 and 4 (ideal model). However, besides the mere numerical differences between both models, it can be seen that the qualitative performance trends are preserved when the average model of effective SNR is considered and that the main conclusions derived from the analysis presented in this section for the ideal model of effective SNR are still valid. This is also true for the performance improvement in the proposed CA-based scheme compared to the single carrier scenario (i.e., where no CA is used) when the average model of effective SNR is considered, which is illustrated in Table 2 based on the results shown in Figure 7. In summary, it can thus be concluded that the mathematical model and closed-form expressions derived in Section 6 can correctly predict the trends observed by simulations in [22] and constitute a useful tool to analyse the performance of CA when used as a diversity technique and to determine the (qualitative) impact of various relevant parameters on the system performance.

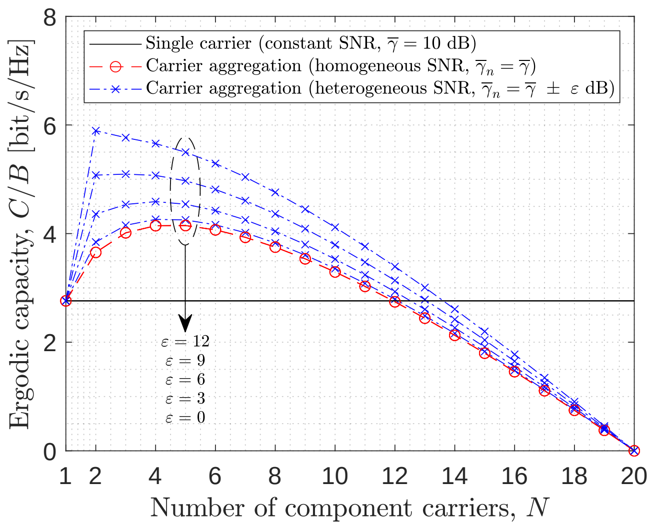

Figure 6. Ergodic capacity as a function of the number of CCs for various values of the spread parameter ε (average SNR = 10 dB, α = 0.05).

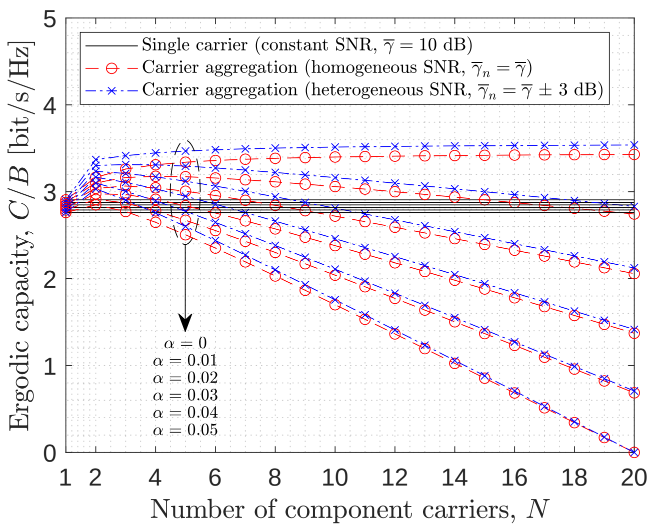

Figure 7. Ergodic capacity as a function of the number of CCs for various values of the bandwidth overhead parameter α (average SNR = 10 dB, ε = 3 dB) (counterpart to Figure 2 based on the average model of effective SNR).

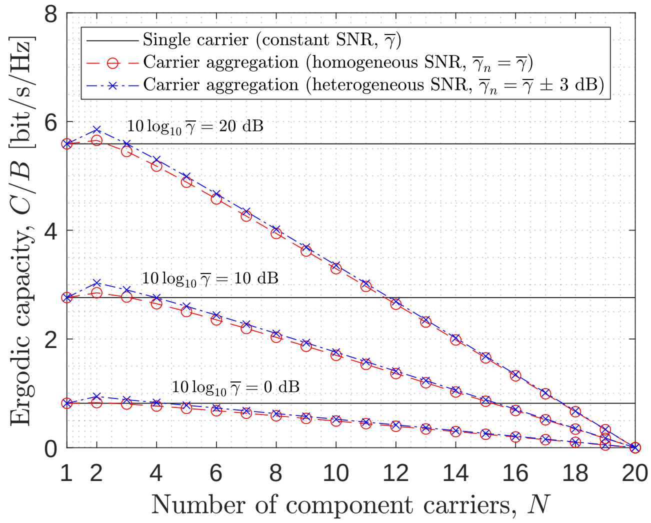

Figure 8. Ergodic capacity as a function of the number of CCs for various values of the average SNR (α = 0.05, ε = 3 dB) (counterpart to Figure 4 based on the average model of effective SNR).

Table 2. Best attainable ergodic capacity for various scenarios and levels of bandwidth penalty (α) according to Figure 7.

	No CA	CA with Homogeneous SNR		CA with Heterogeneous SNR	
α	**Capacity**	**Capacity**	**Improvement**	**Capacity**	**Improvement**
0.001	2.90 bit/s/Hz	3.37 bit/s/Hz	16.2%	3.48 bit/s/Hz	20.0%
0.01	2.88 bit/s/Hz	3.18 bit/s/Hz	10.4%	3.31 bit/s/Hz	14.9%
0.02	2.85 bit/s/Hz	3.07 bit/s/Hz	7.7%	3.24 bit/s/Hz	13.7%
0.03	2.82 bit/s/Hz	2.98 bit/s/Hz	5.7%	3.17 bit/s/Hz	12.4%
0.04	2.79 bit/s/Hz	2.91 bit/s/Hz	4.3%	3.10 bit/s/Hz	11.1%
0.05	2.76 bit/s/Hz	2.85 bit/s/Hz	3.3%	3.03 bit/s/Hz	9.8%

8.2. Secrecy Capacity Results

The performance of CA as a diversity technique in terms of secrecy capacity was also evaluated as part of this study. It is worth noting that the secrecy capacity was observed to follow the same qualitative trends as the ergodic capacity, being affected in the same way by variations in the bandwidth overhead parameter, number of CCs, and average SNR. This is in line with the observation pointed out in Remark 3, which highlights the fact that the numerical value of the secrecy capacity is a reduced version of the ergodic capacity as a result of the presence of an eavesdropper. This means that the figures shown in Section 8.1 for the ergodic capacity would look very similar when calculated for the secrecy capacity, except for the fact that numerical values in the case of the secrecy capacity would be slightly lower.

The analysis presented in this section focuses on the impact of the eavesdropper on the secrecy capacity, which is the main aspect that determines the difference between ergodic and secrecy capacities. As explained in Section 7, the eavesdropper needs to use the same configuration as the main link (i.e., same B, N, and α); however, they may experience a different average SNR depending on their relative location with respect to the transmitter and receiver in the main link. Therefore, the impact of the eavesdropper can be analysed and quantified in terms of their average SNR with respect to the average SNR in the main link.

Figure 9 shows the secrecy capacity of a system with CA as a diversity technique as a function of the number of CCs for various values of the bandwidth overhead parameter α, when both the main and eavesdropper links experience the same average SNR of 10 dB (based on the ideal model of effective SNR). These results suggest that the use of CA as a diversity technique, while improving the ergodic capacity with respect to the single carrier scenario (see Section 8.1), may actually lead to a lower secrecy capacity compared to the case of single-carrier transmission. In other words, while CA allows the system to transmit a higher quantity of bits per second in the same bandwidth (ergodic capacity), it reduces the level of confidentiality of the link at the physical layer (secrecy capacity). This means that the use of CA not only benefits the transmission of data in the main link, but also the transmission of data in the (undesired) link between the same transmitter and the eavesdropper, thus potentially reducing the level of confidentiality between the transmitter and the legitimate receiver. However, it is worth noting that this is due to the rather favourable propagation conditions in the eavesdropper link, which in the example of Figure 9 enjoys the same average SNR as the main link. In a more realistic setup, the main link can typically be expected to experience a higher average SNR than the eavesdropper link, in particular with modern communication systems where the use of multiple antenna technologies and beamforming techniques are used to direct the transmitted signal towards the desired recipient. This should lead to a much lower SNR at any potential eavesdroppers (unless they are perfectly aligned in the same direction as the transmitter and the legitimate receiver, which is rather unlikely in practical scenarios). When the legitimate receiver in the main link experiences a higher average SNR than the eavesdropper link, then the use of CA can effectively result in an improvement in the secrecy capacity, as illustrated in Figure 10, where the eavesdropper link remains at an average SNR of 10 dB and the main link experiences a higher average SNR of 20 dB. By only increasing the average SNR in the main link by 10 dB with respect to the eavesdropper link, the secrecy performance of CA can be substantially improved (if the number of CCs is correctly configured). This is true not only when assuming the ideal model of effective SNR (Figure 10) but also when the more conservative and realistic average model of effective SNR is considered (Figure 11).

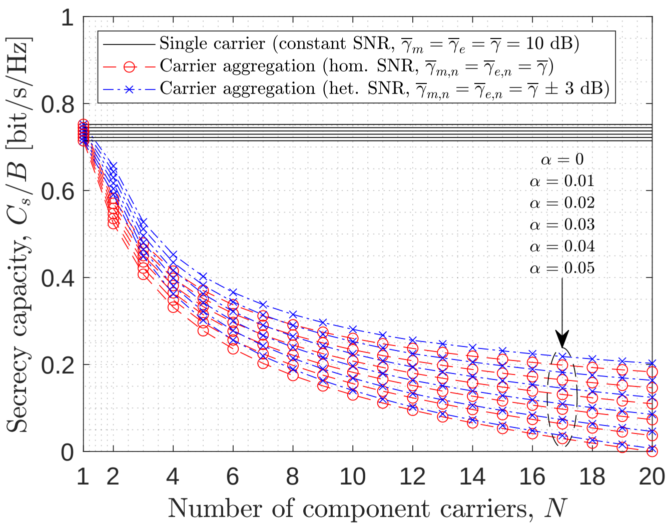

Figure 9. Secrecy capacity as a function of the number of CCs for various values of the bandwidth overhead parameter α (ideal effective SNR model, 10 dB SNR in both main and eavesdropper links).

From the discussion above, it can be concluded that the secrecy capacity can potentially be improved with the use of CA as a diversity technique when compared to the single carrier scenario; however, it may also be degraded depending on the average SNR of the eavesdropper links, which in practical scenarios may or may not be known. In a worst-case scenario, the use of CA would lead to a degraded secrecy capacity compared to the equivalent single carrier scenario; however, this does not mean that confidential communication may not be achievable. A degraded secrecy capacity means that the level of confidentiality is reduced at the physical layer, from an information-theoretic point of view. However, confidentiality can still be guaranteed by taking appropriate measures at higher layers of the protocol stack, which usually involves the use of encryption techniques. The results presented and discussed in this work suggest that CA can be used as a diversity technique to increase the user data rates and system ergodic capacity; however, when doing so, special attention should be paid to higher-layer techniques for communication confidentiality since the secrecy capacity may in some cases be degraded when using CA as a diversity technique. With an adequate consideration of both ergodic and secrecy capacities, a robust system design for CA as a diversity technique can be accomplished. In this context, the analytical results presented in this work constitute a useful tool to achieve this end.

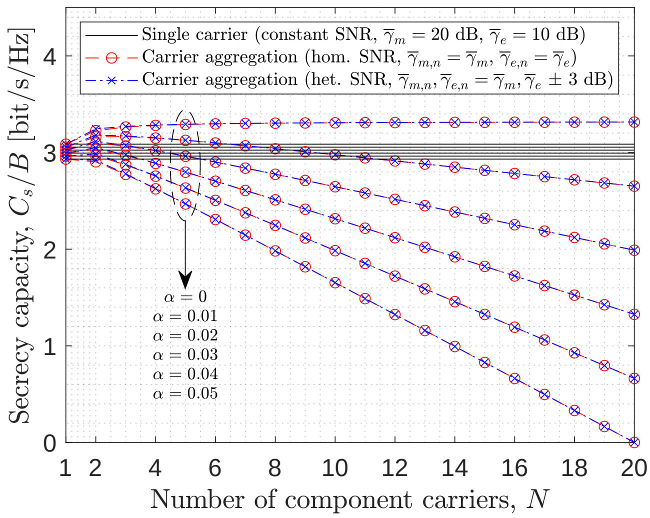

Figure 10. Secrecy capacity as a function of the number of CCs for various values of the bandwidth overhead parameter α (ideal effective SNR model; 20 dB SNR in the main link and 10 dB SNR in the eavesdropper link).

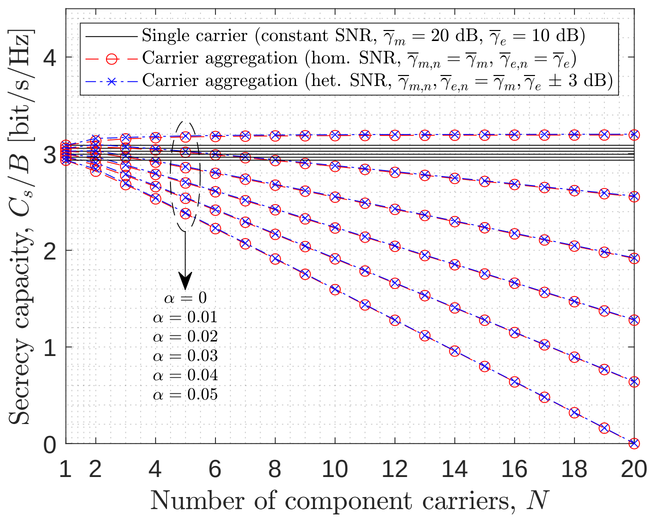

Figure 11. Secrecy capacity as a function of the number of CCs for various values of the bandwidth overhead parameter α (average effective SNR model; 20 dB SNR in the main link and 10 dB SNR in the eavesdropper link).

9. Discussion

The main aim of the analysis presented in Section 8 was to determine whether the mathematical model and closed-form expressions derived in this work can correctly predict the trends observed by simulations in [22] and evaluate the impact of various relevant parameters on the system performance. The numerical results obtained by evaluating the mathematical expressions derived in this work have been shown to be in line with our previous simulation study and demonstrate that CA can be effectively exploited as a diversity technique to increase the data rate of the system without increasing the available bandwidth (owing to a higher spectral efficiency per unit bandwidth), thus improving the capacity and performance of mobile communication systems compared to the case of single-carrier transmission over the same amount of bandwidth.

The performance of the considered CA-based transmission scheme has been evaluated under various SNR scenarios, namely, a homogeneous SNR scenario, where all CCs experience the same average SNR, and a heterogeneous counterpart, where the SNR values in the CCs are different and spread around a certain average SNR value. The performance has been observed to be noticeably higher in the heterogeneous SNR scenario than in the homogeneous counterpart, obtaining better performance improvements when the SNR values are spread over broader intervals. This is an indication not only of the ability of the proposed CA-based scheme to exploit and benefit from the frequency diversity existing in wireless communication channels but also the capability of the developed mathematical modelling framework to capture this phenomenon.

It has been shown that several parameters can affect, to different extents, the performance of CA when exploited as a diversity technique. The two main parameters are the number of CCs into which the available spectrum is divided (N) and the overhead parameter, representing the fraction of the available bandwidth that needs to be sacrificed to accommodate for signalling traffic and guard bands between CCs (α). Increasing the number of CCs initially has a beneficial effect as it enhances the diversity gain of the system. However, each new CC has an associated bandwidth penalty as a result of its required signalling traffic and guard bands, which has a negative effect on performance. If N is too low, the diversity gain may not be significant, while if N is too high, the bandwidth penalty may completely cancel out the obtained diversity gain and even reduce the performance below that of the single-carrier transmission scenario. Therefore, the existence of an optimum number of CCs that provides the best trade-off between these two conflicting aspects and maximises the overall capacity has been shown. This optimum number of CCs, which was indeed suggested by the simulation results obtained in [22], has a strong dependency on the bandwidth penalty parameter α.

An important practical limitation in real mobile communication systems is the maximum number of CCs that may be supported in certain versions of the 3GPP standard for mobile communication systems (e.g., up to five CCs in the case of 4G LTE systems). Even in those cases where a larger number of CCs is supported (e.g., 5G NR), mobile operators may actually implement a lower number of CCs in their real network deployments. As a result, the optimum number of CCs that provides the best capacity performance from a theoretical point of view may not be supported in some practical scenarios. However, even in those cases where the maximum number of CCs that can be employed is constrained by practical limitations, the use of CA as a diversity technique can still provide substantial capacity improvements with respect to the single carrier scenario. This indicates that the proposed CA-based transmission scheme is beneficial under practical conditions.

The secrecy performance of the considered CA-based transmission scheme was also evaluated as part of this work. In general, the use of CA as a diversity technique can improve the capacity not only of the links to legitimate users but also to undesired eavesdroppers. If both links experience similar SNR conditions, then the confidentiality of transmitted information may be compromised. However, such a situation should be unlikely in practical system implementations since, in a more realistic setup, the main link can typically be expected to experience a higher average SNR than the eavesdropper link, in particular with modern communication systems where the use of multiple antenna technologies and beamforming techniques are used to direct the transmitted signal towards the desired recipient. When the legitimate receiver in the main link experiences a higher average SNR than the eavesdropper link, then the use of CA can effectively result in an improvement in secrecy capacity as well. The observation above suggests that CA can in principle be safely used as a diversity technique to increase the user data rates and system ergodic capacity; however, when doing so, special attention should be paid to higher-layer techniques for communication confidentiality, since the secrecy capacity might in some unfavourable cases be potentially degraded when using CA as a diversity technique.

10. Conclusions

Carrier aggregation (CA) was originally proposed as a way to increase data rates in mobile communication systems by increasing the amount of spectrum available to users through the aggregation of different spectrum bands. This work has shown that CA can also lead to increased data rates without requiring additional spectrum when used as a diversity technique. By dividing a block of existing spectrum into sub-blocks and treating each of them as a component carrier (CC) via regular CA, the channel frequency diversity can be exploited, which results in a higher spectral efficiency, and therefore, in a higher user data rate with the same amount of available spectrum. In this context, a set of mathematical models and analytical expressions have been proposed to characterise the performance of CA as a diversity technique in terms of both the ergodic and secrecy capacities. The definitions of these capacities are independent of the type of information being transmitted, and therefore, the obtained results are representative for any type of data service. It has been shown that the proposed mathematical modelling approach can correctly predict the performance of CA as a diversity technique as well as the impact of various relevant configuration parameters. The obtained numerical results are in line with previous simulation studies and demonstrate that CA can be effectively exploited as a diversity technique to improve the performance of mobile communication systems. However, it has also been shown that both the ergodic and secrecy capacities should be taken into account in order to provide a robust system design. In this context, the mathematical models and expressions presented in this work constitute a useful tool to achieve this end.

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