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Connectivity and Coverage in Machine-Type Communications

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***Abstract*—Machine-type communication (MTC) provides a potential playground for deploying machine-to-machine (M2M), IP-enabled 'things' and wireless sensor networks (WSNs) that support modern, added-value services and applications. 4G/5G technology can facilitate the connectivity and the coverage of the MTC entities and elements by providing M2M-enabled gateways and base stations for carrying traffic streams to/from the backbone network. For example, the latest releases of long-term evolution (LTE) such as LTE-Advanced (LTE-A) are being transformed to support the migration of M2M devices. MTC-oriented technical definitions and requirements are defined to support the emerging M2M proliferation. ETSI describes three types of MTC access methods, namely a) the direct access, b) the gateway access and c) the coordinator access. This work is focused on studying coverage aspects when a gateway access takes place. A deployment planar field is considered where a number of M2M devices are randomly deployed, e.g., a hospital where body sensor networks form a M2M infrastructure. An analytical framework is devised that computes the average number of connected M2M devices when a M2C gateway is randomly placed for supporting connectivity access to the M2M devices. The introduced analytical framework is verified by simulation and numerical results.**

I. Introduction

The proliferation of mobile Internet provides nationwide ubiquitous coverage and mobility support [1]. The exponential explosion of smart phones, tablets and netbooks created a huge playground of ubiquitous connectivity. In many cases, those devices could operate an autonomous fashion, without needing of human interaction. The emergence of the Internet of Things (IoT) verify that feature, where a massive number of objects, things and items become connected players in that playground. The Machine-to-Machine (M2M) technology has gained a lot of attention in the context of a IoT playground with ubiquitous connectivity. M2M refers to to Information and Communication Technologies (ICT) able to measure, deliver, digest, and react upon information in an autonomous fashion, i.e., with no or really minimal human interaction during deployment, configuration, operation, and maintenance phases [2].

M2M communications can support a wide range of applications such as monitoring, metering, surveillance, military applications, infrastructure management, eHealth and environmental applications. However, there is a need of a robust connection between the M2M infrastructure and the cellular network. According to the 3GPP proposal, the higher layer connections among M2M devices are provided by attaching M2M devices to an existing cellular infrastructure (e.g., Long Term Evolution-Advanced - LTE-A) [3]. LTE and LTE-A emerge as promising solutions for supporting M2M communications due to their longevity, cost-effectiveness and scalability. From Release 10 onward, 3GPP started to work in the design of a suitable core network architecture (from the application to the devices), services, specific signaling reduction and optimization at the Radio Access Network (RAN) for M2M services [4]. According to the ETSI M2M architecture and the network improvements for M2M developed by the 3GPP, three main access methods are defined, namely the direct access, where a M2M device can directly access an evolved NodeB (eNodeB), the gateway access, where M2M devices gain access through M2M gateways, and the coordinator access, where a set of the existing M2M devices act as coordinators, or small gateways, for facilitating the connectivity access of their neighbors [4].

One of the most challenging problems in linking M2M infrastructure with 4G/5G cellular networks is the connectivity coverage. Coverage could be deemed as a performance metric

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of the underlying M2M network since it quantifies the quality of the M2M applications. For example, the lack of coverage could lead to malfunctions or even worse, when the data streams from a sensitive sensor network, as a part of the M2M infrastructure, are not able to be delivered by the 4G/5G base station, e.g. the a LTE-A eNodeB. Furthermore, given that the development of higher layer of communication between M2M and LTE-A is still in its way, it is even more important to state on optimized and stable design options and choices when a M2M deployment area is covered by cellular network elements.

In the light of the aforementioned remarks, this paper studies connectivity coverage options in interconnecting a set of M2M devices with a LTE-A eNodeB. In this context, a deployment area is considered where multiple M2M devices are already, randomly in place. A number of M2M gateways are deployed realizing a gateway access, as previously mentioned. First, the probability of a M2M device to be connected to the cellular network is calculated using a single gateway. Then, the analysis is extended using multiple gateways in random locations within a specific deployment area. Lastly, the probability of connected at least k M2M devices using a specific number of gateways is computed.

The remainder of the paper is organized as follows. Section II outlines existing works in M2M coverage. A detailed description of the introduced analytical framework is provided in Section III. Section IV-B is dedicated to the validity of the introduced model through numerical results. Finally, conclusions are given in Section V.

II. Related Work

The coverage problem in M2M communications is quite similar with the coverage problem in wireless sensor networks. It can be seen as deterministic or stochastic and homogeneous or heterogeneous [5]. A deterministic device placement implies that the minimum number of devices is investigated for ensuring a completed connected M2M network. For example, in [6] the adequate node placement is examined in providing optimized network performance. A classification of placement strategies in Wireless Sensor Networks (WSNs) is given in terms of static and dynamic deployment, meaning that optimization is favored in the static and the network operation is prioritized in the dynamic. Another popular deterministic study is the problem of deterministic coverage under specific constraints. For instance, deployment strategies are investigated where each device must have at least k neighbors. Authors in [7] study the satisfaction of local and global constraints, highlighting deployment configuration that maximize the mobile device coverage. Similarly, in [8] dynamic aspects of the coverage of mobile sensors/devices are explored subject to the movement characteristics. The authors also apply a game theoretic approach to derive optimal mobility strategies for both sensors/devices and potential intruders. The work in [9] studies the idea of having first a sensor deployment randomly in some initial region within the area of the network, and then a movement around, leading to maximizing the network coverage.

The path exposure problem can be considered as an another problem formulation. Using various techniques the discovering of the minimum exposure path seems to lead to paths that maximize the coverage. In [10] a minimal exposure path problem that requires the passage of the path through the boundary of a certain region is considered. The authors transform the problem into an optimization problem with constraint conditions. Also, a hybrid genetic algorithm is proposed to resolve the introduced problem.

In large scale networks, there is often the need of providing at least k device coverage in a specific field of interest. This behavior can be considered as a group-based action in M2M networks. The work in [11] assumes this group-based behavior as one of the features of M2M communications, meaning that the M2M devices are likely with correlated mobility and may perform mobility management at the same time.

The study of physical effects, such as shadowing and fading, in deploying mobile networks is also a common problem aspect [12]. The effect of interference on the coverage and connectivity of generic ad hoc networks is considered in [13]. The authors assume a random distribution for modelling the number of interfering signals at each receiving node. Also, the aggregate interference at the receiver is approximated using the shifted Gamma distribution. Closed-form expressions are derived for measuring the overall network connectivity in a wireless channel with co-channel interference and noise.

Linking load balancing with network coverage is also an interesting approach. The work in [14] a load-balancing cover tree was developed for ensuring full coverage and connectivity (with the cellular network). The load of each node is shared in sensing and transmitting, leading to energy gains. The same aspect is studied in [15]. A group division of nodes is applied and a group-based connection mechanism is functioned to avoid blindness of connection. The cost deployment is reduced by load balancing on-demand.

On the contrary, in this work the network coverage problem is specified in linking the M2M infrastructure with the underlying cellular network. We keep a deterministic device placement but we advance the study of gateway placement by considering that the position and the number of the existing M2M devices is unknown. Assuming a planar intersection, we compute the M2M device connectivity probability by considering multiple gateway placements.

III. Coverage Study

A. Problem Formulation

A deployment planar field F is considered having D area and L perimeter. Table I summarizes the notation used in the following analysis. A number of N machines have deployed within the field F according to a uniform distribution, i.e., the coordinates of each machine were randomly selected. This scenario could be applied to e-health, military or environmental use cases where the exact coordinates of the machines are unknown. Also this problem can be attached to smart cities where

TABLE I
NOTATIONS

Parameter	Description
F	M2M device deployment field
L	Perimeter of the deployment field
N	Number of M2M devices
G	Coverage field of the M2C gateway
H	Perimeter of the M2C coverage field
R	Transmission radius of the M2C gateway
I	Radius of the deployment field
D	Area of the deployment field
K	Area of the M2C gateway coverage field
J	M2C gateway deployment field
p	M2M device connection probability
M	Average number of connected M2M devices
A	Number of M2C gateways

IP-enabled things or machines exist in a field (e.g., in an urban area) of specific area without knowing their exact location. The objective of this work is to map coverage problem challenges when a Machine-type Communication (M2C) gateway will be deployed in the planar field. Let G denote the coverage field of the gateway while H stands for the perimeter of this coverage area. The gateway has a transmission radius of R. In particular, the intersection of these two sets will be examined through the Geometric Probability methodology. It is assumed that the M2C gateway is connected to a M2M base station, e.g., an LTE-A eNodeB, via wired medium such as optical fiber. As a result, the machines that exist within the coverage field of the M2C gateway will have access to the cellular network. Given the aforementioned deployment scenario, it is interesting to investigate what is the connection probability of each machine, meaning the probability of accessing the M2M base station through the gateway, and the average number of connected machines as well. The following assumptions are set for this study: a) a disk shaped planar field without obstacles is assumed as the deployment field having a radius of I, where $I > R$ and b) the connection coverage that the gateway supports is shaped as a circle with radius equal to R. In the following the problem formulation is given.

Given the aforementioned aspects, the coverage problem is defined as follows. Given a deployment planar field of a disk shaped F without obstacles having an area $D = \pi I^2$ and a perimeter L, a number of N machines are randomly deployed within the area F. A M2C gateway is set up to support connection access to the machines towards the M2M base station forming a connection field G shaped as a circle with a radius R, an area K and a perimeter H. Its connection coverage forms a connection field of πR^2. Each machine that is placed within the range of the gateway is considered connected. The objective is to scholastically compute the machine connection probability and the average number of connected machines.

B. Plane Intersection

As the problem is specified it is important to define whether the two planes (deployment and gateway connection coverage fields) are intersected. In our to simplify our analysis we consider that the gateway is placed in such as way that it intersects with the deployment field. This means that the gateway might be placed inside or outside of the deployment plane. The following lemma determines the deployment area of the gateway subject to the field F.

Lemma 1. *The deployment planar field of the gateway is a circle with a radius $R+I$ and a perimeter $2\pi(I+R)$, having the same center with the deployment planar field F.*

Proof. Given that a) the connection coverage of the gateway is shaped as a disk with radius R, b) the deployment field F is a disk with radius I, perimeter L and area D and c) the two planes (F and G) interact each other, the gateway should be placed wither inside F or in such a position that due to symmetry the distance between the centers, i.e., the center of the F and G disks/circles is less or equal to R. By examining all possible positions to place the gateway outside the disk F an annulus is formed due to the circle F symmetry. The formed annulus has an area of $\pi(I^2 - R^2)$. Thus the gateway can be placed inside the circle F and inside the formed annulus. The combined shape forms a new disk/circle, concentric with the circle F, with a radius $I+R$. This gateway deployment planar field is denoted by J and forms a circle with a radius $I+R$, a perimeter equal to $2\pi(I+R)$ and the same center as the circle F. $\square$

C. Machine Connection Probability

With the aim of Integral Geometry and Geometric Probability, the machine connection probability is computed in the following lemma.

Lemma 2. *Given a machine deployment field F, shaped as a circle with a radius I, an area $D = \pi I^2$ and a perimeter $L = 2\pi I$, where N M2M devices are randomly deployed, a M2C gateway that is randomly placed in a gateway deployment field J, shaped as a circle with a radius $I+R$, an area $\pi(I+R)^2$ and a perimeter $2\pi(I+R)$, where the M2C gateway forms a connection access plane G as a circle with a radius R, an area $K = \pi R^2$ and a perimeter $H = 2\pi R$, the probability of a M2M device is connected to the M2C gateway, denoted as p, is given as follows:*

$$p = \frac{R^2}{(R+I)^2} \tag{1}$$

Proof. Using the average area of computing the intersection of multiple sets in plane of [16] and the probability of a randomly selected point in a plane in such a way that it intersects with another plane [5], the probability of covering a M2M device, that is randomly located within the F field, by the gateway coverage field G is given as follows:

$$p = \frac{2\pi K}{2\pi(D+K)+L+H} \tag{2}$$

Eq. (2) holds for any convex set of area D, K while it is only dependent on the area and the perimeter of the convex sets that intersect and not on the shape of those sets. Thus, we can replace $K = \pi R^2$, $H = 2\pi R$, $D = \pi I^2$ and $L = 2\pi I$ since the two convex sets are circles. The probability becomes now:

$$p = \frac{2(\pi R)^2}{2\pi^2(I^2 + R^2) + 2\pi(I + R)} = \frac{R^2}{(R + I)^2} \tag{3}$$

□

D. Average Number of Connected Machines

Having calculated the probability of a M2M device to be connected to the gateway, the average number of M2M devices that are connected to the M2M base station, denoted as M, is easily computed. Given that the N M2M devices are independently deployed in the F field the average number of connected M2M devices is given as follows:

$$M = \frac{NR^2}{(R + I)^2} \tag{4}$$

E. Multiple Gateway Connection Probability

In this subsection, we extend our analysis in order to calculate the connection probability of a M2M device. A number of A M2C gateways are considered. The gateways are randomly deployed in the G area under the assumption that their coverage field do not overlap together. Thus, given that the deployment of each of the A M2C gateways in the G area are independent each other, the probability of a M2M device to have a connection with the cellular network follows a binomial distribution. A M2M device has a connection to the cellular network, if it exists in the coverage area of at least one M2C gateway. As a result

Lemma 3. *Given a number of A M2C gateways deployed in the G area in a random way such as there are no intersections between the coverage areas of each one of the A gateways and a connection probability p for a M2M device to be connected to a single gateway, the probability, denoted as p', of a single M2M device to be connected to the cellular network is given as follows:*

$$p' = 1 - (1 - p)^A \tag{5}$$

Proof. The probability of a M2M device to be connected to the cellular network through a M2C gateway is p when only a single gateway exists in the deployment area. If a second gateway is deployed in the same area, then the probability of a single M2M device to be connected to the cellular network is to be located within the coverage area of the first or the second gateway, having in mind that the existence of the first gateway does not affect the second one in terms of coverage. Similarly, each deployed gateway does not affect all the other gateway that have already being deployed. Hence, the probability of a single M2M device in being connected with the cellular network follows a binomial distribution. The probability of having no connection at all comes from the fact that the single device is not covered from any of the available gateways. This probability is given by Eq. (6):

$$\binom{A}{0} p^0 (1 - p)^{A-0} = (1 - p)^A \tag{6}$$

Obviously, the probability of having a connection is equal to the fact that at least a single gateway succeeds to cover the M2M device. This expression is denoted by Eq. (7):

$$p' = 1 - (1 - p)^A \tag{7}$$

□

IV. Validation and Results

A. Validation Environment

A simulation framework was developed for verifying the derived analytical equations. The framework was based on the LTE Systems toolbox in Matlab. Initially, a disk-shaped M2M deployment field was considered assuming a suburban scenario. The radius of deployment field was set to $I = 1000$ m. A number of N M2M devices were randomly placed within the field. Then, a number of A gateways were randomly deployed in the area in such a way of intersecting with the initial M2M deployment field. The radius of each M2C gateway is fixed and equal to 100 m [17].

A series of simulations have been conducted in measuring a) the connection probability of a M2M device to have access to the cellular network (p'), b) the average number of the connected M2M devices (M), and c) the probability of having at least k M2M devices connected. A total number of 10000 deployment scenarios were examined while the average values have been recorded accordingly.

B. Numerical Results

The numerical results are presented in three parts. First, the impact of the gateway density is investigated. The number of the deployed gateways changes from 10 to 100. The number of deployed M2M devices is 500 while the radius of the deployment area was 1000 m. Second, the dimension of the deployment area was changed to acquire how the connection performance behaves. Keeping fixed the gateway transmission radius (100 m), the number of the M2M devices (500) and the number of the deployed gateways (50), the radius of the deployment field was changed from 500 to 1500 m. In the final part, the impact of the M2M machine density is explored. The number of the deployed M2M devices alters from 100 to 1000. The radius of the deployment area has been kept fixed and equal to 1000 m. Also, the gateway transmission radius was stable and equal to 100 m.

Figure 1 illustrates the probability of a M2M device to have access to the cellular network. The probability is less than 10% when $A = 10$ while it receives its maximum value (58% when $A = 100$ following an almost linear increase. This is attached to the fact that each additional gateway offers more coverage area. Also, the average additional area that each new gateway brings is identical for each gateway, since the connections coverage of each additional gateway does not intersects with any other gateway.

Figure 2 shows the average number of the connected M2M devices. It verifies the results obtained in Figure 1, since the trend of the average connected M2M devices is identical with that of the connection probability. This is clear since it holds that the average number of the connected M2M devices is $p' \cdot N$. It is worth mentioning that the average number of gateways for ensuring the connection of 200 M2M devices is almost 62 gateways.

The probability of ensuring at least $N/2 = 250$ M2M devices is given in Figure 3 as the number of gateways changes. The required number of gateways for ensuring the connection of at least the half of the deployed M2M devices is 100.

Figure 4 draws the connection probability of a M2M device to have access to the cellular network when the deployment area changes. This leads to different values of deployment area; in other words, the area of the deployment disk becomes larger. The number of the deployed gateways is stable and equal to 50. As expected, the probability is reduced as the field becomes larger. When the radius is equal to 500 m the connection probability is maximized to 76%.

The average number of the connected M2M devices when the deployment field is changed is given in Figure 5. As expected the trend of both curves is identical (Figure 4 and Figure 5). The maximum number of the average connected connected devices is almost 370. Figure 6 depicts the connection probability of at least 250 M2M devices. Having a deployment disk of 500 m radius, the connection of the half M2M devices is ensured. The probability totally diminishes when the number of the radius becomes 900 m. Note that the number of the underlying gateways is only 50.

Finally, the impact of the M2M device density is explored in Figure 7 and Figure 8. Figure 7 shows the connection probability when the number of the deployed M2M devices is changed. The probability remains stable since the number of the deployed gateways remains fixed as well. Accordingly, the average number of the connected M2M devices is linearly increased following the unchanged behavior of the connection probability.

In a nutshell, the provided simulation results verify the accuracy of the introduced analysis. Moreover, the obtained numerical results shed light in the required geographical conditions for ensuring minimum levels of connectivity, i.e., at least 500 m radius of the deployment disk is required for ensuring the connection of at least 250 M2M devices.

V. Conclusions

This work was focused on discussing coverage aspects in M2M deployment fields. A deployment planar field was considered, where multiple M2M devices were randomly deployed. An analytic framework was presented for investigating coverage problem challenges when a M2C gateway is deployed in the planar field as well. By using geometric probabilities the average number of the connected M2M devices

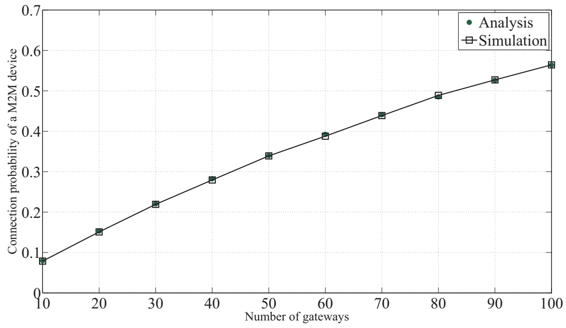

Fig. 1. Probability of a M2M device to be connected to the cellular network as the number of gateways changes.

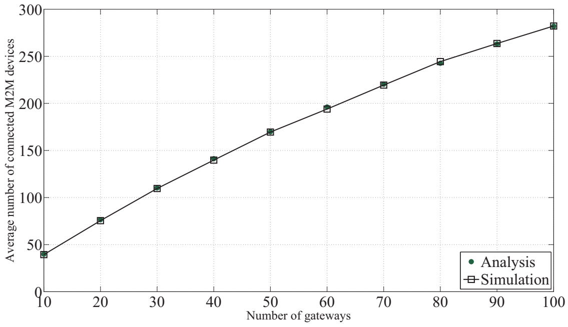

Fig. 2. Average number of connected M2M devices as the number of gateways changes.

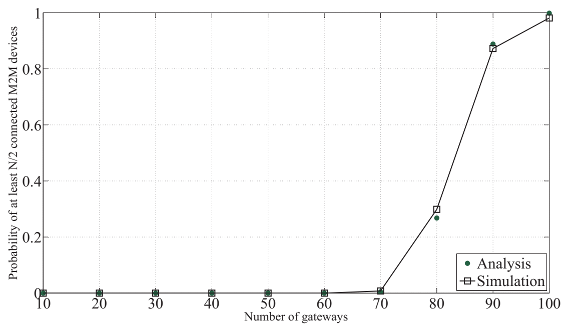

Fig. 3. Probability of at least $N/2$ connected M2M devices.

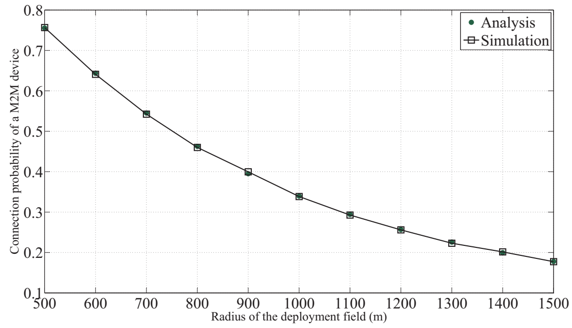

Fig. 4. Probability of a M2M device to be connected to the cellular network as the deployment field changes.

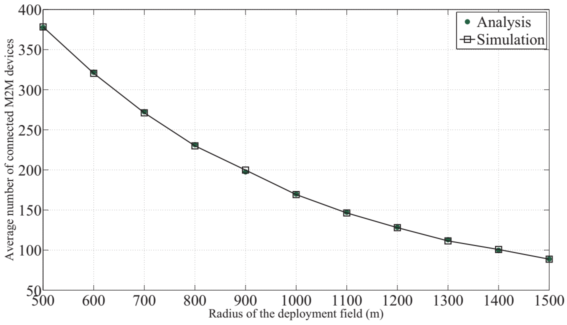

Fig. 5. Average number of connected M2M devices as the deployment field changes.

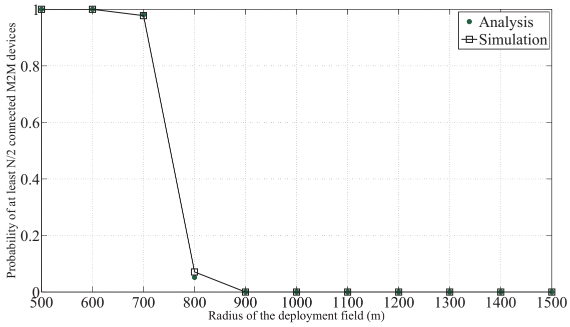

Fig. 6. Probability of at least $N/2$ connected M2M devices as the deployment field changes.

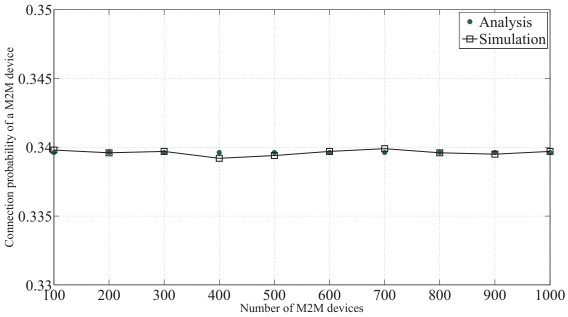

Fig. 7. Connection probability of a M2M device as the device density changes.

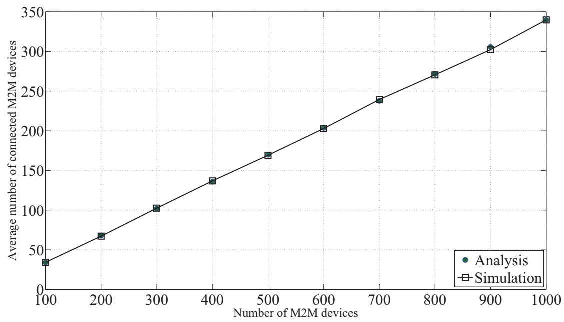

Fig. 8. Average number of connected M2M devices as the device density changes.

is computed, given that the M2C gateway has access to the cellular network. In addition, the probability of having at least k M2M devices connected is also calculated. Our research findings were verified through simulation results. Our future plans include th extension of this work by taking into account obstacles and different topologies.

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