# Successive Interference Cancellation in Uplink Cellular Networks

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***Abstract*—In recent years, operators addressed the explosive growth of mobile data demand by densifying the cellular network so as to achieve a higher spectral efficiency and increase their capacity. The intense proliferation of wireless devices resulted in interference limited networks, which suggests the use of interference mitigation and coordination techniques. In this work, we study successive interference cancellation (SIC) for uplink communications and we define an analytical framework that describes the performance benefits of SIC which accounts for the computational complexity of the cancellation scheme and the relevant network related parameters such as the random position and density of the base stations and mobile users, and the characteristics of the propagation channel. In our analysis, we explicitly model the consecutive events of canceling interferers and we derive expressions of the success probability to cancel the $k$th strongest signal and to decode the signal of interest (SoI) after $k$ cancellations. The analysis indicates that the performance benefit of SIC diminishes quickly with $k$. The framework also reveals that a substantial performance gain can only be obtained for low values of the target signal-to-interference ratio (SIR).**

***Index Terms*—successive interference cancellation, cellular network, stochastic geometry, aggregate network interference**

## I. Introduction

The most efficient way to meet the increasing throughput requirement is to reduce the cell size by deploying additional base stations. The resulting networks are called interference-limited since the thermal noise is negligible with respect to the interference. As the aggregate network interference is the most important obstacle for successful communication, effective interference management schemes are essential to further enhance the performance of dense networks. These mechanisms impose the orthogonality between transmitted signals in frequency, time, or space, and include adaptive spectrum allocation policies [1], medium access control (MAC), spatial interference mitigation by means of zero-forcing beamforming [2], and signal processing algorithms usually referred to as interference cancellation (IC) techniques [3]–[9]. Although interference mitigation techniques such as successive interference cancellation (SIC) and multi-antenna interference cancellation can be used both for uplink and downlink transmissions, they are particularly attractive in the uplink since they harness the processing power of base stations to cancel strong interfering signals from nearby transmitters.

The interference power can be reduced by decoding and canceling interfering signals by means of IC techniques such as joint detection (JD) [3] or SIC. In this work, we focus on the SIC receiver which decodes multi-user signals according to descending signal power and subtracts the decoded signal from the received multi-user signal, so as to improve the signal-to-interference ratio (SIR). The process is repeated until the signal of interest (SoI) is decoded. The performance of SIC is related to the ordering of the received signal power which depends on the spatial distribution of the active transmitters and on the propagation channel conditions. In [4], [5], a stochastic geometric model is adopted to capture the spatial distribution of the interfering nodes. The key idea of this work is the division into near field and far field interferers, where every near field interferer is able to cause outage at the reference receiver. This methodology allows to define closed-form upper and lower bounds of the outage probability accounting for cancellation and decoding errors, yet, fading effects are ignored. Building on this work, [6], [7] propose bounds on the outage/success probability including the effects of the fading channel. None of these works concerns a specific cancellation technique, since the order statistics of the interference power are disregarded. In [8], closed-form expressions are presented for the outage probability accounting for the order statistics of the received signal power, assuming that all interferers are at the same distance of the intended receiver, while [10] derives a lower bound of the outage probability based on the order statistics of the strongest uncanceled and partially canceled signals accounting for distance and fading. Finally, [9] describes accurately the consecutive steps of the SIC scheme and presents bounds of the success probability based on [4].

A unified approach to define the performance of SIC that jointly accounts for the interference cancellation scheme, channel fading, and the distance distribution, and that does not resort to bounds is still missing. In this work, we provide an analytical framework that describes the success probability for uplink transmissions in a single-tier cellular network where the macrocell base station (MBS) is provided with SIC capabilities. We derive the probability of successfully canceling the $k$th interferer assuming that the order statistics averaged over time are dominated by path loss attenuation. We extend the scheme of [9] and show how the effectiveness of SIC depends on the path loss exponent, the density of users and base stations, and the maximum number of cancellations.

## II. System Model

We consider uplink (UL) transmissions in a cellular network composed of macrocell base stations (MBSs) distributed according to a homogeneous Poisson point process (PPP) $\Theta$ in the Euclidean plane with density $\lambda_\mathrm{m}$ such that $\Theta \sim \mathrm{PPP}(\lambda_\mathrm{m})$. The PPP assumption for the MBSs yields conservative predictions of the network performance [11]. The set of macrocells forms a Voronoi tessellation of the two dimensional plane, where each Voronoi cell $C_j$ consists of those points which are closer to the MBS $x_j$ than to any other MBS $x_i$ and is formally defined as $C_j = \{y \in \mathbb{R}^2 \mid \|y - x_j\| \leq \|y - x_i\|, \forall x_i \in \Theta \backslash \{x_j\}\}$. The total available spectrum $W$ is divided in subchannels by aggregating a fixed number of consecutive subcarriers of bandwidth $B$, such that the total number of available subchannels equals $\lfloor W/B \rfloor$.[1] We denote the subchannel index as $j$, where $j \in \mathcal{J} = \{1, 2, \dots, \lfloor W/B \rfloor\}$. In order to maximize the frequency reuse and throughput, each cell has access to the entire available spectrum. Hence, denoting the available channels of base station $x_i$ as $\mathcal{J}(x_i)$, we have $\mathcal{J}(x_i) = \mathcal{J},\ \forall i$. Within a Voronoi cell, mobile users are independently and uniformly distributed over the cell area. Fairness between users is accomplished by proportional allocation of the time and frequency resources. We consider an orthogonal multiple access scheme which assures that at any given time and frequency, only a single user per macrocell is active. The spatial distribution of the mobile users is modeled as $\Omega \sim \mathrm{PPP}(\lambda_\mathrm{u})$, yet, due to the multiple access scheme and the coupling between the locations of mobile users and base stations, the point processes $\Theta$ and $\Omega$ are not independent. It can be shown that the dependence has a marginal effect on the results, and in the sequel we will therefore assume independent PPPs to maintain the tractability of the system model [12]. Each user connects to the closest MBS such that the distribution of the distance $D$ with respect to the intended base station is given by $f_D(r) = 2\lambda_\mathrm{m}\pi r \exp(-\lambda_\mathrm{m}\pi r^2)$ [13].[2] For notational convenience, we denote users and base stations by their location. As interference dominates noise in modern cellular networks, we consider networks to be interference-limited. For the link between user $u$ and base station $x$, we define the signal-to-interference ratio (SIR) as

$$\mathrm{SIR}(u \to x) = \frac{Q h_u g_\alpha(u - x)}{\sum_{v \in \Omega_j \backslash \{u\}} Q h_v g_\alpha(v - x)} \tag{1}$$

where $Q$ is the node transmission power, $h$ represents the channel fading coefficient for the link between the user and the typical MBS, and $g_\alpha(x) = \|x\|^{-\alpha}$ is the power path loss function with path loss exponent $\alpha$. To alleviate the notation, we will use $v$ to denote a mobile user as well as its position. The set of nodes active on subchannel $j$ is represented by $\Omega_j$, such that the set of users that interferes with $u$ on subchannel $j$ is represented by $\Omega_j \backslash \{u\}$. A transmission is successful if the SIR of the intended link exceeds a prescribed threshold $\eta$ which reflects the required quality-of-service (QoS). Hence, the success probability can be written as $\mathbb{P}_\mathrm{s}(\eta) = \mathbb{P}[\mathrm{SIR}(u \to x) \geq \eta]$.

[1] Without loss of generality, we assume $B = 1$.

[2] Note that this distance distribution is only exact in case the point processes of users and base stations are independent.

## III. Successive Interference Cancellation

In this section, we study how successive interference cancellation impacts the success probability of uplink transmissions. In the analysis, we explicitly model the sequence of events that is followed in the cancellation process. We define the success probability as a function of the threshold, the number of canceled interferers, and all relevant signal environment parameters such as the interferer density, transmission power, path loss exponent and channel fading.

Owing to constraints on computational complexity and delay, the number of interferers that can be canceled is limited to $n \in \mathbb{N}$. At the typical MBS, the transmission is successful if one of the following events occur [9]. First, the MBS attempts to decode the intended signal without any interference cancellation. If an outage occurs, the MBS seeks to decode the strongest signal, subtract it from the incoming signal, and performs a new attempt to decode the SoI. We can order the power of the signals received at the MBS as $\{X_{(1)}, X_{(2)}, ...\}$ such that $X_{(i)} \geq X_{(j)}$, with $i \leq j$ and $X_{(i)} = Q h_i v_i^{-\alpha}$. The same actions are repeated until the SoI is decoded while satisfying the constraint on the maximum number of cancellations. Hence, uplink transmission is successful in case of success of one of the following events

$$\begin{aligned}
0 &: \left( \frac{Q h_u u^{-\alpha}}{I_{\Omega_j^0}} \geq \eta \right) \\
1 &: \left( \frac{Q h_u u^{-\alpha}}{I_{\Omega_j^0}} < \eta \right) \bigcap \left( \frac{X_{(1)}}{I_{\Omega_j^1}} \geq \eta \right) \bigcap \left( \frac{Q h_u u^{-\alpha}}{I_{\Omega_j^1}} \geq \eta \right) \\
&\ \vdots \\
n &: \left( \bigcap_{k=0}^{n-1} \frac{Q h_u u^{-\alpha}}{I_{\Omega_j^k}} < \eta \right) \bigcap \\
&\quad \left( \bigcap_{k=1}^{n} \frac{X_{(k)}}{I_{\Omega_j^k}} \geq \eta \right) \bigcap \left( \frac{Q h_u u^{-\alpha}}{I_{\Omega_j^n}} \geq \eta \right)
\end{aligned} \tag{2}$$

where the set of interferers on subchannel $j$ after cancellation of the $k$ strongest interferers is represented by $\Omega_j^k = \Omega_j \backslash \{X_{(1)}, \dots, X_{(k)}\}$. The aggregate interference after cancellation is given by

$$I_{\Omega_j^k} = \sum_{i=k+1}^{\infty} Q h_i v_i^{-\alpha}. \tag{3}$$

$$\mathbb{P}_{\mathrm{s,IC}}(\eta, R_{\mathrm{I},k}) \approx \int_{R_{\mathrm{I},k}}^{\infty} \exp\left(-\pi\lambda_{\mathrm{u}}\eta^{2/\alpha}r^2 C(R_{\mathrm{I},k}^2/(\eta^{2/\alpha}r^2),\alpha)\right) 2\pi\lambda_{\mathrm{m}} r \exp(-\lambda_{\mathrm{m}}\pi r^2) dr \quad (5)$$

The first and third factor in the $k$th event of (2) represent outage and success for decoding the SoI when $k-1$ and $k$ interferers are canceled, respectively. The second factor in the $k$th event of (2) represents the event of successfully canceling $k$ interferers. Two lemmas are now formulated which define the success probability for UL transmissions after successfully canceling $k$ interferers and the success probability of canceling the $k$th interferer.

*Remark 1:* In the remainder, we will often make use of integrals of the form $\int 1/(1+u^{\alpha/2})du$. For the integration interval $[b,\infty)$, we define

$$\begin{aligned} C(b,\alpha) &= \int_b^{\infty} \frac{1}{1+u^{\alpha/2}} du \\ &= 2\pi/\alpha \csc(2\pi/\alpha) - b\, {}_2F_1(1, 2/\alpha; (2+\alpha)/\alpha; -b^{\alpha/2}) \end{aligned} \quad (4)$$

where ${}_2F_1(.)$ is the Gaussian hypergeometric function. The special cases $C(0,\alpha) = 2\pi/\alpha \csc(2\pi/\alpha)$ and $C(b,4) = \arctan(1/b)$ have a compact solution.

*Lemma 1:* A mobile user is connected in uplink to a typical MBS which has successfully canceled $k$ interferers. The success probability of uplink transmission in the presence of network interference is given by (5) at the top of this page, where $R_{\mathrm{I},k} = \sqrt{k/\lambda_{\mathrm{u}}\pi}$ is the cancellation radius that defines the area around the victim receiver without interferers.

*Proof:* Similar to the downlink coverage probability derived in [11], we define the uplink coverage probability conditioned on the distance of the intended link after successfully canceling $k$ interferers as

$$\begin{aligned} \mathbb{P}_{\mathrm{s,IC}}(\eta, k \,|\, u) &= \mathbb{P}^{!u}\left\{\frac{Q h_u u^{-\alpha}}{\sum_{v\in\Omega_j^k\setminus\{u\}} Q h_v v^{-\alpha}} \geq \eta\right\} \\ &\overset{(a)}{=} \mathbb{E}_{I_{\Omega_j^k}}\left\{\mathbb{P}\left[h_u > \eta u^{\alpha} I_{\Omega_j^k}\right]\right\} \\ &\overset{(b)}{=} \mathbb{E}_{I_{\Omega_j^k}}\left[\exp(-\eta u^{\alpha} I_{\Omega_j^k}\right] \\ &= \mathcal{L}_{I_{\Omega_j^k}}(\eta u^{\alpha}) \end{aligned} \quad (6)$$

where $(a)$ holds because of Slivnyak's theorem [14], and where $(b)$ assumes a Rayleigh fading channel. The Laplace transform of the random variable (r.v.) $I$ is represented as $\mathcal{L}_I(s)$. Similar to [11], the Laplace transform of the partially canceled interference is obtained applying the probability generating functional, and the conditional coverage probability can be written as

$$\mathbb{P}_{\mathrm{s,IC}}(\eta, k \,|\, u) = \exp\left(-2\pi\lambda_{\mathrm{u}} \int_{R_{\mathrm{I}}(k)}^{\infty} \frac{v}{1+\frac{v^{\alpha}}{\eta u^{\alpha}}} dv\right) \quad (7)$$

where $R_{\mathrm{I}}(k)$ is the distance from the origin to the $k$th interferer. By the change of variable $r = v^2/(\eta^{2/\alpha}u^2)$, we find

$$\begin{aligned} &\mathbb{P}_{\mathrm{s,IC}}(\eta, k \,|\, u) \\ &= \exp\left(-\pi\lambda_{\mathrm{u}}\eta^{2/\alpha}u^2 \int_{b(u)}^{\infty} \frac{1}{1+r^{\alpha/2}} dr\right) \\ &= \exp\left(-\pi\lambda_{\mathrm{u}}\eta^{2/\alpha} C(b(u),\alpha) u^2\right) \end{aligned} \quad (8)$$

where $b(u) = R_{\mathrm{I}}(k)^2/\eta^{2/\alpha}u^2$. The integration interval of the function $C(b(u),\alpha)$ depends on $R_{\mathrm{I}}(k)$, and therefore, the expectation should be taken with respect to the distance to the $k$th interferer. The probability density function (PDF) of $R_{\mathrm{I}}(k)$ is given by [13]

$$f_{R_{\mathrm{I}}(k)}(r) = \exp(-\lambda_{\mathrm{u}}\pi r^2) \frac{2(\lambda_{\mathrm{u}}\pi r^2)^k}{r\Gamma(k)}. \quad (9)$$

Since the expectation can only be solved by numerical integration, we approximate $R_{\mathrm{I}}(k)$ by the cancellation radius which encloses on average $k$ mobile users $R_{\mathrm{I},k} = \sqrt{k/\lambda_{\mathrm{u}}\pi}$, such that $b(u) = R_{\mathrm{I},k}^2/(\eta^{2/\alpha}u^2)$. As the SIC procedure cancels at each step the signal with the strongest power, on average we have that $u \in [R_{\mathrm{I},k},\infty)$. To find the unconditional success probability, we take the expectation over $u$ as expressed in (5) which concludes the proof. □

Notice that (5) cannot be further simplified as $C(b(r),\alpha)$ is a function of $r$. In the following lemma, the success probability is derived to cancel the strongest signal.

*Lemma 2:* Consider an MBS that successfully canceled the $k-1$ strongest signals. Then, the success probability to decode the $k$th strongest signal is given by

$$\mathbb{P}_{\mathrm{s,can}}(\eta, k) = \frac{1}{(1+\eta^{2/\alpha}C(1/\eta^{2/\alpha},\alpha))^k} \quad (10)$$

*Proof:* In the SIC scheme, interferers are canceled according to descending received signal power. To perform an exact analysis, we consider the order statistics $X_{(j)}$ of the signal power to define the probability of successfully decoding the $k$th strongest signal. After successfully decoding and subtracting $k-1$ signals from the incoming multi-user signal, the success probability can be written as

$$\mathbb{P}\left[\frac{X_{(k)}}{\sum_{i\in\Omega_j^k} X_{(i)}} \geq \eta\right] = \mathbb{P}\left[\sum_{i=k+1}^{\infty} X_{(i)} \leq X_{(k)}/\eta\right]. \quad (11)$$

The cumulative distribution function (CDF) of the sum of order statistics requires to define the joint distribution of infinitely many order statistics, which is unwieldy to solve [15]. Therefore, we assume that averaged over time the order statistics are determined by the distance, such that $|X_{(j)}| \geq |X_{(i)}|$ with $i < j$ is equivalent to $v_j \leq v_i$. When the strongest signal is decoded and subtracted from the received multi-user signal, this means that on average the remaining interferers will be further away than the canceled signal.

$$\mathbb{P}_{\text{s,SIC}}(\eta, n) = \mathbb{P}_{\text{s}}(\eta) + \sum_{i=1}^{n} \left( \prod_{k=0}^{i-1} (1 - \mathbb{P}_{\text{s, IC}}(\eta, R_{\text{I},k})) \right) \left( \prod_{k=1}^{i} \mathbb{P}_{\text{s,can}}(\eta, k) \right) \mathbb{P}_{\text{s,IC}}(\eta, R_{\text{I},i}) \tag{14}$$

This approximation leads to a remarkable simplification for the calculation of the success probability. The probability of successful cancellation of the $k$th interferer conditioned on $v_k$ can be expressed as

$$\begin{aligned} \mathbb{P}_{\text{s,can}}(\eta, k \,|\, v_k) &= \mathbb{P}\left( \frac{X_{(k)}}{I_{\Omega_j^k}} \geq \eta \right) \\ &\overset{(a)}{=} \exp\left( -\pi\lambda_{\text{u}} \eta^{2/\alpha} v_k^2 \int_{R_{\text{I}}(k)^2/(\eta^{2/\alpha} v_k^2)}^{\infty} \frac{1}{1+u^{\alpha/2}} du \right) \\ &\overset{(b)}{=} \exp\left( -\pi\lambda_{\text{u}}\ \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha) v_k^2 \right) \end{aligned} \tag{12}$$

where $(a)$ follows from analogue manipulations as in (8). Note that the residual interferers are located outside the circular area with radius $v_k$, wherefore $R_{\text{I}}(k) = v_k$ and the function $C(1/\eta^{2/\alpha}, \alpha)$ in $(b)$ is independent of $v_k$. Deconditioning with respect to $v_k$, we get

$$\begin{aligned} \mathbb{P}_{\text{s,can}}(\eta, k) &= \int_0^{\infty} \exp\left( -\pi\lambda_{\text{u}} \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha) r^2 \right) \\ &\qquad \exp(-\pi\lambda_{\text{u}} r^2) \frac{2(\pi\lambda_{\text{u}} r^2)^k}{r\Gamma(k)} dr \\ &= \frac{(\pi\lambda_{\text{u}})^k}{\Gamma(k)} \int_0^{\infty} \exp\left( -\pi\lambda_{\text{u}} (1 + \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha)) r^2 \right) \\ &\qquad r^{2k-2} dr^2 \\ &= \frac{(\pi\lambda_{\text{u}})^k}{\Gamma(k)} \int_0^{\infty} \exp\left( -\pi\lambda_{\text{u}} (1 + \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha)) u \right) \\ &\qquad u^{k-1} du \\ &= \frac{(\pi\lambda_{\text{u}})^k}{\Gamma(k)} (\pi\lambda_{\text{u}} (1 + \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha))^{-k} \Gamma(k) \\ &= \frac{1}{(1 + \eta^{2/\alpha} C(1/\eta^{2/\alpha}, \alpha))^k}. \end{aligned} \tag{13}$$

□

It is worthwhile to note that (10) is independent of $\lambda_{\text{u}}$. This is in line with [16] where the authors prove that the probability to successfully cancel at least $k$ interferers is scale invariant with respect to the density as long as the analysis is restricted to the power-law density case. Using Lemma 1 and 2, we can now formulate the following theorem.

*Theorem 1:* The coverage probability $\mathbb{P}_{\text{s,SIC}}$ for a receiver that applies SIC and where maximum $n$ interferers can be canceled is given by (14) at the top of this page, where $\mathbb{P}_{\text{s,IC}}(\eta, R_{\text{I},k})$ and $\mathbb{P}_{\text{s,can}}(\eta, k)$ are defined as in (5) and (10), respectively.

*Proof:* Since the success of SIC occurs as one of the steps described in (2) is successful, the proof follows directly from the definition of the sequence of events and the derivation of $\mathbb{P}_{\text{s,IC}}$ and $\mathbb{P}_{\text{s,can}}$ in Lemma 1 and 2. □

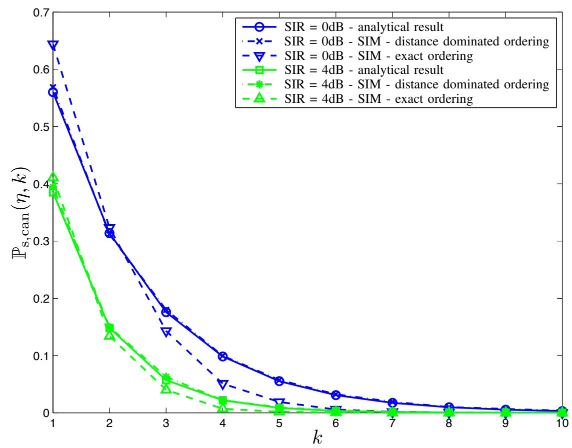


Fig. 1. Success probability for canceling the $k$th interferer for different values of the SIR. The path loss exponent is chosen as $\alpha = 4$.

## IV. Numerical Results

In this section, we provide some numerical results that illustrate the effectiveness and expected benefits from SIC. Moreover, the results provide a guideline for the receiver computational requirements corresponding to the number of cancellations that result in an appreciable enhancement of the receiver performance.

We consider a network of MBSs arranged over the two-dimensional plane with density $\lambda_{\text{m}} = 10^{-4}\ /\text{m}^2$. We assume a fully loaded network where each cell allocates at a given time every subchannel to an active user. Hence, the density of mobile users on subchannel $j$ is given by $\lambda_{\text{u}} = 10^{-4}/\text{m}^2$. In Fig. 1, $\mathbb{P}_{\text{s,can}}$ is depicted for different values of the threshold as a function of the order of the canceled signal power. Simulation results are added to validate the model. When the received signal power is ordered according to the distance, the simulations coincide with the analytical results, and a good agreement between analysis and simulations is achieved when the ordering is performed based on the joint effect of distance and fading. The figure illustrates that the probability to cancel an interferer decreases quickly with the order of cancellation and with increasing target SINR. Figure 2 illustrates the success probability in the presence of SIC as a function of the threshold for different values of the maximum number of cancellations. So as to validate our analysis, we compare the results with bounds that have been proposed in [6] for the scenario of spectrum sharing between cellular and mobile ad hoc networks (MANET). In this work, the authors consider both the spatial distribution of the nodes and the fading affecting each link. The derivation of the bounds is based on the separation of interferers into

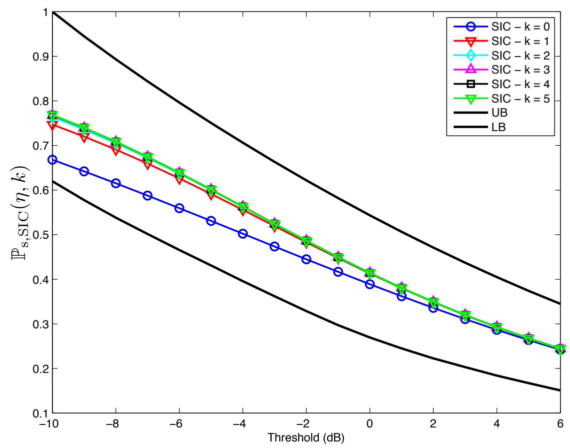


Fig. 2. Coverage probability in the presence of SIC for different values of the maximum number of cancellations. The blue curve represents the success probability when no IC technique is used.

groups of strong and weak interferers, where each strong interferer alone can cause outage. Interference cancellation is performed in descending order or received signal power, and the received power of each interferer intended for cancellation must exceed the SoI signal power multiplied with a factor $\kappa > 1$. The model proposed in [6] can be applied to model a single-tier cellular network, and the first observation is that the curves derived by our analysis strictly fall within the bounds. Further, we note a modest improvement in the success probability when SIC is applied for threshold values lower than 2 dB, whilst for higher threshold values the improvement is negligible. The numerical results illustrate that the cancellation of the first order interferer has a sensible effect on the receiver performance, while the cancellation of higher order interferers yields a marginal improvement of the success probability.

## V. Conclusions

In this work, the success probability is derived for uplink transmissions in a single-tier cellular network considering successive interference cancellation. SIC is modeled as a sequence of events, where success of the SIC scheme is met as one of the consecutive events is successful. To define the SIC uplink success probability, two lemmas are proposed which define the success probability of decoding the SoI after cancellation of the $k$ strongest signals, and the success probability of decoding the $k$th strongest signal. The numerical results conform with bounds that have been proposed in literature. Moreover, the analysis allows to evaluate the attainable benefits of SIC and illustrates the diminishing effectiveness of canceling consecutive interferers. The possibilities for future work are numerous and include the relaxation of the assumption of perfect cancellation and the extension to multi-tier networks.

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