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Network Lifetime Maximization and Penalty-Based Resource Allocation for Machine-to-Machine Communications in Long-Term Evolution (LTE) Networks

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Abstract

In this paper, we introduce uplink scheduling algorithms based on unique data to minimize energy consumption and to succeed data transmission sent by machine-type communication devices (MTCDs) on LTE networks when radio resources are limited. Important data carried by MTCDs are through a form of statistical data analysis termed statistical priority. The statistical priority is based on statistical attributes, such as exceeding a safety threshold, checking data similarity, and observing constant increasing or decreasing trends. The first suggested algorithm focuses on allocating radio resources based on a lifetime metric and controls transmission power to prolong the network lifetime. While the second suggested algorithm is based on a penalty metric. The simulation results show that the proposed algorithms achieve the highest operating lifetime extension on the network and the considerable success rate of sending important data (above 90%) in comparison to the existing MTC algorithm With Limited CSI for LTE.

Keywords: *cellular IoT, m2m communications, LTE, resource allocation, statistical priority, battery lifetime*.

1. Introduction

The internet of things (IoT) refers to the rapid rise in the network of objects (things) that are capable of achieving a certain task, such as sensing or acting on their environment. At present, cellular IoT is attracting widespread interest due to its ubiquitous coverage and roaming [1]. Machine-to-machine (M2M) communication is one of the major IoT techniques. M2M communication over cellular networks or machine-type communications

(MTC) refers to the communications between the devices in cellular networks with minimal human intervention. Devices that contributed to MTC are usually called machine-type communications devices (MTCDs). MTC is used in many applications (e.g., temperature and humidity sensors, alarms, surveillance cameras, intelligent transportation, healthcare, industry, and farming, etc.). Unlike human-to-human (H2H) communications, MTC is generally characterized by massive access, combined with a small payload size and diverse quality of service (Qos) requirements [2]. MTC is estimated to predominate traffic in fifth-generation (5G) cellular network technology and beyond [3]. The number of MTCDs is estimated to be 3.9 billion by 2022 [3]. However, few researchers have addressed the problem of MTCDs long battery lifetime because most of the MTCDs have limited available energy and once deployed, replacing their batteries costs are more expensive than the costs of these devices especially when deployed in harmful environments; furthermore there remains a need for an efficient method that can manage radio resource allocation for massive MTC.

1.1 Literature Review

1.1.1 MTC Common Structure

MTC are categorized into several types [4], such as MTCDs, machine-type communication gateways (MTCGs) and machine-type communication servers (MTC servers). The first type is used to perform data gathering (e.g., sensing, counting, and surveillance). MTCDs send data to the evolved NodeB (eNB) either directly or by the MTCG. The MTCG is comparable to a cluster head, aggregates the data transmitted by the MTCDs and then forwards it to the eNB. The MTCG can apply different data compression and data filtering methods [5], [6] to reduce the amount of data transmission to the (eNB). The MTC server receives data via backhaul from eNB, which can then be accessed by either machine-type users or human users via an application.

1.1.2 The MTC Scheduling Rule over Cellular Networks

Scheduling is the process carried out by the eNB in order to assign radio resources to a user equipment (UE) or MTCD. Unlike signaling, scheduling is not standardization work, and it is left for vendor implementation. The physical resource block (PRB) is the minimum resource that eNB can assign to UE or MTCD [7]. The scheduling problem can be divided into two stages:-

- Time-domain scheduling: in this stage, the eNB elects a number of users/devices to be assigned PRBs using deferent benchmarks like channel conditions, buffer status, delay requirements, and HARQ.
- Frequency domain scheduling: in this stage, the resources are assigned to preselect MTCDs.

1.1.3 Review of MTC Scheduling Algorithms

Most MTC traffic occurs in the uplink direction. The survey on M2M scheduling algorithms in LTE networks is studied in [8]. This survey indicates that existing scheduling algorithms can be divided into four metrics, which are as follows :- i) Channel aware schedulers, in which the MTCD with the highest signal-to-noise ratio (SNR) must be assigned PRBs first, since the decoding bit error rate and the throughput can be maximized [9]; (ii) delay-aware schedulers, in which the PRBs are allocated based on the delayed deadline [10]; (iii) fairness aware schedulers, in which MTCDs are guaranteed to receive fair PRBs[11] ; and (iv) hybrid schedulers, which take the above-mentioned metrics plus other metrics, such as, power consumption Aijaz et al. [12], buffer status, and packet arrival rates [8]. A. E. Mostafa and Y. Gadallah,[4] introduced statistical priority-based schedulers, in which a data sent by MTCDs with higher value information is scheduled with a higher priority to properly manage radio resources.

1.1.4 Energy Efficient MTC Scheduling

It is generally accepted that Long-Term Evolution (LTE) has many benefits, such as Internet service, capacity, adaptability to radio resources management and scalability. Due to the insufficient capacity of the physical downlink control channel (PDCCH) for large MTC, not all MTC can serve at the same time. Therefore, any scheduler should take into consideration the scarcity of radio resources [8]. Recently, energy efficiency has played an essential role in the deployment of MTC [12], but little work has been done to achieve energy-efficient uplink scheduling for massive MTC. Moreover, the study in [13] indicates that the LTE physical layer is unable to efficiently transmit small data communications. Power-adequate uplink scheduling for delay intolerance data over LTE networks is studied in [14], which acknowledged that both delay and traffic models are unsuited to the nature of MTC[15]. Aijaz et al. [12] conducted uplink scheduling for LTE networks with M2M traffic. Although this helped to maximize the ratio between the sum data rates and the power consumptions for all users, the researchers acknowledged that this was incomplete energy consumption modeling for MTC, because only transmitted power was considered, and the circuit power consumption was neglected. From the aforementioned studies, we can conclude that the detailed model of energy consumption of MTC as a way to quantify the importance of information, and the corresponding scheduling algorithm of limited radio resources, are absent from the literature. A. Azari and G. Miao [16] have shown battery lifetime-based scheduling and provided detailed energy consumption for MTC by considering both circuit and transmission energy consumption. It presented low complexity scheduling with limited channel state information (CSI) for MTC in the context of LTE. In these algorithms, few researchers have addressed the importance of data that is sent in real-time by MTCDs in order to reduce the network traffic and prolong the network lifetime. Based on the uplink scheduling algorithms in LTE networks in A. E. Mostafa and Y. Gadallah. [4] and A. Azari and G. Miao. [16], this paper introduces Algorithm 1 for time/frequency resources for MTC, a mixed scheduling algorithm that utilities energy-preserving features [16] and prioritized scheduling features [4].

1.1.5 Data Compression

Data compression is a method that is used to minimize the data size of the device. Data compression is used to save power on the device and minimise the network’s traffic. Data compression prevents sending new sensed data only if its differences from the previous sensed data. This is achieved by various methods. In a study by M.-H. Li, C.-C. Lin, C.-C. Chuang, and R.-I. Chang. [5], the sensor node uses ‘low-value similarity’ or ‘low temporal correlation’ to indicate the variation of data value by threshold value from the previously sent data value. The data sent by sensors are collected by the gateway, which uses ‘low-value similarity’ or ‘low spatial correlation’ to exclude these readings from other neighboring sensors readings that do not vary significantly from them.

In the present study, the application-based compression approaches or group-based decisions to minimize the transmitted data are far from perfect, because these nodes work outside the control of the network operators, which makes the group-based decisions impractical. Therefore, we present another new algorithm called Algorithm 2 to help eNB to allocate PRBs to MTCDs when the available radio resources are not sufficient to send all data.

1.2 Contributions

The contributions of this paper can be stated as follows:

- Introduce detailed energy consumption models for existing 3rd Generation Partnership Project (3GPP) LTE networks by considering only the importance of information carried in the data to be sent by MTCDs using ‘statistical priority’. This method depends on the statistical attributes of the data, such as value similarity and trend similarity.
- Present a new battery lifetime as a scheduling metric for resource allocations. This algorithm depends on max-max lifetime by exploiting statistical priority (P) to send only high-value information, hence decreasing network maintenance costs.
- Present a novel resource allocation metric, which is called penalty (w)

That improves resource utilization when the radio resources are not enough to send all data.

- Determine the critical packet success rate in uplink MTC resource provisioning and scheduling.

The remainder of this article is organised as follows. The system model and network lifetime are introduced in the next section. In section 3, the concept of statistical attributes to quantify the importance of information carried by MTCDs is presented. In section 4, the statistical priority formulation is introduced. A lifetime-aware solution and power control related to highly important MTCD data over 3GPP LTE networks are investigated in section 5. In section 6, we present novel penalty-based scheduling algorithm over LTE and these two algorithms are evaluated in section 7. Conclusion are presented in section 8.

2. System Model and Network Lifetime

2.1 System Model

Consider a single cell with one base station in the center and a large number of MTCDs, which are uniformly distributed in the cell, performing environmental monitoring. In addition to that, replacing the MTCDs' battery sources when depleted may not be practical. Hence, their batteries must have long lifetimes. Consider an uplink scheduling problem at time (t) in which the total number of MTCDs are denoted by N. Also, suppose that a finite set of radio resources A are dedicated to these devices.

2.2 Network Lifetime

For $MTCD_i$, the remaining energy at a time t_0 is denoted by $E_i(t_0)$. The power consumption in transmission mode is defined as $\xi P_i + P_c$ where P_c is the circuit power consumed by electronic circuits, ξ is the inverse of power amplifier efficiency, P_i is the power for reliable data transmission, and E_s^i is static energy consumption. Thus, the expected lifetime for $MTCD_i$ can be expressed as the multiplication of the reporting period T_i and the ratio between $E_i(t_0)$ and required energy consumption per reporting period, as follows [17]:

$$L_i(t_0) = \frac{E_i(t_0) * Ti}{E_s^i + TTI(P_c + \xi P_i)} \tag{1}$$

Where (TTI=1 millisecond) stands for the transmission time interval. Network lifetime is the time between the initial setup time and the point at which a network is considered to be nonfunctional. There are many definitions of network lifetime, depending on the applications that the MTCDs are working with [16]. In this study, we use the longest individual lifetime (LIL) as the network lifetime, because the correlation between data gathered by different MTCDs is high.

3. Attributes of Statistical Priority

A statistical attribute is a measurement of the importance of redundant information carried by an MTCD, and hence, the reduction of the transmission data [4].

3.1 Threshold

The MTCDs whose sensed data value $g(t)$ at time t is higher than the chosen threshold Th. Therefore, $g(t)$ is considered important information if

$$g(t) > Th \qquad (2)$$

3.2 Value Similarity

The MTCDs whose new sensed data value $g(t)$ at time t is sent only if the difference between the new and the old sensed data $g_0(t)$ is greater than a certain reference threshold α. In other words, $g(t)$ becomes non-redundant only if

$$\mid g(t) - g_0(t) \mid > \alpha \qquad (3)$$

3.3 Trend Similarity

The historical sensed data reported by MTCDs maintains a consistent trend and consequently, the sensed data becomes non-redundant. Therefore, a sensed data value at time *t*, $g(t)$ is said to contain important information if [18] :

$$\big(g(t) - g(t-1)\big) * \big(g(t-1) - g(t-2)\big) > 0 \quad (4)$$

4. Statistical Priority (*P*)

According to A. E. Mostafa and Y. Gadallah.[4], statistical priority (P) is a method used for prioritizing MTC traffic. The statistical priority is based on the statistical attributes like exceeding the chosen threshold value or detecting a new dataset has a significant change in magnitude and/or checking if a series of data maintain a consistent trend (increasing or decreasing). The primary objectives of the *P* function can be summarised as follows:

- To give higher value to data that is transmitting important information;
- To guarantee one survival unit of information per defined interval T to ensure the fairness of scheduling MTCDs data packets.

4.1 Statistical Attributes in a Statistical Priority

For each MTCD, assume that a total of Z arrays are indexed by the set Z $\triangleq \{ z_1(t), \ldots, z_i(t), \ldots, z_n(t) \}$, where $z_i(t)$a set of previous statistical attributes at sample *t*. Statistical priority is can be determined by a weighted sum of $f(z_i(t))$. Hence, $f(z_i(t))$ can be expressed by a sigmoidal (logistical) function whose output takes a value between 0 and 1 A. E. Mostafa and Y. Gadallah. [4] :

$$f\big(z_i(t)\big) = sigmoid(z_i(t), d_i, h_i) = \frac{1}{1+e^{-di(z_i(t)-h_i)}}\ , \quad (5)$$

Where h_i indicates the inflection point of $f(z_i(t))$. the value of h_i can be assumed to be constant (e.g. h_i=0). In addition, d_i administrates the steepness of the function transition from 0 to 1. Moreover, there are three states of statistical attributes related to the real-time environmental monitoring of sensed data, as follows:

State 1: The MTCDs whose sensed data value $g(t)$ at time *t* is higher than the chosen threshold Th. Therefore, $g(t)$ is considered important information if $g(t) > Th$, and $z_i(t)$ can be given by

$$z_i(t) = g(t) - Th. \qquad (6)$$

Consequently, $z_i(t)$ becomes positive and $f(z_i(t))$ should reach 1. In addition, the value of di should be any high value for steep transition (e.g. $d_i = 100$). Therefore, $f(z_i(t))$ could be written as $f(z_i(t)) = sigmoid(z_i(t), 100, 0)$.

State 2: The MTCDs whose new sensed data value $g(t)$ at time *t* is sent only if the difference between the new and the old sensed data $g_0(t)$ is greater than the reference threshold α. In other words, $g(t)$ becomes non-redundant only if $\mid g(t) - g_0(t) \mid > \alpha$.Consequently, $z_i(t)$ can be expressed as:

$$z_i(t) = \mid g(t) - g_0(t) \mid - \alpha \qquad (7)$$

Furthermore, $f(z_i(t))$ could be written as $f\big(z_i(t)\big) = sigmoid(z_i(t), d_i, 0)$, where d_i can be chosen based on the desired level of significance of the value of the differences (e.g., $d_i = 5$).

State 3: The historical sensed data reported by MTCDs maintains a consistent trend (by increasing or decreasing) and consequently, the sensed data becomes non-redundant. Therefore, a sensed data value at time *t*, $g(t)$ is considered to have important information if $g(t) - g(t-1)) * (g(t-1) - g(t-2)) > 0$. Thus, $z_i(t)$ can be given by

$$z_i(t) = \prod_{j=0}^{2l-1}(g(t-j) - g(t - j1 - 1)), l = 1, 2, \ldots \ (8)$$

When *l* = 2, the trend is analyzed in the last five data points. Consequently, $z_i(t)$ becomes positive and $f(z_i(t))$ should reach 1, whereas $z_i(t)$ becomes negative and $f(z_i(t))$ should reach 0. Therefore, $f(z_i(t))$ could be written as $f(z_i(t)) = sigmoid(zi(t), d_i, 0)$. The value of d_i should be any high value for steep transition (e.g., d_i= 100). Furthermore, the total number of weights are indexed by the set W$\triangleq \{ w_1, \ldots, w_i, , w_n\}$. Each $f(z_i(t))$ is assigned a weight w_{i}. Hence, for each MTCD, the statistical priority (P) is represented by the weighted sum of $f(z_i(t))$ of the different statistical attributes, as follows:

$$P_i(W,Z,t) \ = \sum_{i=1}^{n} w_i \ f(z_i(t)). \qquad (9)$$

4.2 Minimum Fairness Guarantee

For each MTCD, statistical priority (P) should ensure some level of fairness and reliability by giving MTCDs a chance to send at the least one piece of survival message data every T seconds in order to support node failure detection, regardless of the importance of the data (e.g., just one live message data out of 10 should be considered important data). This continuously sensed data could be represented by a function $g_0(t)$, as follows A. E. Mostafa and Y. Gadallah. [4]:

$$g_0(t) = 0.5(cos(\frac{2\Pi t}{T}) + 1) \qquad (10)$$

In addition, $g_r(t,T)$ is a binary variable used to restrict data transmission to one piece of sample data every T seconds. Therefore, the statistical priority (p) value for periodic function can be written as follows:

$$P_i(W,G,t,T) = w_0 g_0(t) * \ g_r(t,T) \qquad (11)$$

From Eq. (8) and Eq. (10), the statistical priority value (P) can be expressed as the maximum of the two functions, as follows:

$$P_i(W,Z,t,T) = max\left(w_0 g_0(t) * g_r(t,T), \sum_{i=1}^{n} w_i f\left(z_i(t)\right)\right) \ (12)$$

5. Statistical Priority and Lifetime-Aware MTC Scheduling Over LTE Networks

All of the impact tests used in this work are modified versions of lifetime-aware and power control in A. Azari and G. Miao. [16], with the aim to transmit data packets to base station (BS) in LTE networks. We consider the air interface of 3GPP LTE release 13 [7]. In this standard, single-carrier frequency division multiple access (SC-FDMA) is utilised as the access technique for the uplink transmission. In the time domain, data is organised into frames, where each frame consists of 10 subframes, and each subframe last 1 millisecond (ms). In the frequency domain, the available bandwidth is splited into subcarriers, each with 15 KHz of bandwidth. Physical resource block pairs (PRBP) that consist of 12 (180KHz) subcarriers in one transmission time interval (TTI) are considered the minimum allocable resource elements [7]. The open loop uplink power control mechanism in LTE [7] is slightly modified by allowing the transmission of data that are more important based on the statistical priority described in section 3. Each MTCD calculates its uplink transmission power using downlink pathloss estimation, as follows:

$$Tx(|\,A_i|, \beta_{\,i}) \ = (|\,A_i|P_0\sigma_i\lambda_i \ [\,2^{\frac{ks\,TBS(|A_i|,\beta_{\,i})}{|A_i|Ns\,Nsc}} - 1] \qquad (13)$$

Where $|A_i|$ is the number of PRBs assigned to $MTCD_i$, the estimated downlink pathloss $by \ \lambda_i$, σ_i is the compensation factor, Ns is the number of symbols in a PRBP, and the number of subcarriers in a PRBP is indicated by Nsc. In addition, Ks is often set to 1.25. The transport block size (TBS) is found in Table 7.1.7.2.1 -1 of [7] as a function of both $|A_i|$ and TBS index ($\beta_{\,i}$), $\beta_{\,i} \ \in \{0,1,\ldots,33\}$, and is a function of modulation and coding scheme, according to [7, Table 8.6.1-1]. In [7], P_0 is found according to the target SNR at the receiver, as follows:

$$P_0 \ = \sigma_i \ [SNR_{target} + \ P_n] + [\,1 - \sigma_i\,]\,P_{max}$$

Where P_n = –209.26 dB is the noise power in each resource block. The lifetime of MTCD as presented in Eq. (1) can be modified as a function of $Tx(|Á_{\,\mathrm{i}}|, \beta_{\,i})$, as follows:

$$L_i(t_0) = \frac{Ei(t0).Ti}{E_S^i + TTI(Pc + \xi Tx(|Á_{\,\mathrm{i}}|, \beta_{\,i}))} \qquad (14)$$

We can then formulate an optimisation problem to find the optimal $|A_\mathrm{i}|$ and $\beta_{\,i}$ for each $MTCD_i$ as follows:

$$\begin{aligned}
&maximize_{|A_i|,\beta_{\,i}} \ L_{net}^{lil} \\
&s.t\!: C.15.1\!: \sum\nolimits_{i\in|\boldsymbol{A}|} |A_i| \preccurlyeq |A|, \\
&\quad C.15.2\!: Ď_i \preccurlyeq TBS\ (|A_i|, \beta_{\,i}), \forall i \in Ñ_i, \\
&\quad C.15.3\!: Tx(|A_i|, \beta_{\,i}) \ \preccurlyeq T_{max}, \forall i \in Ñ_i, \\
&\quad C.15.4\!: \beta_{\,i} \in \{0, \ldots, 33\};\ |A_i| \in \{1, \ldots, |A|\}, \forall i \in \\
&Ñ_i, \qquad (15)
\end{aligned}$$

Where $|\ A\ |$ is the total number of possible PRBPs, $Ď_i \ = \ D_i \ + \ D_{oh}$, D_i is the size of payload and D_{oh} is the size of payload for user data protocol (UDP), Internet protocol (IP), packet data convergence protocol, radio link control and medium access control (MAC) overhead. In our proposed algorithm, it is possible to use a refined version of the algorithm provided in A. Azari and G. Miao.[16]. Thus, the battery lifetime expression in (14) could be found as a function of assigned PRBPs to the MTCD ($Ñ_i$) that carries important data in real time and optimal modulation and coding scheme (β_i^*). In addition, we find the minimum PRBP for $MTCD_i$ $|A_i|^{min}$ which satisfies the constraints in C.15.3 and C.15.4 A. Azari et al. [16], as follows:

$$\begin{aligned}
&|A_i|^{min} = \text{minimise}_{\beta i}\ |A_i|, \\
&\qquad Subject\ to\!: TBS\ (|A_i|, \beta_{\,i}) \ \succcurlyeq\ Ď_i\,; \\
&\qquad Tx(|A_i|, \beta_{\,i}) \ \preccurlyeq T_{max} \qquad (16)
\end{aligned}$$

Algorithm 1: Statistical priority traffic and lifetime-aware scheduling with limited CSI over LTE networks.

```
1. $Initialization;$
- $Derive\ \tilde{N}, where\ \forall i \in \tilde{N}\ if\ P_i \succ 0;$
- $Derive\ |A_i|^{min}, \forall i \in \tilde{N}, from\ (16);$
    - $|A_i|^{min} \longrightarrow \mathbf{u}(i), \forall i \in \tilde{N};$
    - $FnD(\mathbf{u}(i), \check{D}_i) \longrightarrow \beta_i^*, \forall i \in \tilde{N};$
    - $Tx(\mathbf{u}(i), \beta_i^*) \longrightarrow \mathbf{t}(i), \forall i \in \tilde{N};$
    - $\mathcal{F}(\mathbf{u}(i), \beta_i^*) \longrightarrow \mathbf{f}(i), \forall i \in \tilde{N};$
    - $\tilde{N} \longrightarrow \tilde{N}_t;$

2 while $\acute{A}_t^n$ do
    - $arg\ max_{i\in\tilde{N}}\ \mathbf{f}(i) \longrightarrow s;$
    - $\mathbf{u}(s)+1 \longrightarrow x;$
    - $FnD(x, \check{D}s) \longrightarrow \beta_s^*;$
    - $Tx(x, \beta_s^*) \longrightarrow T;$
    - If $T \preccurlyeq Tmax, \mathcal{F}(x, \beta_s^*) \succ \mathbf{f}(m)$ then
        - $A_i{}^n\text{-}1 \longrightarrow A_i{}^n, x \longrightarrow u(s), T \longrightarrow t(s);$
        - $\mathcal{F}(x\ \beta_s^*) \longrightarrow f(s);$
  else
  -$\tilde{N}_t \setminus s \longrightarrow \tilde{N}_t, and\ \infty \longrightarrow \mathbf{f}(s);$
    - $If\ \tilde{N}_t\ is\ empty, then\ 0 \longrightarrow \acute{A}_i{}^n$

3 return $\mathbf{u}$ and $\mathbf{t}$;
```

Furthermore, the function $FnD(|A_i|, \check{D}_i)$ is used in this Algorithm to determine the TBS index β_i^* in order to reduce transmit power as follows:

$$\beta_i^* \triangleq FnD(|A_i|, \check{D}_i)$$
$$= minimize_{\beta i}$$
$$s.t: \check{D}_i \preccurlyeq TBS\ (|A_i|, \beta_i), \forall i \in \tilde{N}_i, \quad (17)$$

By considering the $(|A_i|)^{th}$ *the* column of the TBS table in [7], β_i^* can be obtained. Therefore, the minimum TBS index is found to satisfy the constraint in Eq. (17). Algorithm 1 solves the frequency domain scheduling problem, where the minimum PRBP $|A_i|^{min}$ requirements to MTCDs based on the non-redundant sensed information carried in their datasets. Then, Algorithm 1 attempts to maximize the network lifetime by allocating PRBs the $MTCD_i$ with the longest battery lifetime. Then, in the next iterations, it attempts to maximize the longest lifetime of the remaining MTCDs; the outputs of this algorithm are PRBP and transmission power vectors for each device. Detailed complexity analysis and merits of this algorithm have been presented in A. Azari and G. Miao. [16]. However, this algorithm has a major deficiency: when the radio resources are limited, machine nodes may fail to transmit their data and they may need to wait for a longer period of time to gain access to the reserved resources. We solve this issue in section 5, by presenting a penalty-based scheduling algorithm.

6. Statistical Priority Value Penalty-Aware MTC Scheduling Over LTE Networks

A statistical priority penalty was used in this study as a scheduling metric in order to maintain fairness among MTCDs. In this way, the performance of MTC experience can be enhanced in terms of the critical packet success rate when the radio resources are limited. We can formulate this optimization as follows:

$$minimize \quad g$$
$$s.t.: C.18.1: \sum_{i\in|A|} |A_i| \preccurlyeq |A|,$$
$$C.18.2: \check{D}_i \preccurlyeq TBS\ (|A_i|, \beta_i), \forall i \in \tilde{N}_i,$$
$$C.18.3: Tx(|A_i|, \beta_i) \preccurlyeq T_{max}, \forall i \in \tilde{N}_i,$$
$$C.18.4: \beta_i \in \{0, \dots, 33\};\ |A_i| \in \{1, \dots, |A|\}, \forall i \in \tilde{N}_i$$
$$C.18.5: P_i - \Phi|A_i| \succ 0 \quad (18)$$

Algorithm 2: Statistical priority value penalty-aware scheduling with limited CSI over LTE networks

```
1 $Initialization;$
- $Derive\ \tilde{N}, where\ \forall i \in \tilde{N}\ if\ P_i \succ 0;$
- $Derive\ |A_i|^{min}, \forall i \in \tilde{N}, from\ (16);$
    - $|\acute{A}_i|^{min} \longrightarrow \mathbf{u}(i), \forall i \in \tilde{N};$
    - $FnD(\mathbf{u}(i), \check{D}_i) \longrightarrow \beta_i^*, \forall i \in \tilde{N};$
    - $Tx(\mathbf{u}(i), \beta_i^*) \longrightarrow \mathbf{t}(i), \forall i \in \tilde{N};$
    - $\mathcal{F}(\mathbf{u}(i), \beta_i^*) \longrightarrow \mathbf{f}(i), \forall i \in \tilde{N};$
    - $\tilde{N} \longrightarrow \tilde{N}\_t;$

2 while $\acute{A}_t^n$ do
    - $arg\ max_{i\in\tilde{N}}\ \mathbf{P}(i) \longrightarrow s;$
    - $\mathbf{u}(s) + 1 \longrightarrow x;$
    - $s - x\Phi \longrightarrow g;$
    - $FnD(x, \check{D}s) \longrightarrow \beta_s^*;$
    - $Tx(x, \beta_s^*) \longrightarrow T;$
    - If $\mathbf{P}(i) \succ 0, T \preccurlyeq Tmax, F(x, \beta_s^*) \succ \mathbf{f}(m)$ then
        - $\acute{A}_t^n - 1 \longrightarrow \acute{A}_t^n, x \longrightarrow u(s), T \longrightarrow t(s);$
        - $\mathcal{F}(x\ \beta_s^*) \longrightarrow f(s);$
    else
`     -$\tilde{N}t \setminus s \longrightarrow \tilde{N}t, \infty \longrightarrow \mathbf{P}(s); \infty \longrightarrow \mathbf{f}(s);$
    - $If\ \tilde{N}_t\ is\ empty, then\ 0 \longrightarrow \acute{A}i^n$
3 return $\mathbf{u}$ and $\mathbf{t}$;
```

process. The value of Φ is used as an upper bound on the penalty during the assignment of PRBPs to node i. First, the scheduler selects the devices that have the most important information (i.e., highest P-value). Then, the prioritized data packet receives a penalty Φ for each PRBP allocation to MTCD As the set of remaining PRBPs is not empty, this process continues to occur normally for every allocation process until the penalty value becomes invalid (i.e., $P \nleqslant 0$). This device is then removed and the second-highest P is selected, and so on. Although Algorithm 2 offers an opportunity to allocate the scarce radio resource, the penalty Φ cannot be infinitely valued. Future work should consider an optimal penalty value using the interior-point methods described in D. Bertsekas. [19] to maximize the success rate of sending critical packets.

7. Performance Evaluation

The main purposes of this work were to test the proposed algorithms of lifetime improvement and to increase the success rate of the important packets with limited radio resources. The simulated model implements the uplink transmission of a single cell with one BS at the center, and 160 MTCDs over 3GPP LTE-M network with 1.4 MHz of bandwidth [7] in MATLAB R2018b. The detailed simulation parameters can be found in Table 1. MTCDs send the statistical priority P through the physical uplink control channel (PUCCH) to the eNB [4].

Table 1: Simulation parameters [16, 4]

Parameter	**Value**
Cell radius, r	500 m
Path loss model, ($\boldsymbol{\lambda i}$)	128+38$log_{10}(\frac{r}{1000})$
PSD of noise, ($\boldsymbol{P_n}$)	-174 dBm/Hz
System bandwidth	1.4 MHz
PRBPs in TTI $\lvert A_i \rvert$	6
ks, Ns , Nsc	1.25, 12, 12
TBS index, βi	{0… 26}[7]
Number of Runs	10
Number of MTCDs, (N)	160
Duty cycle, T_i	5 sec, $\forall i \in \tilde{N} i$, [20]
SNR_{target}	1 dB
Maximumtransmit power,P_{max}	24 dBm
Circuit power, (P_c)	7 dBm
Static energy consumption, E_s^i	10 μJ
MTC Application & Traffic parameters	
MTC Application	Temperature sensor
Packet size (D_i+D_{oh})	600 Bits
Traffic Description	1 dataset per second 200 datasets per device Datasets extracted from [20]

As suggested in S. Lien and K. Chen. [21], MTCDs reserve a portion of physical uplink shared channel (PUSCH) radio resources in advance. For example, the first two radio frames each of which has six PRBPs have been reserved for uplink transmissions in every second, then eNB sends the scheduling grants to the MTCDs through the corresponding physical downlink control channel (PDCCH) to allow them to send their data in the next set of reserved resources. In this simulation, the three different MTC scheduling algorithms are as follows:

Algorithm 1: This algorithm enables only high priority data transmission by MTCDs and lifetime-aware scheduling with limited CSI over LTE networks, and is based on the algorithm in section 5, where lifetime-aware time and frequency domain scheduling is used for the purpose of maximizing the longest individual lifetime (LIL) network lifetime.

Algorithm 2: This algorithm is based on the algorithm in section 6, and consists of two statistical priority schedulers for time and frequency domain scheduling.

Algorithm 3: This algorithm consists of a round-robin (RR) scheduler for time-domain scheduling and MTC scheduling algorithm 4 in A. Azari and G. Miao. [16] for frequency-domain scheduling, with the aim to maximize the LIL network lifetime. Table 2 summarizes the possible statistical attribute z_i(t) parameters that can be used at a time *t* in order to quantify important data. In addition, Table 3 lists all of the weight values for both statistical function and periodic survival message in order to find the statistical priority P-value.

Table 2: Statistical attribute threshold values [4]

Statistical Attribute	**Value**
Threshold (Th)	$28^o C$
Reference threshold (α)	$0.1^o C$
Trend similarity	Yes

Table 3: Weights for statistical functions [4]

Statistical Attribute Weight	**Value**
Threshold (w_1)	4
Reference threshold (w_2)	3
Trend similarity (w_3)	3
Periodic (w_0)	5

7.1 Performance Evaluation of the Proposed Schedulers

Fig.1 shows the full network lifetime performance evaluation of the proposed algorithms. In this figure, it is evident that a significant lifetime improvement was obtained from Algorithm 1, the aim of which was to maximize LIL network lifetime. This is significantly more effective than the reference Algorithms 2 and 3. Moreover, it is evident that the network lifetime result obtained from Algorithm 1 is 2.5 times greater than the one obtained from Algorithm 2 and 1.9 times greater than the result of Algorithm 3 in A. A. Azari and G. Miao. [16]. These results demonstrate that improved lifetime performance was achieved using Algorithm 1, is better than Algorithm 3 because Algorithm 1 takes into account the uniqueness of the information measured by MTCDs in order to reduce the size of transmission data and prolong the network lifetime. Although Algorithm 2 considers only important datasets sensed by MTCDs, it allocates fair PRBs to all MTCDs which results in the highest transmit power and the worst network lifetime performance. However, it is evident that the longest MTCD battery lifetime is obtained with losing the other devices.

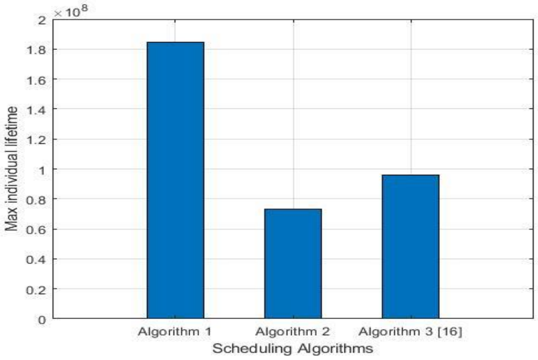

Fig 1. Network lifetime for different scheduling algorithms.

The detailed critical packet success rate [4] is depicted in Fig. 2 when the radio resources are limited, calculated as follows:

$$Ş = \left(\frac{Sent\_Packets}{Total\ critical\_Packets} \right) * 100\% \qquad (19)$$

In Fig. 2, one can observe that the success rate of the proposed Algorithm 2 is above 90%, which is superior to the success rate of the baseline Algorithms 1 and 3. In addition, the success rate of the proposed Algorithm 1 is almost 80%, while the success rate of Algorithm 3 which does not take the uniqueness of data sensed by MTCDs into account is below 30%. Thus, it can be inferred from Figures 1 and 2 that the proposed scheduling algorithms are shown to be fair (i.e., they allow every MTCD to send only important data packets, thus generating an excellent success ratio).

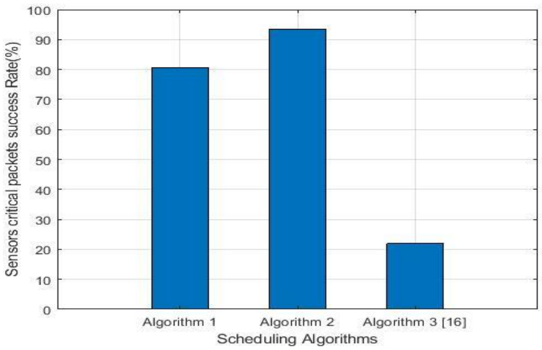

Fig 2. Critical packets success rate for different scheduling algorithms.

8. Conclusion

Algorithm 2 produces more efficient resource utilization than Algorithms 1 and 3. Our results provide compelling evidence to suggest that the proposed Algorithm 1 can reduce maintenance cost by prolonging the MTCD with the longest battery lifetime, but at the cost of losing all other MTCDs, we have made another surprising observation: that almost all of the important data sent by MTCDs can be sufficiently represented with fair radio resource allocation using Algorithm 2. These findings should be extended to the Narrowband-IoT network. Finally, our techniques can be applied in a wide range of applications where the correlation between data gathered by different nodes is high, such as in metering applications.

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