

Direct and Indirect Access in Machine Type Communications: An Analytical Approach Invited Paper

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ABSTRACT

Machine-to-machine (M2M) communications have emerged as a cost-effective, flexible and efficient solution of facilitating the penetration of independent 'things' and machines in local networks and systems. The latest releases of long-term evolution (LTE) such as LTE-Advanced (LTE-A) are being transformed to support the migration of M2M devices to end terminals. 3GPP supports the definition of technical requirements and functional specifications that allows the adapting of existing technologies to support machine type communications (MTC) and the optimization of the design of advanced standards (e.g., LTE-A) for efficient data delivery. According to ETSI M2M architecture three types of MTC access methods are supported, the direct access, the gateway access and the coordinator access. An MTC can access an evolved NodeB (eNB) with or without relay nodes. Hence coverage and connectivity issues appear on designing and deploying MTC architectures. This work is focused on studying and analyzing the probability of having at least k machine devices connected in modern cellular network, where the deployed M2M devices are directly or indirectly connected to the eNB node. The provided analytic framework is verified by simulation results that indicate suitable deployment conditions in specific MTC scenarios.

CCS CONCEPTS

•Networks → Wireless access points, base stations and infrastructure; Network structure; Network range; Intermediate nodes; End nodes;

KEYWORDS

Coverage, Deployment, M2M, LTE, Relay

1 INTRODUCTION

Communication technologies have been evolving rapidly and the pace of change is only increasing. One of the most compelling trends is machine-to-machine (M2M) communications. M2M communications or machine type communications (MTC) are defined as the data communication between independent, machine-based devices without the need for human interaction. The number of those devices is growing exponentially, putting unprecedented load on cellular infrastructure [3], [4]. MTC involve data communication without or with limited human intervention among various devices, ranging from computers and smart sensors to mobile devices and vehicles. M2M devices demonstrate very high density, low bandwidth, small payload and uplink dominant traffic [6]. Long-term evolution (LTE) and LTE-Advanced (LTE-A) constitute promising solution for M2M communications infrastructure because of their longevity, cost-effectiveness and scalability. With the widespread introduction of LTE the migration of MTC devices to LTE is under development. In particular higher-layer system requirements should be addressed for facilitating the data delivery through LTE-A cellular systems. In this context intriguing challenges are emerged such as connectivity and coverage issues [7].

This work investigates coverage and capacity capabilities of direct and indirect access methods to the evolved NodeB (eNB). An analytical framework is provided in terms of full coverage and outage that provides the probability of ensuring a number of machine devices connection by having either them directly to the eNB or indirectly through relay machine gateways. Various topologies are considered, such as square, rectangular and disk areas so as to acquire the potential capabilities of MTC architecture. The provided analytical equations are validated through simulation results.

The remainder of the paper is organized as follows. Section 2 introduces the main features of MTC field. A detailed description of the provided analytical framework is included in Section 3. Section 4 presents the obtained results. Finally, conclusions are given in Section 5.

2 BACKGROUND

M2M devices access the network through wired or wireless links. Wired access methods can be a combination of different technologies such as cable, various digital subscriber line technologies (xDSL) and optical fiber. Wireless access methods can be short range, such as wireless local area network (WLAN), ZigBee and IEEE 802.15.4 or cellular such as global system for mobile communications (GSM), general packet radio service (GPRS), 3G standards,

LTE-A, and worldwide interoperability for microwave access (Wi MAX). Although wired solutions provide reliability, high data-rates, short delays and security, they may not be appropriate for M2M communications due to cost ineffectiveness, lack of mobility and low scalability. On the contrary, wireless cellular solutions offer excellent coverage, good security, mobility support, and ready-to-use infrastructure.

Considering the low-power budget of the M2M devices, coverage becomes a key challenge for a wide-area deployment. Coverage using Category-1 device has been studied in [1], with the maximum coupling loss (MCL) being 140.7 dB and 146.7 dB, for frequency division duplexing (FDD) and time division duplexing (TDD) respectively. Release 13 extends the MCL to 155.7 dB, providing thus increased coverage area as well as supporting devices in locations with high penetration loss. To achieve that, the following coverage improvements concepts are considered [1]:

- Repetition or subframe bundling: Longer transmission time allows more energy to be accumulated at the receiver, thus improving the strength of the desired signals.
- Power boosting: with power boosting more power can be used by the eNB on downlink transmissions to M2M user equipment (UE). For a given level of power boosting concentrates more power into a reduced bandwidth at the eNB or UE.
- Relaxing the current specification requirements, such as delay tolerance.
- Frequency hopping across wideband system to provide frequency diversity gain to narrowband UEs.
- Small cells: an operator may extend the coverage of current cells by deploying small cells such as pico- or femto-cells, relays and repeaters etc.

System deployment scenarios may include urban and suburban macro-cell deployment [4]. Indicatively, For urban macro-cell scenario, the inter-site distance (i.e., the distance between one eNB site to another) is 500 meters, while for suburban macro-cell it is 1732 meters.

3 COVERAGE ANALYSIS

3.1 System Model

A two dimensional, flat field is considered without obstacles. The field is defined as the M2M deployment area. A high degree of spatial randomness may be presented when user and machine terminals are deployed [2]. Hence, in this work we assume a number of N stationary M2M devices that are randomly and independently deployed in the M2M deployment area. It is assumed that all these devices have been deployed in this field by prior arrangement. The M2M deployment area covers an area of E quadratic metric units.

3.2 Direct Access

MTC is feasible in direct access with an eNB in cellular networks without any intermediate device [7]. This type of connection is similar to that of a regular UE. An eNB is considered within the deployment area with a transmission range of R . For simplicity reasons we consider that the eNB is placed in such a location so as its coverage area is fully included within the deployment area.

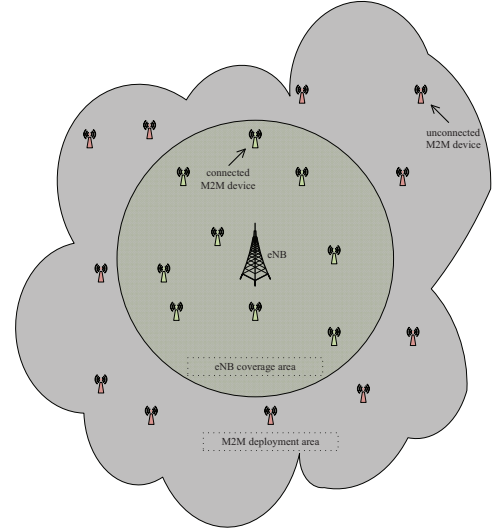


Figure 1: The M2M deployment area.

Figure 1 shows the deployment area where the eNB is placed. The transmission coverage of the eNB is defined as E_e :

$$E_e = \pi \cdot R^2 \quad (1)$$

Obviously the access probability for each machine to be connected with the eNB, denoted by p_d , is $p_d = \frac{E_e}{E} = \frac{\pi \cdot R^2}{E}$. Given that all machines have been randomly and independently deployed in the M2M deployment area and all machines are identical in terms of wireless interface and communication range, the probability of having i out of N machines that establish communication with the eNB follows a binomial distribution:

$$Pr(X = i) = \binom{N}{i} p_d^i (1 - p_d)^{N-i} \quad (2)$$

Accordingly, the probability of having all machines connected is $p_N = p_d^N$. Similarly, the probability of a total outage of all machines becomes $p_0 = (1 - p_d)^N$.

Once we have computed the access probability (p_d) we can derive the probability of at least k machine devices are connected to the eNB. This probability is denoted by p_k^d and it is calculated as follows:

$$\begin{aligned} p_k^d &= Pr(X \geq k) \\ &= 1 - Pr\{X = 0\} - Pr\{X = 1\} - \dots - Pr\{X = k-1\} \\ &= 1 - (1 - p_d)^N - \binom{N}{1} p_d (1 - p_d)^{N-1} \\ &\quad - \dots - \binom{N}{k-1} p_d^{k-1} (1 - p_d)^{N-k+1} \end{aligned} \quad (3)$$

Eq. (3) expresses the probability of having a minimum number of k machine devices connected to the eNB subject to the number of the machines (N), the range of the eNB (R) and the deployment area (E).

3.3 Relay Access

Apart from direct access a machine device may use a relay station to reach the eNB. Relay nodes provide coverage extension and throughput enhancement by forwarding an enhanced version of the received signal from devices to base station [5]. Coverage holes can be resolved by deploying additional infrastructural relays across the M2M network, e.g., M2M gateways. Assume that a number of M relay nodes are additionally deployed in the M2M deployment area in a random way. We assume that the deployment of the relay nodes takes place in a way that no overlapping occurs between the relay nodes and the between the eNB and the relay nodes. In addition it is considered that eNB and relay nodes communicate each other using optical fiber connections. Hence, eNB concentrates the baseband signals from several relay nodes to a server platform for centralized signal processing [5]. Given that the communication range of each relay node is L , the transmission coverage becomes:

$$E_r = \pi \cdot R^2 + M \cdot \pi \cdot L^2 = \pi \cdot (R^2 + M \cdot L^2) \quad (4)$$

Thus, the access probability, denoted by p_r , is now defined as $p_r = \frac{E_r}{E} = \frac{\pi \cdot (R^2 + M \cdot L^2)}{E}$. Accordingly, the probability of at least k machines are connected either directly or indirectly to the eNB is transformed as follows:

$$\begin{aligned} p_k^r &= Pr(X \geq k) \\ &= 1 - Pr\{X = 0\} - Pr\{X = 1\} - \dots - Pr\{X = k - 1\} \\ &= 1 - (1 - p_r)^N - \binom{N}{1} p_r (1 - p_r)^{N-1} \\ &\quad - \dots - \binom{N}{k-1} p_r^{k-1} (1 - p_r)^{N-k+1} \end{aligned} \quad (5)$$

3.4 Special Cases

In this subsection a set of special topologies are investigated. It is likely the deployment area to have a predefined, common shape. We consider three common shapes: a) a square, b) a rectangle and c) a disk. Figure 2 illustrates the a square deployment M2M area. The eNB is placed in the center, or in any place that the supported coverage is fully included within the deployment area. Assuming that the square area has a side of q then the probability of having at least k machine devices connected becomes:

$$\begin{aligned} Pr(X \geq k) &= \\ &= 1 - \left(1 - \frac{\pi(R^2 + M \cdot L^2)}{q^2}\right)^N \\ &\quad - \binom{N}{1} \frac{\pi(R^2 + M \cdot L^2)}{q^2} \left(1 - \frac{\pi(R^2 + M \cdot L^2)}{q^2}\right)^{N-1} \\ &\quad - \dots \\ &\quad - \binom{N}{k-1} \left(\frac{\pi(R^2 + M \cdot L^2)}{q^2}\right)^{k-1} \left(1 - \left(\frac{\pi(R^2 + M \cdot L^2)}{q^2}\right)\right)^{N-k+1} \end{aligned} \quad (6)$$

A rectangular M2M deployment area covers an area of $u \cdot y$, where u and y are the length of the two sides. Figure 3 depicts

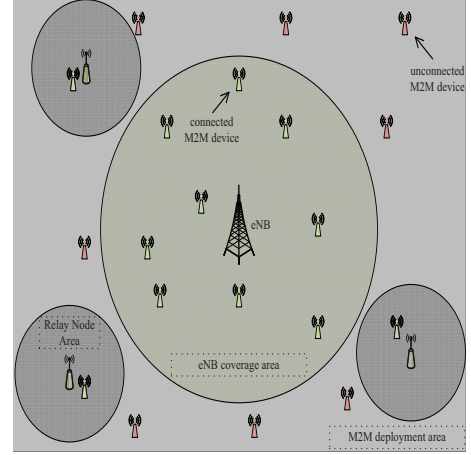


Figure 2: A square shaped M2M deployment area with three relay nodes.

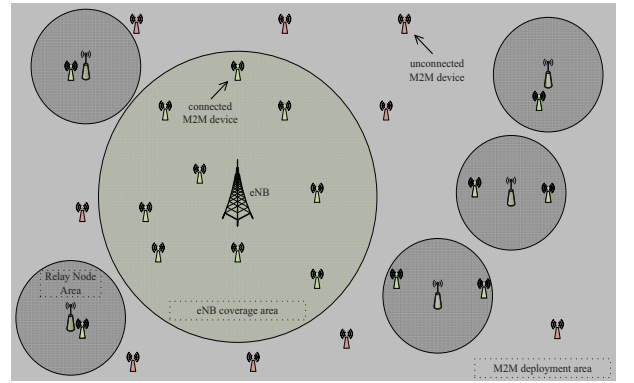


Figure 3: A rectangular shaped M2M deployment area with five relay nodes.

a rectangular deployment area. The at least k probability is now formed as:

$$\begin{aligned} Pr(X \geq k) &= \\ &= 1 - \left(1 - \frac{\pi(R^2 + M \cdot L^2)}{uy}\right)^N \\ &\quad - \binom{N}{1} \frac{\pi(R^2 + M \cdot L^2)}{uy} \left(1 - \frac{\pi(R^2 + M \cdot L^2)}{uy}\right)^{N-1} \\ &\quad - \dots \\ &\quad - \binom{N}{k-1} \left(\frac{\pi(R^2 + M \cdot L^2)}{uy}\right)^{k-1} \left(1 - \left(\frac{\pi(R^2 + M \cdot L^2)}{uy}\right)\right)^{N-k+1} \end{aligned} \quad (7)$$

Lastly, a disk shaped deployment area is drawn in Figure 4. When the deployment area is shaped as a disk with radius h , the at least k probability becomes:

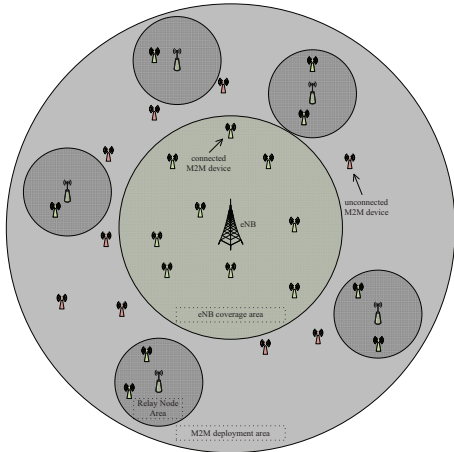


Figure 4: A disk shaped M2M deployment area with five relay nodes.

$$\begin{aligned}
 Pr(X \geq k) &= \\
 &= 1 - \left(1 - \frac{R^2 + M \cdot L^2}{h^2}\right)^N \\
 &\quad - \binom{N}{1} \frac{R^2 + M \cdot L^2}{h^2} \left(1 - \frac{R^2 + M \cdot L^2}{h^2}\right)^{N-1} \\
 &\quad - \dots \\
 &\quad - \binom{N}{k-1} \left(\frac{R^2 + M \cdot L^2}{h^2}\right)^{k-1} \left(1 - \left(\frac{R^2 + M \cdot L^2}{h^2}\right)\right)^{N-k+1}
 \end{aligned} \tag{8}$$

4 VERIFICATION AND DISCUSSION

4.1 Environment

The verification environment was based on the LTE Systems toolbox in Matlab. An eNB and multiple machine devices were considered in the direct access method while an eNB, several relay machine gateways and multiple machines devices were assumed in the indirect approach. Three M2M deployment areas were considered: a) a square area of 3000 m × 3000 m (default values), a rectangular area of 3000 m × 6000 m (default values) and c) a disk area of $\pi \times 3000 \text{ m} \times 3000 \text{ m}$. The eNB has a coverage range of 1732 m. Each relay gateway has a coverage range of 100 m.

The at least k machine devices probability is explored when a) the number of k changes and b) the M2M deployment area alters.

4.2 Machine Density Impact

First, the impact of the machine devices density is investigated. The number of k changes from 50 to 200 while the M2M deployment area remains stable. Figure 5 and Figure 6 depict the probability of having at least k machine devices connected in the eNB directly and indirectly respectively. The best performance is observed in the case of the square case since it the M2M deployment area is the lesser between the evaluated cases. The square case guarantees the connectivity of at least 150 out of 300 machine devices with probability 1. Then the probability diminishes and is

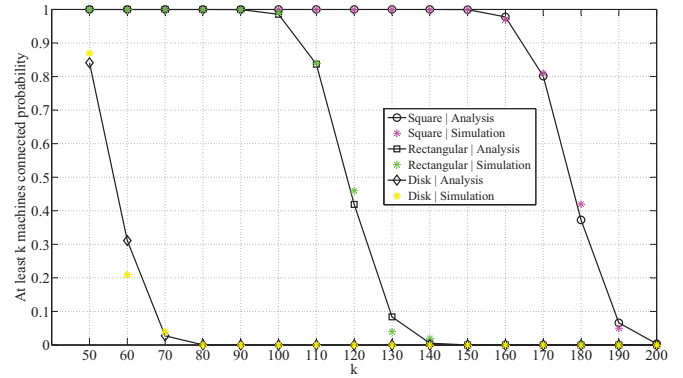


Figure 5: At least k connected machine devices probability. The deployment area includes the eNB only.

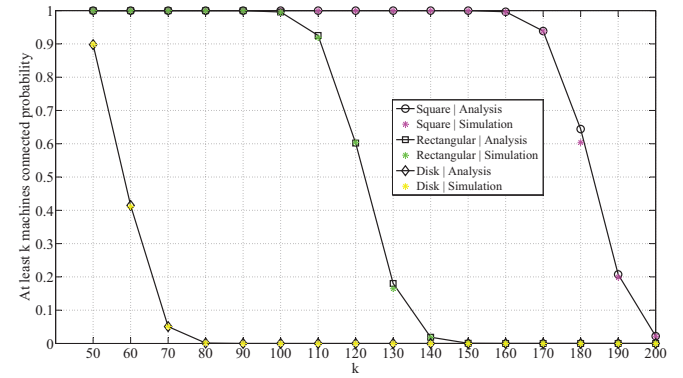


Figure 6: At least k connected machine devices probability. The deployment area includes the eNB and 10 relay nodes.

getting almost zero when the number of devices becomes 200. By observing Figure 6, we can infer that the presence of the 10 relay nodes increases the number of guaranteed machine devices from 150 to 160. In addition the probability diminishes less sharply than in Figure 5. In the rectangular case a number of 90 machine devices are guaranteed when a directly connection is applied. This number is getting larger in the indirect architecture, reaching almost 100 devices. Lastly, the disk architecture presents the lowest performance since the M2M deployment area is even larger compared to the first two cases. The number of guaranteed machine devices is less than 50 (it is about 30 devices). The impact of the additional relay nodes is minimum since the probability of at least k machine devices is still low. Obviously additional relay nodes are needed to address the coverage gap of the disk architecture.

4.3 Deployment Area Impact

Second, the impact of the deployment area is examined. Figure 7 and Figure 8 illustrate the probability of having at least k machine devices connected in the eNB directly and indirectly respectively. The number of k is fixed and equal to 100. When the area is $24 \cdot 10^6 \text{ m}^2$ the probability is almost 1, meaning that at least 100 machine devices are ensured. The probability is enhanced when a number of

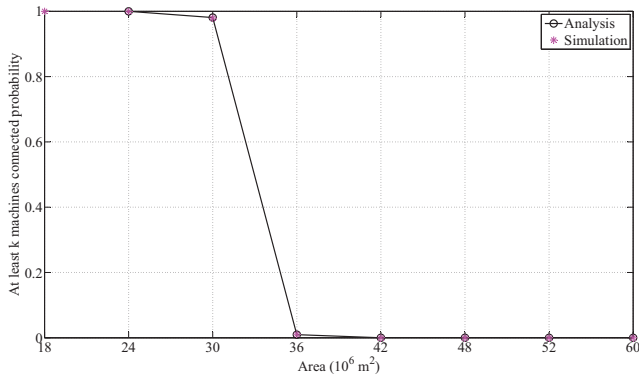


Figure 7: A disk shaped M2M deployment area with five relay nodes.

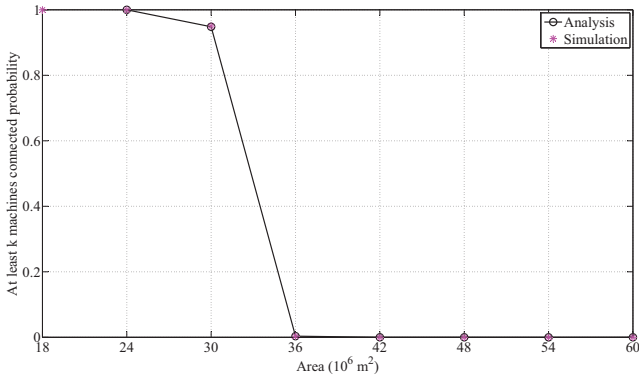


Figure 8: A disk shaped M2M deployment area with five relay nodes.

10 additional relay nodes increase the connectivity coverage of the M2M architecture. According to Figure 8 this number of machines devices are almost guaranteed when the area increases to $24 \cdot 10^6 \text{ m}^2$.

5 CONCLUSIONS

An analytical framework for studying the coverage capabilities in MTC was presented in this paper. Both direct and indirect access methods were investigated. In addition three shapes of architecture were considered including square, rectangular and disk. The study was focused on the connectivity guarantees of different architectures in terms of connecting at least k machine devices with the eNB. The analytical framework was verified by simulation results that highlight specific remarks given different topologies.

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