This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2017.2700409, IEEE Access

A Statistical Priority-based Scheduling Metric for M2M Communications in LTE Networks

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***Abstract*— Resource allocation, or scheduling, is one of the main challenges that face supporting Machine-to-Machine (M2M) communications on Long Term Evolution (LTE) networks. M2M traffic has unique characteristics. It generally consists of a large number of small data packets, with specific deadlines, generated by a potentially massive number of devices contending over the scarce radio resources. In this paper, we introduce a novel M2M scheduling metric that we term the "statistical priority". Statistical priority is a term that indicates the uniqueness of the information carried by certain data packets sent by Machine-type Communications Devices (MTCDs). If an MTCD data unit is significantly dissimilar to the previously sent data, it is considered to carry non-redundant information. Consequently, it would be assigned higher statistical priority and this MTCD should then be given higher priority in the scheduling process. Using this proposed metric in scheduling, the scarce radio resources would be used for transmitting statistically important information rather than repetitive data, which is a common situation in M2M communications. Simulation results show that our proposed statistical priority-based scheduler outperforms the other baseline schedulers in terms of having the least number of deadline misses (less than 4%) for critical data packets. In addition, our scheduler outperforms the other baseline schedulers in non-redundant data transmission as it achieves a success ratio of at least 70%.**

***Index Terms*— Internet of Things; LTE; Machine-to-Machine Communications; Statistical Priority; Uplink Scheduling**

I. INTRODUCTION

The Internet of Things (IoT) is considered the network of the foreseen future [1]. It is the network through which all objects (things) with communication capabilities are connected to achieve certain goals with minimal human intervention. Machine-to-Machine (M2M) communications [2] is one of the main IoT enabling techniques. The devices that are involved in M2M communications, or Machine Type Communications (MTC), are usually called Machine Type Communications Devices (MTCDs). Unlike Human-to-Human (H2H) communications, M2M communications are generally characterized with massive access, combined with small data payloads. MTCDs' data can be generated by event triggering or in the form of periodic reports.

M2M communications are used in a wide variety of applications including environmental monitoring (e.g. temperature, pressure, etc.), surveillance (e.g. security cameras), alarm systems (e.g. fire alarms), statistical survey and counting systems (e.g. people and vehicle counting), intelligent transportation systems, healthcare, farming and industrial production lines. M2M communications are expected to dominate traffic in cellular networks in 5th generation (5G) time frame and beyond [3]. The number of MTCDs is expected to reach 3.2 billion by year 2020 [3]. Long Term Evolution (LTE) is now seen as the best technology to support MTC due to its Internet compatibility, high capacity, flexibility in radio resources management and scalability.

One of the main challenges in adopting LTE for M2M communications is the problem of radio resource management or scheduling. Existing H2H LTE uplink scheduling algorithms [4] that focus mainly on throughput maximization and preserving the contiguity of radio resources that are assigned to a certain device are not efficient to use with MTC. This is due to the fact that M2M communications have different characteristics when compared to H2H communications. MTC traffic consists of mainly small bursty payloads that exist mostly in the uplink direction (i.e. from a device to the serving base station). MTCDs are also used in a wide variety of applications. Each application has its own requirements that may include specific Quality of Service (QoS) level, energy consumption minimization, or data transmission deadlines. A deadline in this context is the time by which data must be transmitted to avoid unwanted consequences e.g. in the case of emergency alerts.

Since radio resources are limited for massive M2M communications, the scheduling algorithm should mainly consider the importance of the information carried by the data traffic of the different MTCDs. The data reported by many monitoring devices are repetitive in many situations. This means that they do not necessarily carry high-value information all the time. For the data to be considered of high-value (i.e. unique data), the information should differ significantly from the latest communicated data by an MTCD. This means that value similarity is low or, in other words, the difference between current and previous data unit values exceeds a minimum threshold. In addition, data are also considered to have high-value information if they show a constant increasing or decreasing trend with previous data, i.e. high trend similarity. This consistent trend may indicate a problem e.g. the consistent increase of temperature inside an industrial system, which may indicate a possible fire or explosion and hence requires emergency procedures to be initiated. Furthermore, the data sent by an MTCD are considered valuable if they fall outside an expected range of

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values (i.e. upper and lower thresholds) since this may indicate abnormal conditions. The importance of data also increases if data have small time-autocorrelation (i.e. less correlation with previous data). An M2M scheduling algorithm should give data with high-value information higher priority compared to redundant data.

In order to address this problem, there is a need to find a method to define and quantify the importance of information carried in the data sent by MTCDs. In this paper, we propose a novel scheduling metric that quantifies data importance using the aforementioned statistical attributes of data such as value similarity, trend similarity and time-autocorrelation. We term this metric the "Statistical Priority". We use the statistical priority value as a scheduling metric and prove its effectiveness for M2M communications when radio resources are limited (i.e. radio resources are not sufficient to send all data). We have two main contributions in this paper:

- We propose a novel scheduling metric "statistical priority" to quantify the importance of information carried in the data to be sent by MTCDs. This metric is calculated based on statistical attributes of the data such as value similarity, trend similarity and time-autocorrelation.
- We use the "statistical priority" metric as the basis of a scheduling algorithm to allocate the scarce radio resources to MTCDs based on the importance of information carried in their data.

The rest of this paper is organized as follows. In Section II, the necessary background of M2M communications and M2M uplink radio resource scheduling is discussed. In Section III, we introduce the concept of statistical priority for M2M uplink scheduling over LTE. In Section IV, we present our novel statistical priority metric. The statistical priority-based scheduling algorithm is described in Section V and it is evaluated in Section VI. Section VII concludes the paper.

II. BACKGROUND

A. M2M Communications General Structure

Several types of devices are involved in M2M communications, such as MTCDs, Machine Type Communication Gateways (MTCGs) and Machine Type Communication Servers (MTC Servers). The MTCD is the device used to collect information from the environment (e.g. sensing, surveillance and counting). The MTCD sends data to the base station, which is known as eNB in LTE, either directly or via an MTCG. The MTCG acts as a cluster head for a group of MTCDs. The MTCG applies some forms of processing on data coming from MTCDs, e.g. combining and filtering [5]-[6] to compress the amount of data to be sent to the eNB. The MTC server is the end-target of the data sent by MTCDs. It receives data via the backhaul from the eNB and makes it available for access by human or machine type users through some application.

M2M communications' characteristics differ from those of H2H communications in several aspects such as the following:

- Most of the M2M communications traffic occurs in the uplink direction, i.e. from the MTCDs to the eNB.
- MTC traffic is bursty and consists mostly of low-rate small-size packets.
- Many MTC applications have strict data transmission deadlines. Abiding by deadlines is necessary to report an alarm for a disaster, to maintain a certain data rate or a certain QoS and to send data before they become useless or obsolete.
- There are numerous types of MTCDs and they are used in a wide variety of applications. Hence, MTCDs vary widely in terms of requirements of deadlines and needed QoS.

B. The M2M Scheduling Process

Scheduling is the process carried out by the eNB to allocate radio resources according to the requests of human user equipment (UEs) or MTCDs in downlink or uplink direction. The minimum radio resource unit that can be allocated to one UE/MTCD is called the Physical Resource Block (PRB) [7]. The PRB is a resource grid that consists of 12 subcarriers in one time slot. The scheduling process can be divided into 2 stages:

- Time Domain Packet Scheduling (TDPS): In this stage, the eNB selects a terminal (UE or MTCD) or a group of terminals to be assigned PRBs according to certain criteria (e.g. channel state, QoS, fairness, etc.).
- Frequency Domain Packet Scheduling (FDPS): In this stage, the eNB selects the PRBs to be assigned to the terminal or group of terminals that have been selected in the TDPS stage. The eNB allocates PRBs that the terminal can make the maximum use of. For example, it may allocate the PRBs at which the given terminal has the best channel conditions.

The design of uplink scheduling techniques for M2M communications should take into consideration that MTCDs in M2M communications may have strict deadline requirements. In addition, scheduling should consider the fact that a massive number of MTCDs may contend for the limited radio resources [8].

C. M2M Scheduling Algorithms Review

M2M scheduling algorithms design follows different approaches. The first approach is to use data transmission deadlines as the scheduling metric [9]-[11]. The authors in [9] propose two scheduling techniques for M2M communications that combine both channel state and MTCDs deadlines as metrics for scheduling decisions. The first algorithm adapts a conventional channel state-based algorithm to take into consideration MTCD deadlines. The second algorithm gives MTCD deadlines higher priority as compared to channel state in the scheduling decisions. The authors in [10] propose a new metric called urgency that combines deadline requirements and the buffer size (size of the data to be sent) to allocate PRBs to MTCDs with higher urgency value. In [11], the authors propose an algorithm that alternates between channel-state and MTCD deadlines interchangeably in time to balance

throughput maximization and deadline missing ratio minimization objectives heuristically.

The second approach is to group the MTCDs into QoS classes and allocate radio resources accordingly [12]-[17]. In [12], a grouping-based algorithm is proposed as an improvement to the algorithm in [13]. The MTCDs are grouped in clusters that belong to a QoS class characterized by the packet arrival rate and the size of data to be downloaded or uploaded. When the product of the aforementioned two factors for a certain group is higher than that of the other groups, this group gets allocated radio resources more frequently. The authors in [14] define three QoS Class Indicators (QCI) for M2M applications. In [15], a Class-Based Dynamic Priority (CBDP) scheme is presented. This scheduling technique suggests that a hybrid scheduler for both M2M and H2H traffic is the most efficient. The authors design their algorithm in such a way that enables it to prioritize delay-sensitive M2M traffic over delay-tolerant H2H traffic. In [16], the authors propose a multi-step scheduler that divides MTCDs into groups where each group is assigned a portion of resources based on the required QoS and the buffer status. The authors in [17] propose a hybrid scheduling algorithm for a heterogeneous network that deals with both H2H and M2M communications. The traffic is divided into two queues and each queue is scheduled separately. The first queue includes all H2H users (UEs) and delay-sensitive MTCDs. Scheduling is based on a combination of metrics that include buffer waiting time, proportional fairness and delay thresholds. The second queue includes all remaining (delay-tolerant) MTCDs that are scheduled using a combination of channel-state-based and round-robin-based schedulers.

The third approach is to design a scheduling algorithm that is tailored for a specific application. The authors in [18] introduce the idea of predictive scheduling that allocates radio resources to MTCDs that are in vicinity of an MTCD that is currently sending a Scheduling Request (SR). The algorithm is suitable for specific applications such as cascaded alarm systems and Wireless Sensor Networks (WSNs).

The fourth approach formulates the scheduling problem as an optimization problem with different objectives [19]-[21]. In [19], the authors propose an algorithm to solve an optimization problem whose objective is allocate power and radio resources such that the minimum lifetime of a group of MTCDs is maximized. The constraints of maximum transmission power and LTE transport block size are taken into consideration. The authors in [20] propose an energy-efficient scheduling algorithm by minimizing the transmission time of MTCDs while considering their data transmission deadlines. In [21], power consumption minimization is the objective, and minimal data rate requirements are added to deadline constraints.

The novel feature in our proposed metric is that we consider the nature of the real-time data sent by MTCDs. We introduce a metric that helps the eNB allocate radio resources to the MTCDs that need to send more important data in real-time instead of just depending on fixed priority assignments.

D. Data Compression

Data compression is the process of reducing the size of a data stream reported by a device. This is done for many purposes such as saving the device's power and reducing traffic within the network. The main method for data compression is to limit data transmissions by refraining from sending data values that are highly similar to previously sent data points using different methods. In [5], the sensor node does not send the measured data value except if it differs by at least a certain threshold from the last sent data value (i.e. low value similarity or low temporal correlation). Furthermore, the gateway node (e.g. MTCG) collects the data sent by sensor nodes and excludes those readings that do not differ significantly from the readings of the other sensors within the vicinity of this sensor (i.e. low value similarity or low spatial correlation). In [6], a gateway node collects measured data values from sensors and sets a distribution of data values based on normal distribution or T-distribution with a certain range. This range is broadcasted to all sensor nodes so that every sensor node does not transmit its measured value except if it is out of the broadcasted range.

As we will discuss later in the paper, we do not rely on application-based compression techniques or group-based decisions to reduce transmitted data. This is due to the fact that imposing such rules on application developers would be restrictive and impractical. In addition, in many cases, network nodes act individually and autonomously with regard to data transmission decisions, which renders group-based decisions inapplicable.

III. The Attributes of Statistical Priority

In this section, we present possible statistical attributes that can be used to quantify the importance of information of the data to be sent by MTCDs. This offers an opportunity for allocating the scarce radio resources on the basis of data uniqueness. Hence, the MTCDs with unique data are given higher priority that we term the *Statistical Priority* (SP).

We classify M2M data according to [15] into three classes, namely, environmental monitoring data, video data and alarm data. The environmental monitoring class represents periodic data with low rate, relaxed deadlines (i.e. the data transmission deadline is relatively long compared to that of other MTCDs) and redundant data. The video surveillance class is characterized by large payloads with many similar video frames due to monitoring a stable situation most of the time. It is worth noting that we focus on video applications within the context of MTC only (i.e. H2H video applications like streaming and video conferencing are not considered). The alarm class represents the event-driven data with high importance and very strict deadline requirements in the order of milliseconds. While there is a wide variety of MTC data, we only consider the aforementioned classes as sample applications that represent different traffic characteristics. We therefore define the possible statistical attributes that can be used to determine the uniqueness of the data of each of these classes in the following.

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A. Environmental Monitoring Data

Environmental monitoring data are produced by sensors that monitor a given phenomenon such as temperature, humidity, pressure, light intensity and gas concentration in a gas leakage detection system. These data may be collected for recording and archiving purposes. For example, it could be required to keep records of the daily temperature changes of a city throughout the year to support weather forecast and meteorological studies. In addition, data may be collected to ensure the safety/stability of industrial processes and monitor the contents of warehouses for theft detection. The environmental monitoring data are generally characterized by small packet sizes and low data rates. There are several statistical parameters that can help define the value of information reported by MTCDs performing environmental monitoring such as threshold, value similarity and trend similarity.

- Threshold

MTCD data that exceed a certain upper/lower threshold may need an action as a response. These data points also become even more important when the difference between them and the threshold increases.

If an MTCD reports a data value, $x(t)$, at a discrete time instant t where we have an upper threshold of interest Th_{upper} and a lower threshold of interest Th_{lower}, $x(t)$ is said to have highly valuable information if:

$$x(t) > Th_{upper} \text{ or } x(t) < Th_{lower} . \quad (1)$$

- Value Similarity

Let the data point reported by an MTCD at a given instance $x(t)$ be different from the last reported data point x_p by $|x(t) - x_p|$. If the value of $|x(t) - x_p|$ exceeds a certain threshold Δ, this means that the reported data point is not redundant and its information has a unique value. For example, let us assume a temperature sensor that reports the data points of values (27.1, 27.1, 27.15 and 27.4 degrees Celsius). If the first data point is reported, the second data point is redundant since it is the same like the previous one (especially when the time difference between them is small). The third data point is not considered redundant but it has less valuable information when compared to the fourth data point. Hence, setting Δ to a value of 0.1 to define the data points of high-value information is reasonable. The data point becomes more important when the change level threshold is exceeded by a higher difference since it presents a higher change in the measurement of the monitored phenomenon. Hence, $x(t)$ is said to have unique information of high value if:

$$| x(t) - x_p | > \Delta . \quad (2)$$

- Trend Similarity

When a sequence of data points reported by an MTCD maintains a constant trend (increasing or decreasing) for a series of points, this may be more valuable to report than points oscillating around an average value with small variations. For example, consider an MTCD that reports humidity data points of (40%, 41%, 39% and 40%). This can be seen as minor fluctuations around an average value. On the other hand, if it reports data points of humidity of (39%, 40%, 41% and 42%), it is easily concluded that there is an increasing trend in humidity data. This may be of more interest to know and report than the modestly fluctuating case.

If an MTCD reports a data point $x(t)$ at instant t, $x(t)$ is said to have a high information value if [22]:

$$(x(t) - x(t-1)) \times (x(t-1) - x(t-2)) > 0 . \quad (3)$$

B. Video Data

Video data represent one of the common data types in M2M networks. Their sources are mainly cameras that are used in many applications e.g. surveillance, people counting and object counting. These cameras have higher data rates (for seamless transition between consecutive frames, cameras operates at a minimum of 30 frames/second) and harder delay tolerance requirements when compared to environmental monitoring data. Throughout this paper, videos are represented in RGB format, where any pixel at a given position (x, y) and time instant (t) has an 8-bit represented level (Maximum Level = 255) for each of the R, G and B components. However, the statistical attributes we use for video data (correlation) can be applied to other video formats like YCbCr, without loss of generality. Video encoding, compression and special frames are out of the scope of this paper. The video data are considered to have high-value information when the frames carry significant changes when compared to previous frames. For example, a surveillance camera recording a stable status with no changes should be given lower priority in data transmission when radio resources are scarce.

- 2-D Frame Correlation

The best statistic to measure the value of information carried by a given video frame is the correlation with previous frames. A frame that is very highly correlated (correlation ≈ 1) with the last transmitted frame has less importance and value if compared to frames carrying new events and many changes and hence less correlated with last reported frame. For example, a surveillance camera recording at late night or early morning will barely carry useful information to tell since the frames are almost constant (except at the time of threats).

Consider an MTCD that reports a video frame at instant t represented by the vector $F(x, y, t) = [F_R(x, y, t)\ F_G(x, y, t)\ F_B(x, y, t)]$, where x and y are the coordinates of the pixel in the frame, while F_R, F_G and F_B represent the level of RGB components at this pixel. The 2-D correlation between the current frame and a previous frame at instant t_o can be defined by the vector $\boldsymbol{C}$ as follows:

$$\mathbf{C} = \begin{bmatrix} C_R \\ C_G \\ C_B \end{bmatrix} = \begin{bmatrix} Corr(\mathrm{F_R}(x, y, t), \mathrm{F_R}(x, y, t_o)) \\ Corr(\mathrm{F_G}(x, y, t), \mathrm{F_G}(x, y, t_o)) \\ Corr(\mathrm{F_B}(x, y, t), \mathrm{F_B}(x, y, t_o)) \end{bmatrix} . \quad (4)$$

C. Alarm Data

Alarm data are the data that report the occurrence of abnormal conditions, in general. They are mainly event-triggered. The alarms may be used as alerts for fires or non-authorized building entry. They can be modeled as a sequence of very small payload data packets with tightly strict deadline requirements. The data transmitted by alarm MTCDs are always crucial. Hence, Alarm MTCDs should be given the

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highest priority during the radio resource allocation process.

IV. Statistical Priority Metric

Statistical Priority (SP) is a quantification of the value of information entailed in a data unit reported by an MTCD based on the statistical attributes that we discussed in the previous section. In this section, we propose a bounded output function whose output takes a value between 0 and SP_{max} (a positive real value) to calculate the SP value. The main goals of the SP value evaluation function can be stated as follows:

- Assigning higher priority to data packets carrying non-redundant information of high value or importance in a manner that is adaptive to the various M2M applications.
- Guaranteeing a minimum rate of data transmission by an MTCD. The goal is to ensure that every MTCD reports at least one comprehensive unit of information every defined period T to prevent MTCD resource starvation.

A. Statistical Priority as a Function of Statistical Attributes

Consider the array $Y = (y_1(t), \ldots, y_i(t), \ldots, y_n(t))$ where $y_i(t)$ is a set of the aforementioned statistical attributes. SP can be calculated as a weighted sum of functions $f(y_i(t))$ based on the value of statistical attributes $y_i(t)$ at a discrete time instant t. The value of the function $f(y_i(t))$ indicates whether a certain statistical attribute $y_i(t)$ is detected at instant t. Hence, the function $f(y_i(t))$ can be modeled as a sigmoidal (logistical or s-curve) function that is output bounded between 0 and 1:

$$f(y_i(t)) = sigmoid(y_i(t), b_i, c_i) = \frac{1}{1+e^{-b_i(y_i(t)-c_i)}}, \quad (5)$$

where c_i represents the inflection point of the function such that $f(y_i(t) = c_i)$ is 0.5 and b_i controls how steep the function moves from 0 to 1. A large magnitude of b_i results in a steep transition from 0 to 1 similar to the step function. On the other hand, a small magnitude of b_i makes this transition smooth. If $b_i < 0$, the sigmoid function is reflected around the vertical axis. Fig. 1 shows different realizations of the sigmoid function at $c_i = 0$.

We consider 4 cases of statistical attributes:

Case 1: if $x(t) > Th_{upper}$, $x(t)$ should be considered to have unique and important data and should therefore have a higher SP value. Then, the attribute of interest $y_i(t)$ can be expressed as:

$$y_i(t) = x(t) - Th_{upper}. \quad (6)$$

When $x(t)$ exceeds a threshold (i.e. high-value information), $y_i(t)$ becomes positive and $f(y_i(t))$ should approach 1. When the threshold has not been exceeded, $y_i(t)$ takes a negative value and $f(y_i(t))$ should approach 0. Hence, $f(y_i(t))$ could be represented as $sigmoid(y_i(t),100,0)$ (where b_i can be any large number for steep transition).

A similar case that can be considered is when $x(t) < Th_{lower}$. In this case, we can set b_i of the sigmoid function to be a negative value –100.

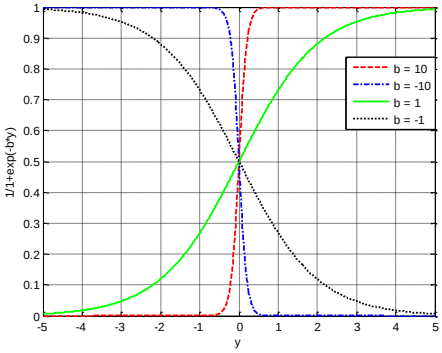

Fig. 1. The Sigmoid Function

Case 2: if the data are considered valuable and unique when the difference between $x(t)$ and last reported measurement x_p by the MTCD exceeds a certain threshold. Consequently, $y_i(t)$ can be represented as:

$$y_i(t) = \left| x(t) - x_p \right| - \Delta. \quad (7)$$

Hence, $f(y_i(t))$ could be represented as $sigmoid(y_i(t),b_i,0)$ where b_i can be selected according to the desired level of significance of the value of the differences.

Case 3: If a data point is shown to follow a trend, it is more valuable to send and should have higher SP value. Then, the function of interest $y_i(t)$ can be represented as:

$$y_i(t) = \prod_{j=0}^{2d-1} (x(t-j) - x(t-j-1)), d = 1,2,\ldots, \quad (8)$$

where d represents the depth of the trend function (when $d = 1$, we consider the trend in the latest three data points, when $d = 2$, we consider the trend in the latest five data points). If the measurements follow an increasing or decreasing trend, the value of $y_i(t)$ will be positive (for an odd number of measurements including the current measurement at instant t) and $f(y_i(t))$ should approach 1. Otherwise, $y_i(t)$ will be negative and $f(y_i(t))$ should approach 0. Hence, $f(y_i(t))$ could be represented as $sigmoid(y_i(t),100,0)$ (where b_i can be any large number for a steep transition). On the other hand, a small value of b_i can be used to assign higher priority to trends with bigger differences between successive data values.

Case 4: 2-D Time autocorrelation between the current frame at time t and a previous frame at time t_o at the three components of the video frame (e.g. RGB components or any other representation) of a given surveillance camera MTCD is calculated to form $\boldsymbol{C}$ as in (4). Then, the minimum correlation C_{min} is obtained as follows:

$$C_{\min} = \min(C_R, C_G, C_B). \quad (9)$$

Therefore, the attribute of interest y_i can be represented as:

$$y_i(t) = C_{\min} - C_{Th}, \quad (10)$$

where C_{Th} is the maximum correlation value that represents an effective change between two video frames. In this case, a negative value of $y_i(t)$ indicates that the current frame at instant t is a unique frame of high SP value and it carries new information (significant changes) as inferred from the fact that it is not highly correlated with last transmitted frame at instant

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t_o. Hence, $f(y_i(t))$ could be represented as $sigmoid(y_i(t),-1000,(1-C_{Th})/2)$ (where b_i is a very large negative number since practically a frame that is correlated by up to ±0.995 carries different information and c_i is a mid-point between C_{Th} and the maximum correlation of 1).

Choosing the type of statistical feature that indicates the value of information entailed in data is dependent on the application. Moreover, multiple statistical features may be useful with different levels of importance. That is, each function $f(y_i(t))$ is given a weight a_i from the vector $A = (a_1, \ldots, a_i, \ldots, a_n)$. These weights take values such that:

$$0 \le \sum_{i=1}^{n} a_i \le SP_{\max} \tag{11}$$

It is worth noting that the condition in (11) applies only to non-mutually exclusive statistics (i.e. mutually exclusive statistical attributes that can never happen together such as exceeding upper and lower thresholds do not need to satisfy this condition). This condition makes the SP value at instant t bounded since it is modeled as a weighted sum of the sigmoidal functions $f(y_i(t))$ of the different statistical attributes as follows:

$$SP(A,Y,t) = \sum_{i=1}^{n} a_i f(y_i(t)) . \tag{12}$$

B. Guaranteeing Minimum Rate of Data Transmission

The SP value should ensure no starvation occurs by allowing each MTCD to send at least one unit of data every period of time, T, regardless of the data importance. For example, a sensor may be configured to provide a measurement every $0.1T$. Of these measurements, at least one measurement should be reported every T seconds (i.e. at least one measurement out of 10 measurements should be assigned a high SP value).

Consider a periodic function $f_o(t)$ whose output ranges between 0 and 1 and has a period T. $f_o(t)$ could be written, for example, as a sinusoidal function with an offset as follows:

$$f_o(t) = 0.5(\cos(\frac{2\pi t}{T}) + 1) \tag{13}$$

This periodic function has a weight a_o that will be used in the SP calculation, as we will illustrate shortly, where:

$$0 \le a_o \le SP_{\max} \tag{14}$$

Furthermore, to limit the guaranteed number of data transmissions to one data transmission per period T, we introduce the variable $f_r(t,T)$ where:

$$f_r(t,T) \in \{0,1\} \tag{15}$$

This variable is set to 0 if any data packet was sent during the current interval T and it remains 1 otherwise. $f_r(t,T)$ is reinitialized to take the value of 1 at the start of every new cycle of length T. Hence, SP value can expressed based on the periodic function $f_o(t)$ and variable $f_r(t,T)$ as follows:

$$SP(A,Y,t,T) = a_o f_o(t) \times f_r(t,T) \tag{16}$$

When the MTCD has non-redundant data, it can send more than one data transmission depending on the SP value, as will be clarified in the following sub-section.

C. Statistical Priority Evaluation Function

The goals of SP that are satisfied by the SP value expressions in (12) and (16) can be combined by selecting the maximum of the two functions as follows,

$$SP(A,Y,t,T) = \max(a_o f_o(t) \times f_r(t,T), \sum_{i=1}^{n} a_i f(y_i(t))) . \tag{17}$$

In this case, the MTCDs with unique data that have important information based on the statistical attributes will cause the second function to influence the SP to assume a high value. As a result, the data become of high priority during the radio resource allocation process. On the other hand, the MTCDs with repetitive data will be guaranteed to send one data unit every period T as a result of the effect of the first periodic function.

A special case exists for alarms. The data from alarms are always considered important and urgent. Hence, SP is directly set to SP_{max} for alarm MTCDs.

This mathematical model for evaluating the SP value is very flexible which makes it suitable for different M2M applications, different statistical attributes of interest (e.g. mean crossing rate) and periodic data transmission. For example, if an MTCD needs to send identical live signals periodically, then a_o can be set to be SP_{max} to guarantee one packet is transmitted every period T.

D. Statistical Priority Reporting in LTE

In LTE, there are three physical uplink channels. The Physical Uplink Shared Channel (PUSCH) is used to carry uplink data. The Physical Random Access Channel (PRACH) is used for random access requests. Finally, the Physical Uplink Control Channel (PUCCH) is used to send uplink control information from UEs/MTCDs to the eNB such as Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI), Rank Indicator (RI), Scheduling Request (SR) and Buffer Status Report (BSR) [7].

We propose to report the SP via a Statistical Priority Report (SPR) that could be sent by the MTCD through the PUCCH. It can follow similar structure to that of the BSR. This means that there should be an SPR value for every radio bearer (logical channel). The SPR value can be reported using 6 bits (64 levels) like the BSR [7]. Although, this approach imposes more control traffic on the PUCCH, it will help reduce the amount of redundant data traffic to be sent over LTE M2M networks.

V. Statistical Priority-based Scheduling Algorithm

The scheduling algorithm is based on the statistical priority metric that we discussed in Section IV. Algorithm I is designed such that it dedicates a set of radio resources for serving M2M communications traffic. Due to the scarcity of radio resources in general, the PRBs are allocated first to the MTCDs that have the highest SP score, i.e. they are allowed to send data that are more unique and carry information of higher SP value. Consider a set of N PRBs and a set of M active MTCDs (active MTCDs are the ones that request data

transmission and have not missed the deadline yet). Every MTCD m (m = 1, …, M) has a deadline D_m, an SP value of SP_m and an SNR value at the n^{th} PRB of $S_{m,n}$.

ALGORITHM I. STATISTICAL PRIORITY-BASED SCHEDULING ALGORITHM

Statistical Priority-based Scheduling Algorithm
Step 1: Sort SP_m values in a descending order to select an active MTCD m that carries data with maximum statistical priority score (i.e. most valuable information)
Step 2: Assign PRB n (at which the selected MTCD m has maximum SNR $S_{m,n}$) to MTCD m
Step 3: Allocate PRBs on the right and the left of PRB n to MTCD m and keep expanding in both directions till any of the following conditions applies [23]: - MTCD m acquires enough PRBs to send its data. - Expanding in any direction is blocked by PRBs allocated to other MTCDs.
Step 4: Consider MTCD m as served and remove the allocated PRBs from the set of available PRBs. Then repeat *Step 1* till all PRBs are allocated, or the needs of all MTCDs have been fulfilled

In summary, this algorithm starts by selecting the MTCD with higher SP value in *Step 1*. In *Step 2*, it chooses the PRB n at which this MTCD has the best SNR. The MTCD keeps acquiring PRBs to the left and the right of the PRB n till it either gets sufficient PRBs to send its data or it hits PRBs already allocated to other MTCDs as shown in *Step 3*. In Step 4, the allocated PRBs become no longer available and the MTCD is considered served before continuing to allocate the remaining PRBs.

The following points are worth noting:

- SNR could be replaced by any channel-state metric like SINR or CQI
- Any MTCD that misses the deadline returns to the idle state (except when there are still data packets in its buffer) till it needs to transmit data once again.

VI. EXPERIMENTAL EVALUATION

A. Simulation Setup

We compare the statistical priority-based scheduling with delay-based scheduling in realistic M2M deployments where MTCDs have different profiles (i.e. different delay tolerances, data sizes, data types and traffic structure). In addition, we use an SNR-based scheduler in the comparison knowing that it does not address deadline priorities. In this comparison, we introduce novel performance evaluation metrics that focus on measuring the critical data that were successfully transmitted rather than measuring the mere throughput that does not consider the level of importance of the transmitted data packets.

We consider a single base station serving 100 – 400 MTCDs using 3 or 5 MHz dedicated bandwidth to M2M communications in an AWGN channel. The simulation parameters are shown in Table I. Four groups of MTCD types, namely, emergency alarms, cameras and two groups of environmental monitoring (temperature and humidity sensors) are used to represent different types of M2M traffic. Table II shows the details of delay tolerance, packet size and percentage of MTCDs that belong to the four groups. Further details about the traffic generation of each MTCD group are given in Table III. Table IV describes the performance evaluation metrics used to compare our proposed scheduling scheme with the other schemes. In this table, we introduce the metric "Critical Packets Success Rate" that shows how successful an algorithm is in allowing every MTCD to send sufficient data to represent the whole set of data given the scarce radio resources.

TABLE I. SIMULATION PARAMETERS FOR SP-BASED SCHEDULING EVALUATION

Parameter	*Value*
Number of MTCDs (M)	100 – 200 – 300 – 400
Number of Base Stations	1
Average SNR Range	Uniform (4dB,10dB)
Number of Subframes	200000
Number of Runs	10 Independent Runs
Bandwidth (MHz)	3 – 5
Number of PRBs (N)	15 – 25
Channel Model	Additive White Gaussian Noise (AWGN)
Scheduling Algorithms	• Deadline-based Scheduler • SNR-based (Channel-state) Scheduler • SP-based Scheduler

TABLE II. MTCD CONFIGURATION

Application	*Delay Tolerance (ms)*	*Packet Size (Bytes)*	*%*
Emergency Alarms	Constant (10)	32	10%
Surveillance Camera	Uniform (125,250)	512	10%
Regular Monitoring (Temperature)	Uniform (800,900)	128	40%
Regular Monitoring (Humidity)	Uniform (800,900)	128	40%

TABLE III. MTCD TRAFFIC DESCRIPTION

Application	*Packet Content*	*Traffic Description*
Emergency Alarms	Alert	• 5 packets within 200ms
Surveillance Camera	Compressed Low-quality Video Frame	• 30 frames per second • 400 frames per MTCD • Random start time • Frames extracted from [24]
Regular Monitoring (Temperature, Humidity)	Data Point	• 1 data point per second • 200 data points per MTCD • Data points extracted from [25]

TABLE IV. PERFORMANCE EVALUATION METRICS DESCRIPTION

Evaluation Metric	*Description*
Overall deadline-missing ratio	The ratio between packets that missed deadline to the overall number of packets for all MTCD types
Alarm deadline-missing ratio	The ratio between alarm packets that missed deadline to the overall number of alarm packets
Critical packets success rate (Sensors)	The ratio between successfully sent packets for regular monitoring MTCDs to the number of its critical packets. The number of critical packets is the number of packets that are sufficient to claim that linearly interpolated summarized data represent the full data set for every regular monitoring MTCD.
Critical packets success rate (Cameras)	The ratio between successfully sent packets for surveillance camera MTCDs to the number of critical packets for every surveillance camera MTCD.

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TABLE V. STATISTICAL ATTRIBUTE THRESHOLDS FOR MTCDS

Statistical Attribute	*Temperature Sensor*	*Humidity Sensor*	*Camera*
Upper Threshold (Th_{upper})	28° C	48%	N/A
Lower Threshold (Th_{lower})	27° C	42%	N/A
Difference Threshold (Δ)	0.1° C	0.1%	N/A
Trend	Yes	Yes	N/A
2D Correlation (C_{Th})	N/A	N/A	0.995

In addition, SP parameters are selected to boost the importance of the data points or the frames that have high-value information. The high-value information for sensors' data points, as described in Section III, is found in statistical attributes like exceeding a threshold, following a trend, experiencing a big change with respect to last reported data. In case of video frames, high-value information exists in a frame if it is fairly uncorrelated with last sent video frame. For alarms, all packets are of maximum importance ($SP = SP_{max}$) and are therefore prioritized over all other types of traffic. SP_{max} equals 10 in simulations. Table V shows the thresholds used to calculate the different statistical attributes $y_i(t)$ at an instant t such as the upper and lower thresholds of interest, the minimum difference threshold Δ and minimum correlation threshold for sensors and cameras, respectively. Table VI lists the values of parameters b_i and c_i for the sigmoid functions $f(y_i(t))$ associated with the different statistical attributes $y_i(t)$. Finally, Table VII presents the values of the weights a_o and a_i given to each statistical feature function and periodic data reporting to calculate the SP value using (17).

Overall, eight scenarios (two values of channel bandwidth × four values of the number of MTCDs) are simulated according to the aforementioned parameters to represent different traffic loads. The evaluation metrics stated in Table IV are measured for the eight simulation scenarios. Each simulation scenario is performed using each of the tested schedulers for ten independent runs. The final results represent the average of these runs with 95% confidence interval analysis. It is worth noting that, as indicated in Table IV, each of the performance evaluation metrics focuses on a certain type of MTCD traffic (i.e. sensor data, video and alarms).

TABLE VI. SIGMOID FUNCTION PARAMETERS OF STATISTICAL ATTRIBUTES

Statistical Attribute	*Temperature Sensor*		*Humidity Sensor*		*Camera*	
	b_i	c_i	b_i	c_i	b_i	c_i
Upper Threshold	100	0	100	0	N/A	N/A
Lower Threshold	-100	0	-100	0	N/A	N/A
Difference Threshold	5	0	5	0	N/A	N/A
Trend	100	0	100	0	N/A	N/A
2D Correlation	N/A	N/A	N/A	N/A	-1000	0.0025

TABLE VII. WEIGHTS OF STATISTICAL FEATURE FUNCTIONS

Statistical Attribute	*Temperature Sensor*	*Humidity Sensor*	*Camera*	*Alarm*
Upper Threshold (a_1)	4	4	0	N/A
Lower Threshold (a_2)	4	4	0	N/A
Difference Threshold (a_3)	3	3	0	N/A
Trend (a_4)	3	3	0	N/A
2D Correlation (a_5)	0	0	10	N/A
Periodic Priority (a_0)	5	5	5	N/A
Default	N/A	N/A	N/A	10

B. Overall Deadline-Missing Ratio

Overall deadline-missing ratio results, which are shown in Fig. 2 and Fig. 3, show that non-deadline-based schedulers such as SNR-based and SP-based schedulers have less deadline misses than the deadline-based scheduler when radio resources are insufficient for satisfying all data transmission requests. This is due to the fact that the deadline-based scheduler tries to meet all densely successive deadlines for a large number of MTCDs which results in missing many of these deadlines. On the other hand, the strategy of the non-deadline-based schedulers helps reduce the ratio of deadline misses for different densities of MTCDs as shown in Fig. 2 and Fig. 3. We see from the figures that SNR-based scheduler outperforms our proposed SP-based scheduler due to the fact that the SNR-based scheduler allocates PRBs to the MTCDs with the best channel conditions so that they would utilize the scarce radio resources efficiently (i.e. without packet drops or the need for additional PRBs per packet). However, the disadvantages of SNR-based scheduling will be revealed through the other performance evaluation metrics.

C. Alarm Deadline-Missing Ratio

Using this performance evaluation metric, we focus on alarm MTCDs due the high importance of their data and the strict deadline requirement they have. A perfect scheduler should be able to allow the transmission of all alarm packets (or miss as few as possible if alarm redundancy is assumed). The alarm deadline-missing ratio results in Fig. 4 and Fig. 5 show that the SP-based scheduler outperforms the deadline-based scheduler with an alarm deadline-missing ratio that does not exceed 4% for all the simulation experiments. On the other hand, the SNR-based scheduler deals with alarm MTCDs and other MTCDs on equal basis despite the fact that alarm packets need to be given higher priority due to the high-value information they carry about abnormal conditions or threats. Hence, it performs significantly worse than the other schedulers from the perspective of this metric. The reason behind the superior performance of the statistical priority-based scheduler is that it prioritizes alarm MTCDs based on data importance or SP score in which alarm MTCDs always have higher priority over other MTCDs. On the other hand, the deadline-based scheduler prioritizes alarm MTCDs based on deadline where other non-alarm MTCDs may have closer deadlines.

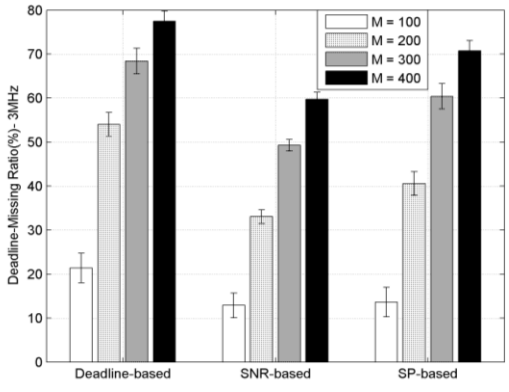

Fig. 2. Overall Deadline-missing Ratio (BW = 3MHz)

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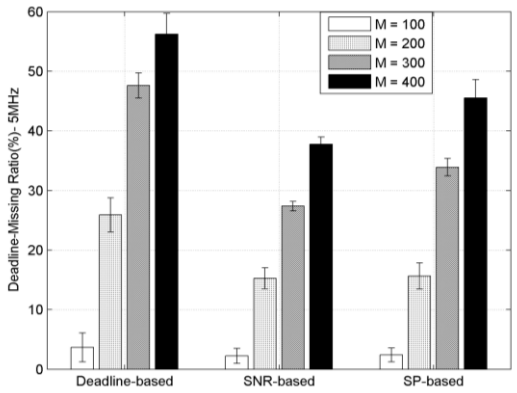

Fig. 3. Overall Deadline-missing Ratio (BW = 5MHz)

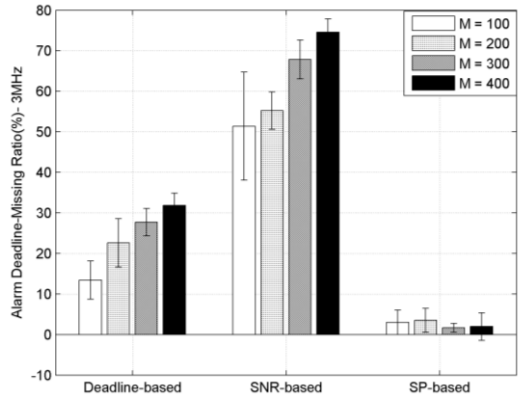

Fig. 4. Alarm Deadline-missing Ratio (BW = 3MHz)

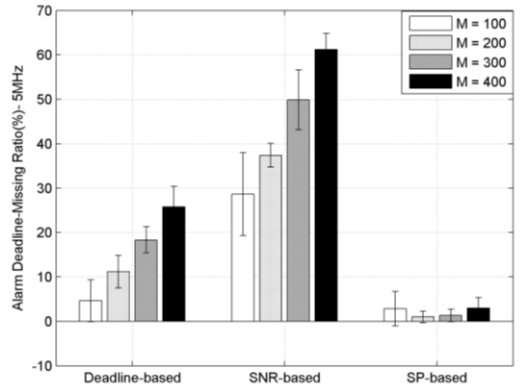

Fig. 5. Alarm Deadline-missing Ratio (BW = 5MHz)

D. *Critical Packets Success Rate (Sensors)*

When we evaluate the performance of the scheduler for regular monitoring MTCDs (e.g. temperature and humidity sensors), more focus should be given to data of high-value information. Regular monitoring devices usually send repetitive data values and the same data features could be preserved even with sending a reduced number of data values selected on the basis of their importance calculated by statistical priority. Hence, to evaluate the success of a given scheduler with respect to regular monitoring MTCDs, we measure the success rate of sending the critical packets in terms of the ratio of the actual sent data packets to the number of critical packets that must be sent to fully represent the whole data stream. This success ratio is measured for every regular monitoring MTCD as in (18) and the average is calculated. With limited radio resources, it is not efficient to strive to send as much data as possible. Rather, the focus should be on ensuring the success of sending critical data packets.

$$Critical\_Packets\_Success\_Rate = \min\left(\frac{\#\ Sent\_Packets}{\#\ Critical\_Packets},1\right) \times 100\% \quad (18)$$

The results of this performance evaluation metric are shown in Fig. 6 and Fig. 7. It is clear that the statistical priority-based scheduler outperforms the other schedulers especially as the number of the MTCDs increases. The success rate of the proposed technique is almost 100% for the system bandwidth of 5MHz at any traffic load. When the system bandwidth is reduced to 3 MHz, i.e. less number of PRBs, SP-based scheduler suffers the least losses and keeps the success rate above 90% when number of MTCDs is 300 or less.

Although SNR-based scheduler enables transmitting more data packets than SP-based scheduler, it does not take the importance of data collected by MTCDs into consideration. Hence, some MTCDs (usually with high SNR) succeed to send more data packets (critical and non-critical) regardless of redundancy in data. On the other hand, MTCDs with worse channel conditions may not be able to transmit critical packets with information of high value since the priority of radio resource allocation is given to MTCDs with better channel conditions. An evaluation metric like critical packet success rate refutes the conclusion that the SNR-based scheduler outperforms SP-based scheduler due to success in sending more data packets. Furthermore, the SP-based scheduler is shown to be fairer than baseline schedulers by allowing a larger number of MTCDs, on average, to be closer to transmitting 100% of their critical data packets (which is equivalent to the higher success rate for critical packets).

E. *Critical Packets Success Rate (Cameras)*

The critical success rate evaluation metric can also be used for surveillance camera MTCDs. Sending the critical frames is sufficient to represent video information. The success rate for surveillance cameras MTCDs is less than that of regular monitoring MTCDs due to the larger packet size, denser traffic (i.e. more packets per second) and stricter deadlines. However, visual inspection has shown that a 70-80% success rate is sufficient to represent the information in a video without much negative impact as noticed by the human eye. In this simulation experiment, the success ratio is measured for every surveillance camera MTCD using (18) and the average is then calculated. The SP-based scheduler is found to outperform the other schedulers, as shown in Fig. 8 and Fig. 9. The success rate does not drop below 70% except for most severe cases of radio resource limitations (i.e. $M \geq 300$ MTCDs under a system bandwidth of 3 MHz or $M \geq 400$ MTCDs under a system bandwidth of 5 MHz).

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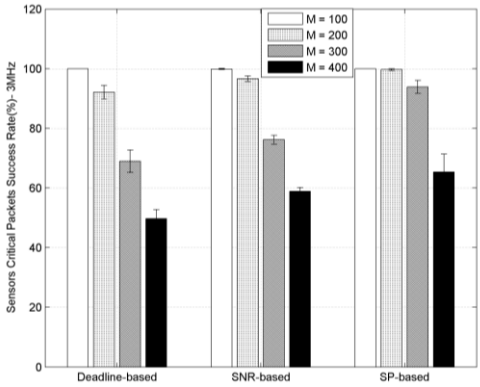

Fig. 6. Critical Packets Success Rate (Regular Monitoring MTCDs) (BW = 3MHz)

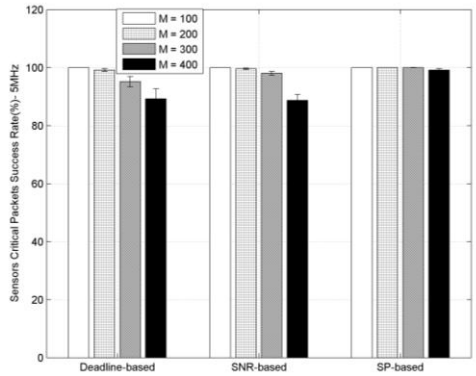

Fig. 7. Critical Packets Success Rate (Regular Monitoring MTCDs) (BW = 5MHz)

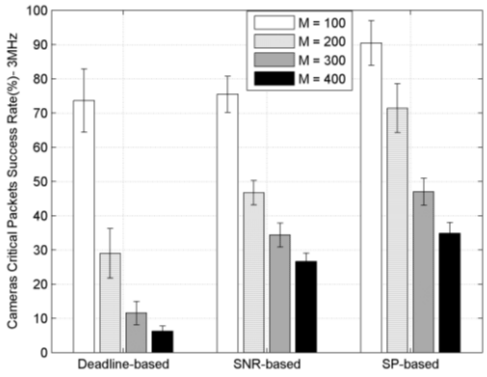

Fig. 8. Critical Packets Success Rate (Surveillance Cameras MTCDs) (BW = 3MHz)

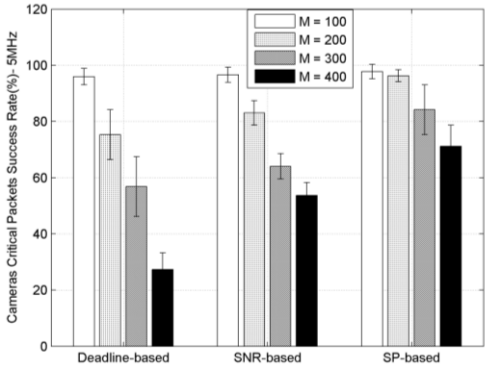

Fig. 9. Critical Packets Success Rate (Surveillance Cameras MTCDs) (BW = 5MHz)

VII. Conclusion

In this paper, we introduced the concept of statistical priority-based scheduling for massive M2M deployments in LTE networks. Statistical priority is calculated by evaluating specific statistical attributes of the data, depending on the data type, that could be used to indicate the importance of a certain data value or video frame. The importance of a data value of a monitoring sensor is determined by testing the points against upper and lower thresholds, checking for magnitude similarity with previous data points and/or checking if a series of data points follow an increasing or decreasing trend. On the other hand, the importance of a video frame is determined through its correlation with the previous frames and as the correlation decreases, the video frame is deemed to carry more changes as compared to the previous ones. Alarm data are given default highest statistical priority value. Therefore, a stream of data values or video frames could be represented sufficiently with a smaller subset of the stream. This selected subset of the high-value information is based on high statistical priority scores.

We then implemented a scheduler that utilizes this metric to allocate radio resources for M2M traffic over LTE-based networks that have multiple types of MTCDs. We compared the new technique against channel-based and deadline-based scheduling techniques. Simulation experiments showed that the statistical priority-based scheduler has the least deadline-missing ratio of data packets generated by alarm MTCDs (less than 4%), which have the highest importance. In addition, the statistical priority-based scheduler makes the best use of the scarce radio resources by allocating them to the MTCDs carrying data with the highest informative value. The SP-based outperforms SNR-based and deadline-based schedulers. It achieves a success rate that is always greater than 70% for environmental monitoring MTCDs. This rate is sufficient to represent the whole stream of data. The same superiority has also been achieved in case of surveillance cameras.

References

[1] J A. Gluhak, S. Krco, M. Nati, D. Pfisterer, N. Mitton and T. Razafindralambo, "A Survey on Facilities for Experimental Internet of Things Research," *IEEE Commun. Mag.*, vol. 49, no. 11, pp. 58-67, Nov. 2011

[2] F. Ghavimi and H.-H. Chen, "M2M Communications in 3GPP LTE/LTE-A Networks: Architectures, Service Requirements, Challenges, and Applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, May 2015

[3] "Cisco visual networking index: Global mobile data traffic forecast update, 2015 - 2020," Feb. 2016

[4] N. Abu-Ali, A. M. Taha, M. Salah and H. Hassanein, "Uplink Scheduling in LTE and LTE-Advanced: Tutorial, Survey and Evaluation Framework," *IEEE Commun. Surveys Tuts.*, vol.16, no. 3, pp. 1-27, Sep. 2013

[5] M.-H. Li, C.-C. Lin, C.-C. Chuang, and R.-I. Chang, "Error-Bounded Data Compression using Data, Temporal and Spatial Correlations in Wireless Sensor Networks," *IEEE International Conference on Multimedia Information Networking and Security (MINES)*, Nov. 2010

[6] S. T. Hong and J. W. Chang, "A New Data Filtering Scheme Based on Statistical Data Analysis for Monitoring Systems in Wireless Sensor Networks," *IEEE 13th International Conference on High Performance Computing and Communications (HPCC)*, Sep. 2011

[7] 3GPP TS136.213 v.10.1.0, "Physical Layer Procedures (Release 10)," April 2011

[8] M. A. Mehaseb, Y. Gadallah, A. Elhamy, and H. Elhennawy, "Classification of LTE Uplink Scheduling Techniques: An M2M

Perspective," in *IEEE Commun. Surveys & Tuts.*, vol. 18, no. 2, pp. 1310-1335, November 2015.

[9] A. Lioumpas and A. Alexiou, "Uplink Scheduling for Machine-to-Machine Communications in LTE-based Cellular Systems," *IEEE GLOBECOM Workshops*, Dec. 2011

[10] N. Afrin, J. Brown and J. Y. Khan, "Performance Analysis of an Enhanced Delay Sensitive LTE Uplink Scheduler for M2M Traffic," *Australasian Telecommunication Networks and Applications Conference (ATNAC)*, Nov. 2013

[11] A. Elhamy and Y. Gadallah, "BAT: A Balanced Alternating Technique for M2M Uplink Scheduling over LTE," *IEEE Vehicular Technology Conference (VTC-Spring)*, May 2015

[12] Y. Hsu, K. Wang and Y. Tseng, "Enhanced Cooperative Access Class Barring and Traffic Adaptive Radio Resource Management for M2M Communications over LTE-A," *Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA)*, Oct. 2013

[13] S.-Y. Lien, K.-C. Chen and Y. Lin, ''Toward Ubiquitous Massive Accesses in 3GPP Machine-to-Machine Communications,'' *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 66–74, Apr. 2011

[14] I. Abdallah and S. Venkatesan, "A QoE Preserving M2M Aware Hybrid Scheduler for LTE Uplink," *International Conference on Selected Topics in Mobile and Wireless Networking (MoWNeT)*, Aug. 2013

[15] M. K. Giluka, N. Rajoria, A. C. Kulkarni, V. Sathya and B. R. Tamma, "Class Based Dynamic Priority Scheduling for Uplink to Support M2M Communications in LTE," *IEEE World Forum on Internet of Things (WF-IoT)*, Mar. 2014

[16] S. N. K. Marwat, C. Goerg, T. Weerawardane, A. Timm-Giel and R. Perera, "Impact of Machine-to Machine (M2M) Communications on Disaster Management in Future Mobile Networks," *General Sir John Kotelawala Defence University Annual Symposium*, Sri Lanka, 2012

[17] S. Zhenqi, Y. Haifeng, C. Xuefen and L. Hongxia, "Research on Uplink Scheduling Algorithm of Massive M2M and H2H Services In LTE," *IET International Conference on Information and Communications Technologies (IETICT 2013)*, Apr. 2013

[18] J. Brown and J.Y. Khan, "Predictive Resource Allocation in the LTE Uplink for Event Based M2M Applications," *IEEE International Conference on Communications (ICC)*, Jun. 2013

[19] A. Azari and G. Miao, "Lifetime-Aware Scheduling and Power Control for M2M Communications in LTE Networks," *IEEE Vehicular Technology Conference (VTC-Spring)*, Glasgow, UK, May 2015

[20] Y. B. Chen, S. R. Yang, J. N. Hwang, and M. Z. Wu, "An energy-efficient scheduling algorithm for real-time machine-to-machine (M2M) data reporting," *IEEE Global Communications Conference (GLOBECOM)*, Austin, TX, Dec. 2014

[21] A. Aijaz and A. H. Aghvami, "On Radio Resource Allocation in LTE Networks with Machine-to-Machine Communications," *IEEE Vehicular Technology Conference (VTC-Spring)*, Dresden, Germany, Jun. 2013

[22] S. Yang, Z. Gao, R. Huang and X. Qiu, "A Data Correlation-based Virtual Clustering Algorithm for Wireless Sensor Network," *International Conference on Mobile Ad-hoc and Sensor Networks* (*MSN*), Dec. 2011

[23] L. R. de Temiño, G. Berardinelli, S. Frattasi and P. Mogensen, "Channel-Aware Scheduling Algorithms for SC-FDMA in LTE Uplink," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2008

[24] https://www.youtube.com/watch?v=aK80efdO7fE

[25] S. Suthaharan, M. Alzahrani, S. Rajasegarar, C. Leckie and M. Palaniswami, "Labelled Data Collection for Anomaly Detection in Wireless Sensor Networks," *International Conference on Intelligent Sensors, Sensor Networks and Information Processing* (*ISSNIP*), Dec. 2010