Massive Machine Type Communications Uplink Traffic: Impact of Beamforming at the Base Station

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***Abstract*—As the number of machine type communications increases at an exponential rate, new solutions have to be found in order to deal with the uplink traffic. At the same time, new types of Base Stations (BS) that use a high number of antennas are being designed, and their beamforming capabilities can help to separate signals that have different angles of arrivals. In this paper, we consider a network where a BS serves a high number of nodes that lacks a receive chain, and we analyze the evolution of the outage probability as a function of the number of antennas at the BS. We then study the effect of an angle offset between the main beam and the desired node's direction in order to provide realistic results in a beam-switching scenario.**

I. Introduction

With an Internet of Things (IoT) market in exponential growth, analysts predict that between 20 and 50 billion devices will be connected worldwide by 2020 [1], to reach more than 100 billion devices by 2030 [2]. Such devices range from cellphones to a new type of device that will become more and more prominent: sensors. Sensors must have a small footprint and be long-lasting enough to be integrated in all kinds of environments. They are often based on very low power hardware, either to fulfill their task while battery powered, or because the small quantity of data they need to transfer does not require complex solutions. Moreover, reducing the energy consumption is also a desirable feature of IoT, since the energy needs of 100+ billion connected devices could lead to even more CO_2 emissions.

IoT networks aiming to serve a massive device deployment will have to address the uplink access problem. Indeed, such a problem is an important part of the *massive machine type communication* challenge [3], since even small packets transmitted sporadically will eventually contend as the number of devices grows. If packet collision becomes too high, then the effective overall capacity of these networks will drop, leading to their eventual failure. As such, finding solutions to the uplink access problem is of order.

One appealing way to deal with this problem is by using a massive Multiple-Input, Multiple-Output (m-MIMO) grid of antennas, which is essentially a MIMO array comprised of a very large number of antennas [4]. Such m-MIMO arrays can be used to generate precise beams (through beamforming) toward targeted directions or focus the reception of a signal from targeted directions [5], which can be used to separate received signals using their different angles of arrivals, thus reducing the possibilities of contention.

A review of the possible solutions for managing the transmissions of a very large number of objects under 5G networks is given in [3]. In that work, two general classes of solutions for this access are presented, namely the *grant-based* and *grant-free* schemes. In the grant-based class, the BS periodically sends a grant containing basic information pertaining to each node. The nodes have to wait until they receive such a grant to transmit. Such a method has been studied in [6], where they use beamforming to distribute different grants to each angle from the BS. In the grant-free class, the nodes can transmit whenever they want, which significantly saves control traffic when compared to a grant-based solution, but collisions are more likely to happen. This method has been studied in [7] with a focus on propagation delays, where each node is equipped with a massive number of antennas. They analyze the rate of successful uplink transmissions, given that the receiver can only discern nodes that are separated by a certain angle, but they do not take into account the path-loss of each node to the receiver and the actual received beamforming pattern. Furthermore, in this article, each node switches between sending or receiving, during half the time.

Herein we extend [7] by employing a real beamforming pattern, different transmission and duty cycle times, and by taking into account the path-loss between each node and the BS. We focus on simple IoT nodes that lack a receive chain, since the equalization and synchronization procedures used in this chain are known to be energy-consuming. Furthermore, such nodes are not aware of the other nodes' existence and can not cooperate. The numerical results presented herein are computed for a Sigfox-style network using an Ultra Narrow Band (UNB) scheme [8], but we will not take into account the effect of frequency randomness generated by the UNB scheme since it has already been studied [9] and [10]. Thereby, we will make the assumption that every node transmits on the same frequency.

Since the nodes can only transmit, we will focus on the performance of the Random Access Channel (RACH) with respect to the interference seen between colliding transmissions from nodes on the uplink. We study the scenario where a high number of those nodes are served with one many-antenna BS in Line Of Sight (LOS) condition. The study will first focus on determining the number of collisions on such a system, and then on the effect of the number of antennas on the BS regarding the Outage Probability (OP).

The remainder of the paper is divided as follows. Section II details the adopted system model. Then, sections III and IV deal with the analysis of the OP with at most one interferer for the one- and many-antenna case, respectively. Section V extends the analysis for an arbitrary number of interferers, and numerical examples are provided in section VI. The final remarks and conclusions are drawn in section VII.

II. System Model

We consider the scenario depicted in Figure 1, with one base station whose service area is taken as a disk, with a minimum radius of R_{min} and a maximum radius of R_{max}. A total of M IoT nodes are uniformly distributed in this area, and we focus on the transmission of one desired node N_d, whose distance from the BS is denoted r_d.

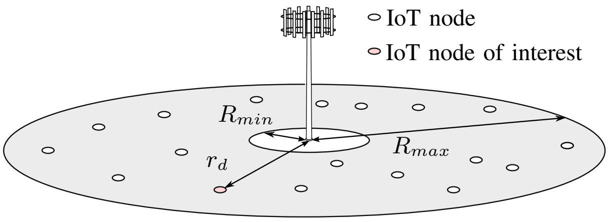

Fig. 1. Illustration of the network topology

Let $\mathcal{N} = \{N_1, \cdots, N_M\}$ be the set of nodes present in the service area. The set of active nodes is denoted $\mathcal{A} = \{N_m : \beta_m = 1\}$, such that $\mathcal{A} \subset \mathcal{N}$, where

$$\beta_m = \begin{cases} 0, & \text{if } N_m \text{ is inactive} \\ 1, & \text{if } N_m \text{ is active} \end{cases} . \tag{1}$$

Finally, the set of nodes which interfere with the desired node N_d is denoted $\mathcal{I}_d = \{\mathcal{A} \setminus N_d\}$. Knowing that every node transmits on the same frequency, this set contains all nodes that transmit at the same time as N_d, potentially disturbing the reception of its message. We denote $I = |\mathcal{I}_d|$ the number of overlapping transmissions.

From the uniform distribution of the nodes within the disk, the probability for a node N_m to be at a distance r from the BS is

$$\mathcal{P}(r_m = r) = \frac{2r}{R_{max}^2 - R_{min}^2}. \tag{2}$$

We make the assumption that all nodes transmit at the same power, denoted P_T, and the power received at the BS from a node N_m is denoted P_{R_m}. We consider that a message suffering interference is received correctly if the Signal to Noise plus Interference Ratio (SINR) is higher than a certain threshold. In our case, we can safely neglect the noise since the signal bandwidth is very narrow (UNB setting) and we can always scale P_T accordingly. Hence, the scenario at hand is an interference limited one and we can instead focus on the Signal to Interference Ratio (SIR) γ. Therefore, to correctly receive a message sent from node N_d, that suffers interference from a set of nodes $\mathcal{I}_d$, we must have

$$\gamma = \frac{P_{\mathrm{R}_d}}{\sum\limits_{\mathcal{I}_d} P_{R_i}} \geq \Gamma \tag{3}$$

where Γ is the SIR threshold.

Since we consider a LOS condition for all nodes with respect to the BS (we assume that the nodes are at ground level) the path loss for node N_m is given by the free space propagation rule $\left(\frac{\lambda}{4\pi d_m}\right)^{\alpha}$. We denote G_T and G_R respectively the transmission and the reception gains, with which we calculate the received power from node N_m :

$$P_{R_m} = P_T \left(\frac{\lambda}{4\pi r_m}\right)^{\alpha} G_T G_R. \tag{4}$$

We consider that the nodes' transmission lasts T_{TX}, and that the emission process for the set of all the non desired nodes follows a Poisson law, whose parameter is

$$\lambda = (M-1)\frac{t_2 - t_1}{T_{inter}}, \tag{5}$$

with T_{inter} being the average time interval between two beginning of transmissions for a single node, and $[t_1, t_2]$, with $t_2 - t_1 \leq T_{inter}$, being the time interval during which interference is analyzed.

III. Outage Probability With One Antenna And At Most One Interferer

In this section we will start with a simple setting comprised of 2 nodes: a desired and a possibly interfering node. We compute η, the OP of the network, given that the BS has one antenna and that the other node is either interfering (active) or not. The computation for an arbitrary number of nodes will be explained in section V. If we denote $\mathcal{P}(S)$ the probability of a successful transmission, we have

$$\eta = 1 - \mathcal{P}(S), \text{ with} \tag{6}$$

$$\mathcal{P}(S) = \mathcal{P}(I=0) + \mathcal{P}(I=1)\mathcal{P}(S|I=1). \tag{7}$$

Since we consider unslotted transmissions, a collision occurs if another node transmits in the interval $[t_1, t_2]$, such that $t_1 = t - T_{TX}$ and $t_2 = t + T_{TX}$, t being the time at which the desired node' transmission starts. We can now compute the probabilities of having K interfering nodes as

$$\mathcal{P}(I=K) = \frac{e^{-\lambda}\lambda^K}{K!}, \text{ with} \tag{8}$$

$$\lambda = (M-1)\frac{2T_{TX}}{T_{inter}}. \tag{9}$$

Then, let us define $r_{i_{min}}$ as the smallest distance an interfering node N_i can be from the BS at which the SIR is equal to Γ by

$$\frac{P_T G_T G_R (\frac{\lambda}{4\pi r_d})^{\alpha}}{P_T G_T G_R (\frac{\lambda}{4\pi r_{i_{min}}})^{\alpha}} = \Gamma \iff r_{i_{min}} = \Gamma^{1/\alpha} r_d. \tag{10}$$

The probability that one interfering node is far enough from the BS such that its SNR is greater than Γ, conditioned to the desired node being at a distance r, is

$$\begin{aligned} \mathcal{P}(S|I=1; r_d = r) &= \begin{cases} \frac{R_{max}^2 - r_{i_{min}}^2}{R_{max}^2 - R_{min}^2} & \text{if } r_{i_{min}} < R_{max} \\ 0 & \text{if } r_{i_{min}} \geq R_{max} \end{cases} \\ &= \max\left(0, \frac{R_{max}^2 - r_{i_{min}}^2}{R_{max}^2 - R_{min}^2}\right), \end{aligned} \tag{11}$$

i.e. the probability that the interfering node is in a disk of minimum radius $r_{i_{min}}$ and of maximum radius R_{max} is $(R_{max}^2 - r_{i_{min}}^2)/(R_{max}^2 - R_{min}^2)$ if this node can be in the service area, and 0 otherwise. Finally, we have

$$\begin{aligned}\mathcal{P}(S|I=1) &= \int_{R_{min}}^{R_{max}} \mathcal{P}(S|I=1; r_d = r)\mathcal{P}(r_d = r)dr \\ &= \int_{R_{min}}^{R_{max}} \max\left(0, \frac{R_{max}^2 - r_{i_{min}}^2}{R_{max}^2 - R_{min}^2}\right) \frac{2r}{R_{max}^2 - R_{min}^2} dr \\ &= \frac{\left(R_{max}^2\left(\frac{R_{max}}{\Gamma^{1/\alpha}}^2 - R_{min}^2\right) - \Gamma^{2/\alpha}\left(\frac{\left(\frac{R_{max}}{\Gamma^{1/\alpha}}\right)^4}{2} - \frac{R_{min}^4}{2}\right)\right)}{(R_{max}^2 - R_{min}^2)^2}.\end{aligned} \tag{12}$$

IV. Outage Probability With Multiple Antennas And At Most One Interferer

In this part we extend the previous result by assuming that our BS station has L isotropic antennas equally spaced on a circle of radius ρ, i.e. placed at each corner of a convex regular n-sided polygon of circumradius ρ. Since we want the antennas to be spaced by $\lambda/2$, and according to the properties of a regular polygon, we choose ρ so that $\rho = \frac{\lambda}{4sin(\frac{\pi}{L})}$.

The Array Factor (AF) for this type of configuration, considering an uniform amplitude distribution among the antennas, can be simplified to

$$AF \approx LJ_0(k\rho sin(\theta)) \tag{13}$$

where $J_0(x)$ is the zero order Bessel function and $k = \frac{2\pi}{\lambda}$ [11] [12]. This function is equal to the receive beamforming pattern directed towards the angle $\theta = 0$, and can be seen in the Figure 2. For other angles, phase weights should be applied at each antenna and would mostly result in a rotation of the received beamforming pattern towards this angle since we use a circular configuration.

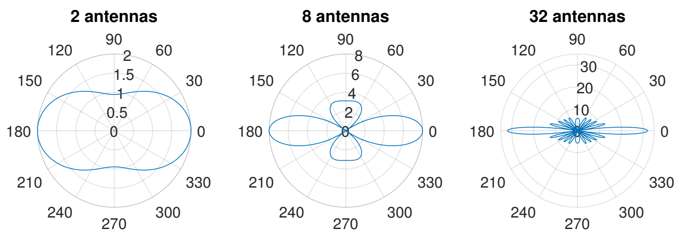

Fig. 2. Polar plot of the receive beamforming pattern directed towards $\theta = 0$, for different values of L, with $\lambda = 868$MHz.

When we take in account the beamforming pattern, the minimum distance $r_{i_{min}}$ at which an interfering node can send and still be sufficiently weaker than the desired one ($\gamma = \Gamma$) is different. In this paper, we consider that our many-antenna BS is not fully digital and the receive beamforming pattern has been set prior to reception. In a fixed beam system, multiple fixed beamforming patterns can be set at the same time, resulting in numerous main lobes that are directed towards different angles [13]. In this system, the desired node's Angle Of Arrival (AOA) will not be perfectly aligned with a main lobe, yielding an angle offset $\Delta\theta$. If we denote θ_i the angle of the interfering node, we have

$$\begin{aligned}&\frac{|AF(\Delta\theta)|P_T G_T G_R \left(\frac{\lambda}{4\pi r_d}\right)^2}{|AF(\theta_i)|P_T G_T G_R \left(\frac{\lambda}{4\pi r_{i_{min}}}\right)^2} = \Gamma \\ \iff\ & r_{i_{min}} = \left(\Gamma \frac{|AF(\theta_i)|}{|AF(\Delta\theta)|}\right)^{1/\alpha} r_d,\end{aligned} \tag{14}$$

and since $r_{i_{min}}$ cannot be less than R_{min}, we finally have

$$r_{i_{min}} = \max\left(R_{min}, \left(\Gamma \frac{|AF(\theta_i)|}{|AF(\Delta\theta)|}\right)^{1/\alpha} r_d\right). \tag{15}$$

Thus, the probability that the transmission from the desired node is successful knowing that it is at a distance r and that one interfering node is transmitting with an angle θ is

$$\mathcal{P}(S|I=1; r_d = r; \theta_i = \theta) = \max\left(0, \frac{R_{max}^2 - r_{i_{min}}^2}{R_{max}^2 - R_{min}^2}\right). \tag{16}$$

For the simpler case of a fully digital system where all the receive chains can be independently decoded, the weights can be applied digitally after the reception. Hence, the beamforming pattern can be perfectly directed towards the node we want to receive, and $\Delta\theta = 0$ in (14) and (15).

Finally, considering that $\mathcal{P}(\theta_i = \theta) = \frac{1}{2\pi}$,

$$\begin{aligned}\mathcal{P}(S|I=1) &= \int_0^{2\pi}\int_{R_{min}}^{R_{max}} \mathcal{P}(S|I=1; r_d = r; \theta_i = \theta)\mathcal{P}(r_d = r)\mathcal{P}(\theta_i = \theta) dr d\theta \\ &= \int_0^{2\pi}\int_{R_{min}}^{R_{max}} \max\left(0, \frac{R_{max}^2 - r_{i_{min}}^2}{R_{max}^2 - R_{min}^2}\right) \frac{2r}{R_{max}^2 - R_{min}^2} \frac{1}{2\pi} dr d\theta\end{aligned} \tag{17}$$

with η calculated the same way as before, with (7) and (6). While (17) can be computed analytically, it is an arduous task due to the high number of beams. In the remainder of the work we consider only numerical solutions of (17).

V. Outage Probability With Many Antennas

Now, we take into account the possibility of multiple simultaneous collisions from several sensors. If we denote $\mathcal{K}_d$ a set of interfering nodes, with $\mathcal{K}_d \in \mathcal{I}_d$ and $K = |\mathcal{K}_d|$, we can write

$$\mathcal{P}(S|I=K) = \mathcal{P}\left(\sum_{\mathcal{K}_d} P_{R_k} \leq \frac{P_{R_d}}{\Gamma}\right). \tag{18}$$

To compute this probability, we have to find every configuration for every node $k \in \mathcal{K}_d$ such that $\sum_{\mathcal{K}_d} P_{R_i} \leq \frac{P_{R_d}}{\Gamma}$. But the complexity of this operation makes it prohibitive, and in the following we look for a lower bound of this probability.

Suppose that each interfering node is at a distance greater or equal to a minimum distance $r_{K_{lim}}$, which is computed by placing every K interfering nodes at this distance given that the sum of their received power must be equal to $\frac{P_{R_d}}{\Gamma}$. As such, we denote the power received from each of the K nodes $P_{R_{K_{lim}}}$, and we have

$$\sum_{\mathcal{K}_d : r_k = r_{K_{lim}}} P_{R_k} = KP_{R_{K_{lim}}} = \frac{P_{R_d}}{\Gamma} \iff P_{R_{K_{lim}}} = \frac{P_{R_d}}{\Gamma K}. \tag{19}$$

Now, the probability that the sum of the K interferences is lower or equal to $\frac{P_{R_d}}{\Gamma}$ knowing that each node is further away than $r_{K_{lim}}$ is inferior to the probability of success with K interferers, since the probability of success given that some interfering nodes are closer than $r_{K_{lim}}$ is not taken into account:

$$\mathcal{P}\left(\sum_{\mathcal{K}_d: r_k \geq r_{K_{lim}}} P_{R_k} \leq \frac{P_{R_d}}{\Gamma}\right) \leq \mathcal{P}\left(\sum_{\mathcal{K}_d} P_{R_k} \leq \frac{P_{R_d}}{\Gamma}\right). \quad (20)$$

According to the equation (19), placing the interfering nodes further than a certain distance is equivalent to multiplying Γ by K. We can now introduce $\Gamma_K = \Gamma K$, the SIR that has to be respected by each interfering node, such that

$$(\mathcal{P}(S|I=1;\Gamma_K=\Gamma K))^K = \mathcal{P}\left(\sum_{\mathcal{K}_d: r_k \geq r_{K_{lim}}} P_{R_k} \leq \frac{P_{R_d}}{\Gamma}\right) \quad (21)$$

is a lower bound of $\mathcal{P}(S|I=K)$. To be clear, $\mathcal{P}(S|I=1;\Gamma_K=\Gamma K)$ means that $\mathcal{P}(S|I=1)$, given in equation (17), has to be computed with

$$r_{i_{min}} = \max\left(R_{min}, \left(K\Gamma\frac{|AF(\theta_i)|}{|AF(\Delta\theta)|}\right)^{1/\alpha} r_d\right). \quad (22)$$

Knowing that $\mathcal{P}(S|I=0)=1$ and that the maximum number of possible interfering nodes in the service area is $M-1$, we can finally have

$$\eta = 1 - \left(\sum_{K=0}^{M-1} \mathcal{P}(I=K)\mathcal{P}(S|I=K)\right). \quad (23)$$

VI. Numerical Examples

In this section we provide numerical results to verify our previous findings. We examine the OP given that $R_{min}=10$ m, $R_{max}=10$ km, $\alpha=2$, and $T_{TX}=2$ s, which is the average time needed for a message to be send in a UNB network. In Figures 3 and 4, we can observe the OP as a function of the number of nodes in the network, for $\Delta\theta=0$ and different values of L. The case $L=1$ correspond to a simple, single antenna BS, while the other cases correspond to a BS with an increasing number of antennas. Figure 3 is computed with $T_{inter}=43200$ s, which means that, in average, each node transmits every twelve hours. In this figure, the lines represent the theoretical results, coming from equation (23), and the symbols represent the simulation results for the same parameters. For the simulations, 100000 Monte-Carlo iterations were performed, in which a set of nodes were randomly placed in the service area. Then, a desired node was selected, and for the remaining nodes a random decision was made on their activity according to as described in section III. Then the SIR, given in equation (3) is computed taking into account the beamforming pattern.

First, we can see that the theory is validated, as it is indeed a tight upper bound of the simulated results. Indeed, since we selected a lower bound for the probability of a correct reception given that there are K interfering nodes in (20), we expected the theoretical results for the OP to be slightly higher than the simulation results. For an OP of 10^{-2} and $\Gamma=10$ dB, the network can support up to 116 nodes with a single-antenna BS, and up to 253 nodes with 128 antennas at the BS. With $\Gamma=3$ dB, the network can support up to 147 nodes with a single antenna BS, and up to 959 nodes with 128 antennas at the BS. We can see that the value of Γ greatly influences the OP for $L=128$, but not for the single antenna case. This suggests that more robust transmissions, i.e., counting with a stronger channel coding, will profit more from the use of multiple antennas. However, if less robust transmissions are expected, adding more antennas only slightly increases the number of nodes that can be placed in the network. This has to be taken into consideration when the increase in the number of antennas incurs in a prohibitive complexity at the BS.

Figure 4 is computed with $\Gamma=3$ dB and $T_{inter}=7200$ s, which means that, in average, each node transmits every two hours. For 150 nodes in the network, the OP equals 0.062

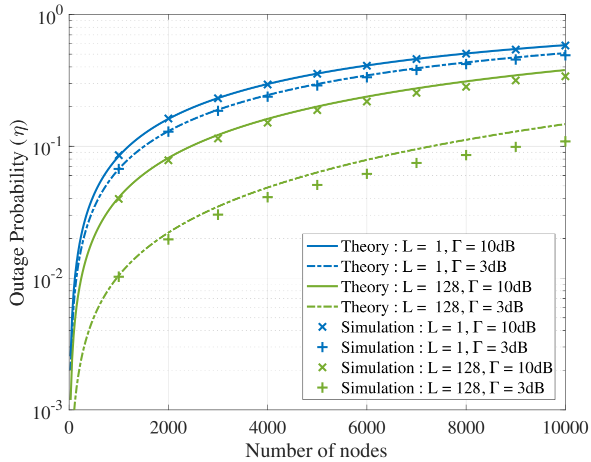

Fig. 3. Outage probability as a function of the number of nodes in the cell for different number of antennas at the BS and different values of Γ, with $T_{inter}=43200$ s

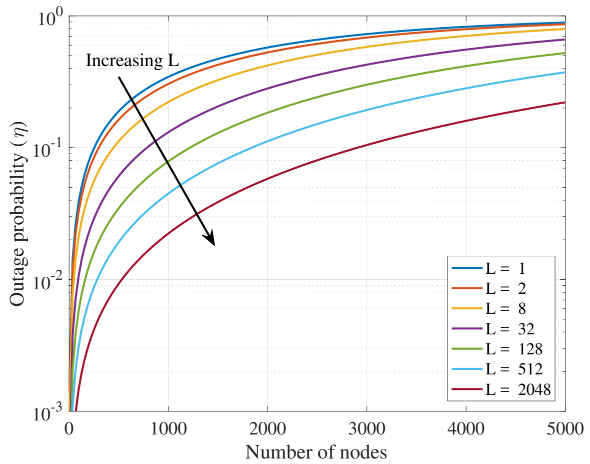

Fig. 4. Outage probability as a function of the number of nodes in the cell for different number of antennas at the BS, with $T_{inter}=7200$ s and $\Gamma=3$ dB

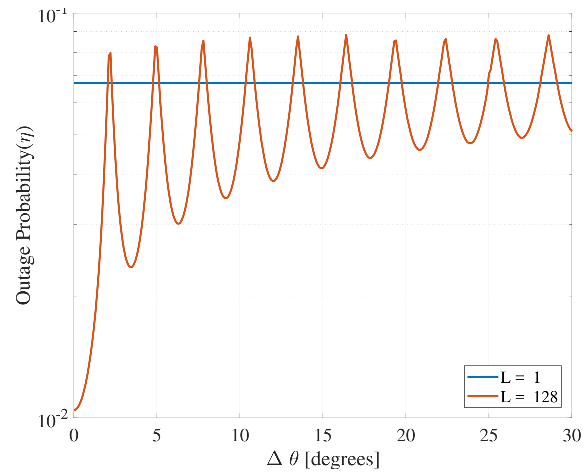

Fig. 5. Outage probability as a function of the angle offset between the desired node and the main beam for different number of antennas at the BS, with $M = 1000$ nodes, $T_{inter} = 43200$ s, and $\Gamma = 3$ dB

with a single antenna BS, 0.034 with 8 antennas, 0.009 with 128 antennas, and 0.002 with 2048 antennas at the BS. For an OP of 10^{-2}, the network can support up to 31 nodes with a single antenna BS, 47 nodes with 8 antennas, 164 nodes with 128 antennas, and 538 with 2048 antennas at the BS. As expected, the OP decreases with the number of antennas for a fixed number of nodes. Moreover, for a fixed OP of 10^{-2} and $\Gamma = 3$ dB, increasing the number of antenna from 1 to 128 multiplies by 6.5 the number of nodes that can be placed in the network with T_{inter} = 43200 s, and by 5.3 with T_{inter} = 7200 s. Finally, increasing T_{inter} obviously leads to an increase in the number of nodes that can be placed in the network. Thus, a network operator can decide on the number of antennas in the BS array given the number of nodes to be addressed.

In Figure 5 we can observe the OP as a function of the angle offset between the main beam and the desired node direction, computed for a single-antenna and a 128-antenna BS, with $M = 1000$ nodes, $T_{inter} = 43200$ s, and $\Gamma = 3$ dB. We can see that the OP is constant and equal to 0.067 for $L = 1$ since the antenna is isotropic. However, the OP for the case $L = 128$ greatly varies as the desired node moves out of the main lobe into the side lobes, as expected. If the multi antenna system is based on a beam switching paradigm, then wherever the node is, the AOA will always be covered by a pre-calculated fixed beam, but may not be perfectly aligned with it. For example, if we form 128 beams, each beam will cover 2.8°, and the average OP for a node in this coverage area is 0.013 which is way better than the single antenna case of 0.067.

VII. Conclusion

This work deals with the interference of very dense MTC networks with a m-MIMO antenna BS. The effect of packet collision on the OP and the number of nodes that can be placed in the network were computed. Our findings show that using a BS with multiple antennas does indeed reduce the OP of the network as a whole, since the narrower beams better separate conflicting nodes. In our configuration, for a fixed OP of 10^{-2} and one transmission every twelve hours, the number of nodes that can be placed in the network is multiplied by 6.5. This performance gain was however greatly influenced by the considered SIR threshold, which implies that a more robust modulation and coding scheme will yield a higher number of nodes served. We have also analyzed the effect of AOA uncertainty, which also had an influence in the OP. Our conclusion is that, using a fixed 128-beam scheme, the system will provide an average 5 times decrease in OP compared to the OP for a single antenna system.

Future directions of this work include a more realistic scenario definition, with propagation effects such as shadowing and multipath fading. Moreover, the considered assumptions such as the varying idle time, the uniform node placement, or the absence of receive chains, may not be realistic or efficient in practice. Finally, the circular physical configuration of the antennas helped us generalize our results toward every angle, but the recent MIMO developments point toward a reevaluation of this work for grid-shaped arrays.

Acknowledgements

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References

[1] Dennis Knake. IoT numbers vary drastically: devices and spending in 2020 - We speak IoT, 2017.

[2] Frederic Paul. IoT market keeps growing, with no end in sight — Network World.

[3] Carsten Bockelmann, Nuno Pratas, Hosein Nikopour, Kelvin Au, Tommy Svensson, Cedomir Stefanovic, Petar Popovski, and Armin Dekorsy. Massive machine-type communications in 5g: Physical and MAC-layer solutions. *IEEE Communications Magazine*, 54(9):59–65, 2016.

[4] T. L. Marzetta. Massive MIMO: An Introduction. *Bell Labs Technical Journal*, 20:11–22, 2015.

[5] David Tse. Fundamentals of Wireless Communication 1. 2004.

[6] Petteri Kela, Henrik Lundqvist, Kari Lepp, and J Riku. Connectionless Access for Massive Machine Type Communications in Ultra-Dense Networks. 2017.

[7] Greg Kuperman, Robert Margolies, Nathaniel M. Jones, Brian Proulx, and Aradhana Narula-Tam. Uncoordinated MAC for Adaptive Multi-Beam Directional Networks: Analysis and Evaluation. *2016 25th International Conference on Computer Communications and Networks, ICCCN 2016*, 2016.

[8] C Goursaud and J M Gorce. Dedicated networks for IoT: PHY/MAC state of the art and challenges. *EAI Endorsed Transactions on the Internet of Things*, 1(1):1–12, 2015.

[9] Yuqi Mo, Claire Goursaud, and Jean Marie Gorce. Theoretical analysis of UNB-based IoT networks with path loss and random spectrum access. *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, 2016.

[10] Yuqi Mo, Minh Tien Do, Claire Goursaud, and Jean Marie Gorce. Up-Link Capacity Derivation for Ultra-Narrow-Band IoT Wireless Networks. *International Journal of Wireless Information Networks*, 24(3):300–316, 2017.

[11] Victor Rabinovich and Nikolai Alexandrov. *Antenna Arrays and Automotive Applications*. 2013.

[12] Constantine Balanis. *Antenna Theory*. 2005.

[13] Shuangfeng Han, Chih-lin I, Zhikun Xu, and Corbett Rowell. Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. *IEEE Communications Magazine*, 53(1):186–194, 2015.