

# Random Access Networks with Spatial Reuse

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**Abstract**—Providing ultra-reliable, low-latency and massive access is a technical challenge that demands a redesign of current Media Access Control (MAC) layer in wireless cellular networks. This work focuses on studying the conventional slotted ALOHA protocol and ways to improve its efficiency with the objective of providing a solution to the massive access of terminals. In particular, we concentrate on the case where multiple neighboring cells use the same resources, so that the system operates under inter-cell interference. While in conventional slotted ALOHA, terminals transmit with a fixed probability, in our scenario we propose instead to exploit channel-state information at terminals so as to define (minimum) signal-to-noise and (maximum) interference conditions, under which a terminal is allowed to transmit. We conduct a theoretical analysis for a simple scenario with Rayleigh fading where the system throughput is shown to scale linearly with the number of coexisting cells and in logarithmic scale with the number of terminals per cell.

**Index Terms**—Random access, ALOHA, interference, opportunistic channel aware, massive connections

## I. INTRODUCTION

Wireless communication systems must continuously adapt to new user and traffic demands. The introduction of a massive and diverse multitude of Internet of Things (IoT) devices communicating in smart cities or factory automation scenarios imposes rethinking communications in conventional cellular systems. In Europe, for instance, over 1.9 billion new IoT connections are expected to appear in smart buildings and homes by 2025, [1]. Commonly, terminals are equipped with batteries transmitting sporadic data. Cellular systems should provide simple protocols enabling low-overhead, low-latency and reliable communication for massive access [2], [3].

Ambitious requirements can hardly be satisfied by current wireless systems based on resource reservation. To this end, 5G NR has introduced the grant-free random access procedure [4]. Random access protocols are media access control (MAC) protocols targeting simplicity and low overhead, where terminals transmit in a probabilistic way. However, their main drawback is their efficiency. For example, slotted ALOHA [5] without feedback can only use up to  $\frac{1}{e} = 0.3679$  of the devoted wireless resources. Among the different research works trying to improve its efficiency, [6] notably shows that the system throughput of a single-antenna base station (BS) increases logarithmically in the number of terminals whenever

the transmission is done opportunistically when the current channel gain exceeds a given threshold.

The concept derived in [6] has been extended to a multicell scenario in [7], where multiple single-antenna BSs share the same resources, see Fig. 1. Basically, terminals adjust the transmission probability as a function of the generated interference to neighboring BSs and the channel with the corresponding BS. It is claimed that the sum throughput of the system scales with the number of coexisting BSs and terminals. Therefore, the poor efficiency of slotted ALOHA can be mitigated by allowing a spatial reuse of multiple cells whenever inter-cell interference is properly managed. This is an important property that should be exploited when dealing with a massive number of connected devices.

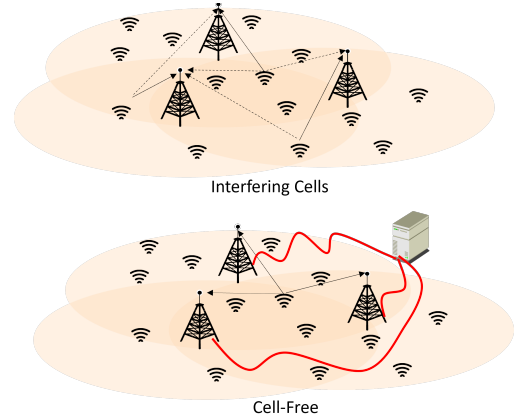


Fig. 1. Top) Interference-based cells. Bottom) Cell-Free. All BSs are equipped with a single antenna.

The coexistence of cells can be grouped into three categories. *Interference-based cells (IC)*: All terminals are allowed to transmit on the shared resources and each BS is performing a single-terminal decoding taking into account the interference, see Fig. 1-Top). *Orthogonal cells (OC)*: Cells employ orthogonal resources (i.e. time slots) to avoid the interference from terminals of neighboring cells. *Cell-Free (CF)*: All BSs are connected through a backhaul to a central processor unit (CPU) where all the processing is done. Just a single terminal is decoded each time. This scheme is akin to having a single BS with  $M$  distributed antennas, see Fig. 1-Bottom).

This work investigates under what circumstances a slotted ALOHA-based protocol might improve beyond the throughput attained by networks with a resource reservation, e.g., Time

Division Multiple Access (TDMA). In our comparisons, we do not take the signalling overhead into account. Although the CF-based approach assumes multiple antennas, so that concepts of multi-user in massive MIMO can be applied [8], we concentrate on a simple protocol where terminals set their transmission rate based on their local channel state information. Having a multi-user detector imposes that BS and terminals must exchange information in order to adjust their transmission rates, so all transmissions will be decoded correctly. Furthermore, since we are pursuing low latency and reliability, we would like that each transmission from terminals be decoded successfully at the BS. We do not consider any protocol to resolve any collisions, such as the ones in [9], because the latency of each terminal would be increased.

The main contributions of the present paper can be summarized as follows:

- The efficiency of conventional random access networks can be improved by allowing the spatial reuse of resources. Despite the interference, the attained throughput can be larger than in the TDMA approach.
- The criterion for adjusting the interference proposed in [7] takes into account the total generated interference. Here, a threshold for each interfering BS is considered. Hence, the inter-cell interference is dependent on the terminal activity in neighboring cells and the threshold.
- The interference-aware transmission scheme, Section IV, shows that the slotted ALOHA performance can scale linearly with the number of coexisting cells, and under what circumstances the inter-cell interference is negligible.
- The channel-interference aware transmission scheme, Section V, depends on the parameter  $\delta$  that defines a trade-off between how the sum throughput scales linearly with the number of cells or logarithmically with the number of terminals.

## II. SYSTEM MODEL

The scenario consists of  $M$  cells, each cell with a single-antenna BS and  $N_t$  single-antenna terminals as is shown in Fig. 1. All terminals present independent fading. It is assumed that BSs in the downlink (DL) are transmitting pilot signals, so each terminal has an estimation of its channel gains to all neighboring BSs. To simplify the analysis, we neglect the specific users' cell distribution and channel geometry and assume the same pathloss with the desired BS and the neighboring ones. The fading distribution is assumed to be equal across terminals.

When the system works in *OC* mode, the received signal at the  $m$ -th BS is given by

$$y_m = \sum_{k=1}^{N_m} h_{m,k} x_{m,k} + n_m \quad (1)$$

where  $h_{m,k} \in \mathbb{R}$  defines the wireless channel fading coefficient from the  $k$ -th terminal to the  $m$ -th BS with power  $\alpha_{m,k} = |h_{m,k}|^2$ ,  $n_m$  stands for the additive noise with power  $\sigma_m^2$ ,  $x_{m,k} \in \mathbb{R}$  is the signal transmitted by the  $k$ -th terminal and associated with the  $m$ -th BS, with power

constraint  $E(x_{m,k}^2) = p_{tx}$ , and  $N_m$  is the number of active terminals. For the *CF* mode, the received signal is similar to (1), but all  $MN_t$  terminals are associated to the equivalent multi-antenna BS.

Likewise, the received signal under the *IC* mode is

$$y_m = \sum_{k=1}^{N_m} h_{m,k} x_{m,k} + \sum_{i=1, i \neq m}^M \sum_{k=1}^{N_i} h_{i,k} x_{i,k} + n_m \quad (2)$$

where  $N_i$  is the transmitting terminals in neighboring  $i$ -th cell.

The communication in the uplink (UL) follows the simple slotted ALOHA-type protocol, assuming that the channel remains constant over the whole time slot, and it varies between slots following an independent and identically distributed (i.i.d.) Rayleigh random distribution. A collision is defined when multiple terminals from the same cell are transmitting simultaneously. On the other hand, the interfering signals from neighboring cells are treated as additive noise.

The system sum throughput under slotted ALOHA becomes,

$$\begin{aligned} S(r, \theta, N_t) &= \frac{MN_t}{\omega} \Pr\{\text{No collision}\} \Pr\{r \leq R\} r \\ &= \frac{MN_t}{\omega} \theta(1 - \theta)^{N_t-1} \Pr\{r \leq R\} r \end{aligned} \quad (3)$$

where  $\omega$  denotes the reuse factor ( $\omega = M$  for *OC* mode,  $\omega = 1$  for *CF* and *IC* modes). Variable  $r$  stands for the selected transmission target rate. The parameter  $\theta$  defines the transmission probability of terminals that depends on the transmission schemes considered in Sections III, IV and V. Finally, the random instantaneous achievable rates  $R$  are,

$$R_{m,k}^{\text{OC}} = \log_2 \left( 1 + \frac{p_{tx}}{\sigma_m^2} \alpha_{m,k} \right), \quad (4)$$

$$R_{m,k}^{\text{CF}} = \log_2 \left( 1 + \frac{p_{tx}}{\sigma_m^2} \sum_{m=1}^M \alpha_{m,k} \right), \quad (5)$$

$$R_{m,k}^{\text{IC}} = \log_2 \left( 1 + \frac{p_{tx} \alpha_{m,k}}{\sigma_m^2 + \sum_{i, i \neq m}^M I_i} \right), \quad (6)$$

where  $I_i$  denotes current received inter-cell interference generated by terminals in the  $i$ -th cell, see (2).

The average sum throughput in (3) depends on how we define the transmission probabilities at each cell,  $\theta$ , and on the selected target rate,  $r$ . The target rate  $r$  can be selected to maximize the average throughput or, in contrast, to ensure high reliability in decoding the message (e.g.,  $\Pr\{r \leq R\} = 0.99$ ). Notice that under the interference-based scenario, the target rate selection must consider the interference,  $I_i$  presented in (6), which depends on the activity of interfering terminals.

We consider four transmission schemes that differ depending on the circumstances under which a terminal is allowed to transmit. All policies are described in Table I. The *Slotted ALOHA* is the conventional one, where terminals transmit with a given probability defined by the system. It is assumed a random uniform distribution to decide when to transmit. *Channel Aware* scheme takes into account the channel with the associated BS, transmitting once the channel exceeds a given threshold  $\alpha^{\min}$ . The policy in the *Interference Aware*

scheme allows the transmission whenever the channel with neighboring BSs is below the threshold  $\alpha_{-m,k} < \alpha^{\max}$ , where the subindex  $-m$  refers to all BSs except  $m$ -th one. *Channel-Interference Aware* scheme combines the concepts of the two previous schemes, a terminal is allowed to transmit in case the channel with the associated BS exceeds  $\alpha^{\min}$  and the interference channel with neighboring BS is less than  $\alpha^{\max}$ .

TABLE I  
EVENT WHEN A TERMINAL IS ALLOWED TO TRANSMIT

Transmission scheme	Condition
Slotted ALOHA (SALOHA)	$U(0,1) \leq \frac{1}{N_t}$
Channel Aware (CA)	$\sum_{l=1}^L \alpha_{l,k} \geq \alpha^{\min}$
Interference Aware (IA)	$\alpha_{-m,k} < \alpha^{\max}$
Channel-Interference Aware (CIA)	$\alpha_{m,k} \geq \alpha^{\min}, \alpha_{-m,k} < \alpha^{\max}$

### III. CHANNEL AWARE (CA)

The transmission scheme based on *channel aware* policy can be applied when cells are working under *OC*, *CF* modes. The scenario with one BS equipped with  $L = 1$  antenna has been investigated in [6], but its extension to  $L$  antennas, i.e. the *CF* mode with  $L = M$ , is straightforward. The channel statistics can be modeled by a chi-square distribution with  $2L$  degrees. Terminals transmit according to the condition presented in the second row in Table I.

In terms of system throughput it turns to be asymptotically optimal to force the transmission probability inversely proportional to the number of terminals, [6]. Consequently, the threshold is selected to satisfy,

$$\theta^{\text{CA}}(\alpha^{\min}, L) = \int_{\alpha^{\min}}^{\infty} \frac{x^{L-1} \exp(-\frac{x}{2})}{2^L \Gamma(L)} dx = \frac{1}{N_t} \quad (7)$$

When  $L = 1$ , the threshold is found in closed-form,  $\alpha^{\min} = 2 \log(N_t)$ . Otherwise, it can be found numerically by means of the Matlab function  $\alpha^{\min}(L) = \text{chi2inv}(\frac{1}{N_t}, 2L)$ .

The sum throughput when we guarantee reliability, i.e.  $\Pr\{r \leq R^{\text{OC}, \text{CF}}\} = 1$ , becomes,

$$S^{\text{OC-CA}} = \left(1 - \frac{1}{N_t}\right)^{N_t-1} \log_2 \left(1 + \frac{2p_{tx}}{\sigma^2} \log(N_t)\right) \quad (8)$$

$$S^{\text{CF-CA}} = \left(1 - \frac{1}{MN_t}\right)^{MN_t-1} \log_2 \left(1 + \frac{p_{tx}}{\sigma^2} \alpha^{\min}(M)\right) \quad (9)$$

### IV. INTERFERENCE AWARE (IA)

This transmission scheme assumes the transmission policy defined in the third row in Table I. A terminal can transmit whenever the channel with each of the neighboring BS is below the threshold  $\alpha^{\max}$ . In such a case, the transmission probability under Rayleigh fading is transformed into,

$$\theta^{\text{IA}}(\alpha^{\max}) = \left(1 - \exp\left(-\frac{\alpha^{\max}}{2}\right)\right)^{M-1} \quad (10)$$

The received interference depends on the activity in neighboring cells. Since the transmission is probabilistic, the number of active interfering terminals is a binomial random

variable that depends on their transmission probability,  $\theta$ . We can model the maximum number of interfering terminals we can have with probability  $\varepsilon$ , and thus characterizing an upper bound on the interference level that will be experienced in the serving cell. The maximum number  $\psi$  of interfering terminals at the  $i$ -th neighboring cell is defined as,

$$\Pr\{N_i \leq \psi(\theta, \varepsilon)\} = \varepsilon \quad (11)$$

$$\psi(\theta, \varepsilon) \in N \mid \sum_{q=0}^{\psi} \binom{N_t}{q} \theta^q (1-\theta)^{N_t-q} \leq \varepsilon$$

For example, in case of having  $N_t = 100$  and  $\theta = \frac{1}{N_t}$ , we get  $\psi = \{1, 2, 4, 5\}$  when  $\varepsilon = \{0.73, 0.90, 0.99, 0.999\}$ .

In order to have a reliable transmission we need that the target rate,  $r$  will be less or equal than  $R_{m,k}^{\text{IC}}$  presented in (6). Such transmission might fail depending on the current channel or interference levels. However, thanks to the upper bound on interfering terminals in (11), the reliability of the transmission can be lower bounded by,

$$\Pr\{r \leq R^{\text{IC}}\} \geq \varepsilon \Pr\{r \leq R'\} \quad (12)$$

$$R' = \log_2 \left(1 + \frac{p_{tx} \alpha_{m,k}}{\sigma^2 + p_{tx}(M-1)\psi(\theta, \varepsilon)\alpha^{\max}}\right) \quad (13)$$

The parameter  $\alpha^{\max}$  can be obtained in closed-form in case we force  $\theta^{\text{IA}} = \frac{1}{N_t}$ ,

$$\alpha^{\max} = -2 \log \left(1 - \left(\frac{1}{N_t}\right)^{\frac{1}{M-1}}\right) \quad (14)$$

This threshold, and consequently the interference level, decreases when the number of terminals increases. In turns out that having a certain number of terminals transmitting with probability defined in (10), the interference becomes negligible when compared with the noise power. The required number of terminals is given by,

$$N_t \gg N_t^{\text{IA}} = \left(\frac{\exp\left(\frac{\sigma^2}{2p_{tx}(M-1)\psi(\theta, \varepsilon)}\right)}{\exp\left(\frac{\sigma^2}{2p_{tx}(M-1)\psi(\theta, \varepsilon)}\right) - 1}\right)^{M-1} \quad (15)$$

$$R' \approx \log_2 \left(1 + \frac{p_{tx} \alpha_{m,k}}{\sigma^2}\right) \quad (16)$$

This result is a consequence of the Rayleigh channel statistics. The transmission probability reduces when there are many terminals. Thus, if we employ the statistic of the channel to adjust the transmission probability, the terminals can wait until the interference channel becomes small.

### V. CHANNEL-INTERFERENCE AWARE (CIA)

Section III showed that by tuning the threshold  $\alpha^{\min}$  we can improve the throughput of the slotted ALOHA, obtaining a throughput that increases in logarithm scale with the number of terminals. On the other hand, in section IV, we derived the conditions on the threshold  $\alpha^{\max}$  to adjust an upper bound of the interference generated to neighboring cells, leading to a negligible interference when the condition (15) is satisfied. Here, we investigate a transmission scheme based on the policy

defined in the last row in Table I combining the concepts of channel-aware and interference-aware. Now, the transmission probability is defined by,

$$\theta^{\text{CIA}} = \exp\left(\frac{-\alpha^{\min}}{2}\right) \left(1 - \exp\left(\frac{-\alpha^{\max}}{2}\right)\right)^{M-1} \quad (17)$$

The threshold selection should be done for maximizing the achievable sum throughput, (3). In case we upper bound the number of interfering terminals according to, (11), then we should optimize,

$$\underset{r, \alpha^{\min}, \alpha^{\max}}{\text{maximize}} MN_t \varepsilon \theta^{\text{CIA}} (1 - \theta^{\text{CIA}})^{N_t-1} \Pr\{r \leq R'\} r \quad (18)$$

with  $R'$  defined in (13). Nevertheless, the optimization presented in (18) is non-convex and must be addressed by an exhaustive search.

We propose a simple procedure where we split the transmission probability into two terms, one associated to the channel-aware threshold ( $\alpha^{\min}$ ) and the other to the interference-aware threshold ( $\alpha^{\max}$ ), both selected to force  $\theta^{\text{CIA}} = \frac{1}{N_t}$ , i.e.

$$\left(\frac{1}{N_t}\right)^{1-\delta} \left(\frac{1}{N_t}\right)^{\delta} = \theta^{\text{CA}} \theta^{\text{IA}} \quad (19)$$

Notice, that by adjusting  $\delta \in (0, 1]$  we are balancing the weight of the channel aware and interference aware concepts. Now we can employ the results obtained in previous sections, so that the thresholds are defined by,

$$\alpha^{\min} = (1 - \delta) \alpha_{\text{CA}}^{\min} = 2(1 - \delta) \log(N_t) \quad (20)$$

$$\alpha^{\max} = -2 \log\left(1 - \left(\frac{1}{N_t}\right)^{\frac{\delta}{M-1}}\right) \quad (21)$$

where  $\alpha_{\text{CA}}^{\min}$  is the threshold obtained in (7). The interference can be assumed negligible with respect the noise power when,

$$N_t \gg N_t^{\text{CIA}} = (N_t^{\text{IA}})^{\frac{1}{\delta}} \quad (22)$$

with  $N_t^{\text{IA}}$  the threshold presented in (15). Notice, that the number of terminals to satisfy the interference-free condition increases exponentially with  $\frac{1}{\delta}$ . The sum throughput under a reliable transmission is then given by,

$$S_{\epsilon}^{\text{CIA}} \geq \varepsilon M \left(1 - \frac{1}{N_t}\right)^{N_t-1} r_{\epsilon}^{\text{CIA}} \quad (23)$$

$$r_{\epsilon}^{\text{CIA}} = \log_2 \left(1 + \frac{p_{tx} \alpha^{\min}}{\sigma^2 + p_{tx} (M-1) \psi(\theta, \varepsilon) \alpha^{\max}}\right) \approx \log_2 \left(1 + \frac{p_{tx}}{\sigma^2} 2(1 - \delta) \log(N_t)\right) \quad (24)$$

where the  $\varepsilon$  factor comes from characterizing the interference level as it was shown in (12). The approximation presented in (24) becomes valid when (22) is satisfied.

## VI. RESULTS

We evaluate a network with  $M$  symmetric neighboring cells, each with a single-antenna BS and  $N_t$  terminals transmitting according to the policies defined in Table I. For comparison purposes, we also consider the possibility of a TDMA system,

where BSs reserve resources to each of the active terminals, avoiding any collision. The approaches are compared in terms of maximum sum throughput and  $\epsilon$  – outage throughput,

$$\underset{r}{\text{maximize}} S \quad (25)$$

$$S_{\epsilon} = S(r) \text{ with } \Pr\{r \leq R\} = \epsilon \quad (26)$$

Notice that the main difference between both metrics is that in the second one, (26), terminals select a target rate so that each transmission that has not collided is decoded with probability  $\epsilon$ . In contrast, the first metric, (25), we might select a target rate that will not be decoded every time.

With the objective of differentiate the various transmission schemes and cell modes, we will use the terminology (**type of coexistence-protocol**) leading to these cases: OC-TDMA, CF-TDMA, OC-SALOHA, CF-SALOHA, OC-CA, CF-CA, IC-IA, and IC-CIA. Where the TDMA-ones assume that terminals can transmit following a TDMA access scheme in each cell. On the other hand, the transmission schemes CA, IA and CIA are the ones described in sections III, IV, V, respectively.

Table II presents the obtained throughput for different transmission schemes under the criteria given in (25)-(26) when  $N_t$  is large and throughput does not depend on the number of terminals. When the throughput is maximized, the difference between TDMA and SALOHA is the factor due to the probability of collisions (i.e. 0.3678 factor). The CF-based schemes attain better results thanks to the interconnection of BSs, allowing an increase of the received signal-to-noise ratio (SNR) per terminal. Additionally, we can observe that the results obtained when throughput is maximized come at the cost of reducing the reliability on each transmission when compared with outage throughput. For example, OC-TDMA can attain 0.6276 bps/Hz but each transmission only will be decoded with probability 0.5103. Nevertheless, if we force that each transmission must be decoded with probability  $\epsilon = 0.99$ , then the throughput reduces to  $S_{\epsilon} = 0.02871$  bps/Hz.

TABLE II  
REFERENCE THROUGHPUT VALUES FOR LARGE NUMBER OF TERMINALS

Protocol	SNR	$M$	Max $S$	$\Pr\{r \leq R\}$	$S_{\epsilon}$
OC-TDMA	0	3	0.62762	0.5103	0.02871
OC-SALOHA	0	3	0.2309	0.5103	0.0073
CF-TDMA	0	3	1.62186	0.7835	0.90465
CF-TDMA	0	5	2.3110	0.8656	1.83115
CF-SALOHA	0	3	0.5966	0.7835	0.3311
CF-SALOHA	0	5	0.8501	0.8656	0.6732

Fig. 2 depicts the throughput values for the channel aware-based schemes, verifying the throughput scalability with the number of terminals. Additionally, we observe that maximizing the throughput and guaranteeing a reliable transmission tends to the same value.

Results for the interference aware-based schemes are explored in Fig. 3, where the throughput tends to the performance of a system with  $M$  BSs without interference whenever the number of terminals satisfy the condition in (15). The condition for  $M = 2$  is  $N_t \gg 9$ , while the throughput

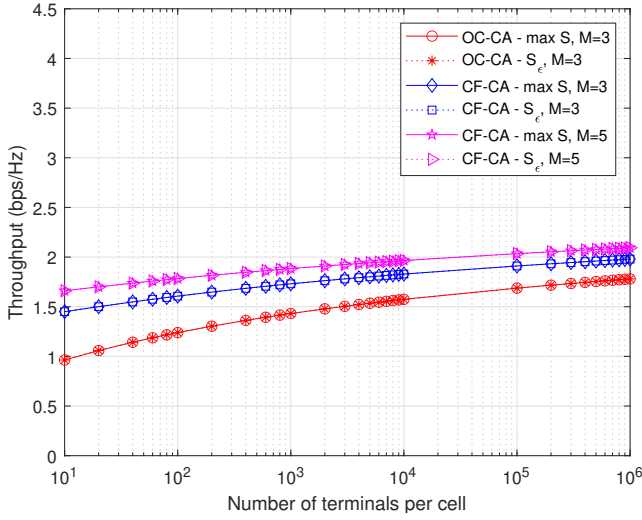


Fig. 2. Throughput results as a function of number of terminals per cell for CA-based transmission schemes. SNR=0 dB

saturates at  $N_t \approx 100$  to  $S = 0.461$  bps/Hz. Notice that for larger  $M$  we get better results, for example with  $M = 3$  we get similar results that the OC-TDMA. Furthermore, when theoretical results are compared with simulations, we can see that when maximizing the throughput Fig. 3-Top, results do not match, and the theoretical ones are a lower bound. This is a consequence of the upper bound used for the interference, (12). In contrast, simulations match with the outage throughput, Fig. 3-bottom. This is because the selected target rate is done according to the lower bound with probability  $\epsilon$ . Actually, the selected rate will be decoded with probability  $> \epsilon$ .

Fig. 4 presents the value of  $N_t^{IA}$  in (15) as a function of SNR and different values of  $M$  and  $\epsilon$ . The number of required terminals to satisfy the condition of interference-free increases with the SNR. For example at SNR=-5 dB, the interference-free can be attained when  $N_t \geq \{4, 30, 500\}$  for  $M = \{2, 3, 4\}$  and  $\epsilon = 0.99$ , respectively. In contrast, for SNR=10 dB, more terminals are required,  $N_t \geq \{80, 2 \times 10^4, 10^7\}$ .

The results for CIA-based scheme under condition (26) are presented in Fig. 5 for  $M = 2, 3$  and  $\delta = 0.9, 0.5, 0.3$ . Results are compared with throughput values obtained by means of an exhaustive search over variables  $\alpha^{\min}, \alpha^{\max}$  in the optimization problem described in (18). We can observe:

- Simulations agree with the theoretical derivations.
- By adjusting the parameter  $\delta$  different types of performance are possible. We can observe that once the number of terminals satisfy (22), i.e. interference becomes negligible, then throughput increases in logarithm scale with the number of terminals and  $\delta$  according to (20).
- The proposed scheme using  $\delta \approx 0.5$  is the one that gets a performance similar to the exhaustive search, but with some differences for a small number of terminals.
- The number of coexisting cells should be adjusted as a function of the number of terminals. For the configuration shown in Fig. 5 we should allow  $M = 2$  cells when

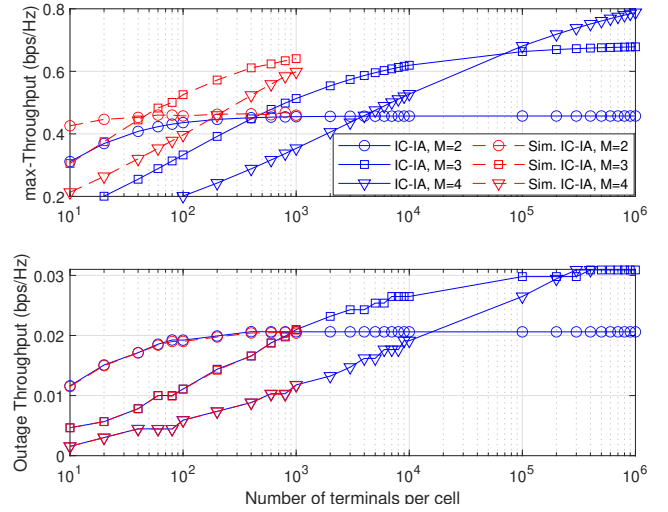


Fig. 3. Throughput as a function of number of terminals per cell for IA-based transmission scheme. SNR=0 dB. Top) rate is selected according to (25), Bottom) rate selected according to (26).

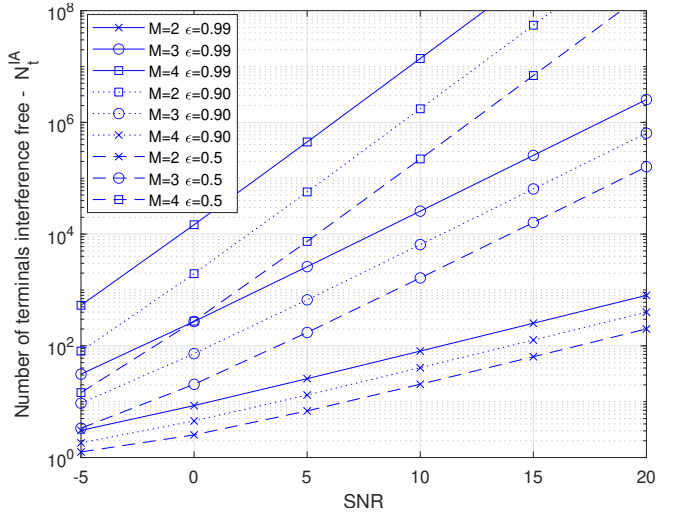


Fig. 4. Threshold on the number of active terminals required to meet the interference-free assumption of (15).

there are  $N_t \leq 4000$ , otherwise it is worth to consider an additional cell ( $M = 3$ ).

- The present approach improves the attained throughputs by CF-TDMA or CF-CA, see Table II and Fig. 2, respectively. CF-TDMA with  $M = 3$  obtains  $S_\epsilon = 0.9046$ , while the proposed IC-CIA with  $M = 2$  and  $N_t \geq 30$  improves that result. Moreover, the obtained throughput with IC-CIA at  $N_t = 10^3$  is 2 bps/Hz using  $M = 2$ , improving around 38%, 14% and 5% the throughput obtained with the OC-CA, CF-CA  $M = 3$  and CF-CA  $M = 5$ , respectively. These gains obtained by IC-CIA can be larger in case we had more terminals and  $M = 3$  cells are coexisting.

Fig. 6 illustrates the performance for higher and lower SNR values (10 dB, -5 dB). For low SNR values the IC-



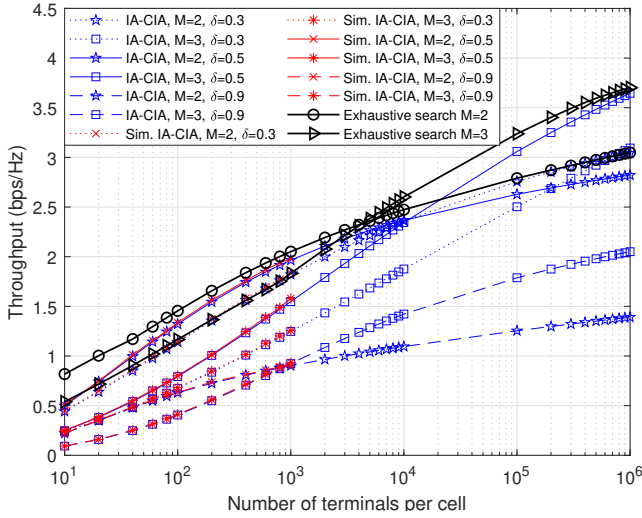


Fig. 5. Throughput as a function of number of terminals per cell for CIA-based transmission scheme, and scheme using thresholds obtained by (18). SNR=0 dB.

CIA with  $\delta = 0.5$  provides a good approximation to the optimal one, but when the SNR increases, then  $\delta$  parameter is dependent on the number of terminals. For example, with  $M = 2$ ,  $\delta = 0.7$  is a better approximation for  $N_t < 10^4$  and afterwards the best approximation is  $\delta = 0.5$ . Another aspect to remark is that the number of interfering cells allowed to increase the system throughput is dependent on the SNR. For example, at low SNR having  $M = 3$  is always better than using  $M = 2$ , but for larger SNRs it is needed  $N_t = 4000$  and  $N_t = 10^5$ , at SNR = 0, 10 dB, respectively. Results are compared with the transmission scheme presented in [7]. That proposal is not exactly the same as the IC-CIA, because [7] includes a constraint on the total interference injected on the system, rather than per neighboring BS. Furthermore, [7] imposes parameter  $\alpha^{\max} = \frac{\sigma^2}{p_{tx}}$  while in our case we propose a threshold that depends on the number of terminals and the  $\delta$ , see (21). A fair comparison is possible for  $M = 2$ , as it is illustrated in Fig. 6. The proposed scheme IC-CIA is able to improve the obtained performance by [7] thanks to the ability of adjusting  $\delta$ -parameter.

## VII. CONCLUSIONS

Different schemes based on slotted ALOHA have been investigated to improve the efficiency of a random access network. It has been shown that the coexistence of multiple cells can be a solution for providing service to a massive number of terminals. This proposal allows improving the throughput of the system when terminals transmit opportunistically based in two thresholds, i.e. whenever the channel with the intended BS exceeds certain threshold and/or when the channel with interfering BSs are below another threshold. We have provided a theoretical analysis that has been confirmed with exhaustive simulations. The number of allowed coexisting cells depends on the number of terminals per cell and the SNR. The throughput of conventional slotted ALOHA can be improved linearly

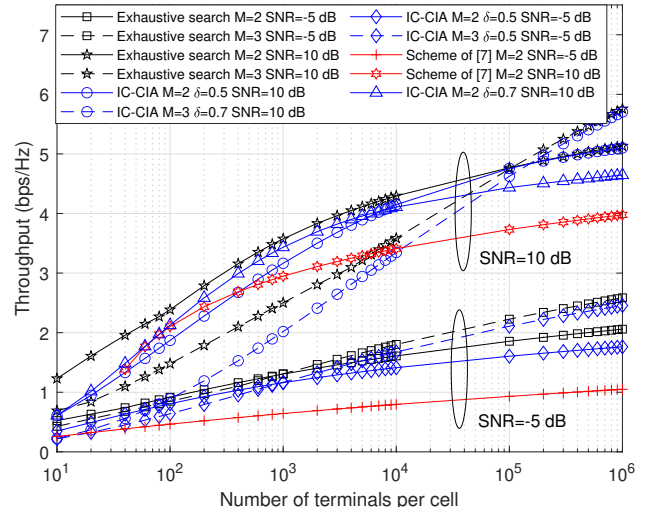


Fig. 6. Throughput as a function of number of terminals per cell for CIA-based transmission scheme, scheme using thresholds obtained by (18), scheme introduced in [7]. SNR=-5, 10 dB.

with the number of coexisting cells when an interference-aware scheme is considered, using just one threshold. When two thresholds are optimized, channel-interference aware, the throughput scales linearly with the number of BSs and in logarithm scale with the number of terminals, improving the TDMA schemes for certain configurations. As further work, we will explore how the obtained gains extend to more realistic scenarios where the geometry of terminals and the use of multiple antennas at the BS are included in the system model. Likewise, we will investigate algorithms based on artificial intelligence to estimate the channel state information and adjust the transmission probability.

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