2D Proactive Uplink Resource Allocation Algorithm for Event Based MTC Applications

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Abstract—We propose a two dimension (2D) proactive uplink resource allocation (2D-PURA) algorithm that aims to reduce the delay/latency in event-based machine-type communications (MTC) applications. Specifically, when an event of interest occurs at a device, it tends to spread to the neighboring devices. Consequently, when a device has data to send to the base station (BS), its neighbors later are highly likely to transmit. Thus, we propose to cluster devices in the neighborhood around the event, also referred to as the disturbance region, into rings based on the distance from the original event. To reduce the uplink latency, we then proactively allocate resources for these rings. To evaluate the proposed algorithm, we analytically derive the mean uplink delay, the proportion of resource conservation due to successful allocations, and the proportion of uplink resource wastage due to unsuccessful allocations for 2D-PURA algorithm. Numerical results demonstrate that the proposed method can save over 16.5 and 27 percent of mean uplink delay, compared with the 1D algorithm and the standard method, respectively.

Index Terms—M2M, machine-type communications, proactive resource allocation, latency-sensitive services

I. INTRODUCTION

Despite the original design of the cellular systems focusing on human-to-human (H2H) communications, the demands for machine-type communication (MTC), e.g., automation in industry 4.0, have created a new range of emerging services [1]. In many MTC applications, such as monitoring systems, security and public safety services, a massive number of MTC devices are used to detect events in the environment, triggering uplink-centric transmissions of infrequent and low volume of delay-sensitive data [2].

Various approaches at the MAC layer have been proposed to achieve the ultra-low delay in MTC. In [3], a scheme combining the access class barring (ACB) and timing advance information was proposed, thereby reducing half of random access slots necessary for MTC devices and improving the delay of both MTC and H2H networks. In [4], a new hybrid protocol for random access and data transmission was developed to solve the random access channel congestion and excessive signaling overhead problems. Other methods are based on the traffic patterns of MTC and proactive resource allocations, e.g., [5]–[7]. Specifically, in [7], exploiting uplink traffic patterns between devices along a line, a proactive uplink resource allocation method, referred to as a 1D algorithm, is proposed for MTC. In this method, when a device sends a scheduling request (SR) for uplink resources, the BS can proactively grant uplink resources to a neighboring device along the line prior to the next SR opportunity. Here, an SR opportunity is a chance to send an SR at a certain time. Being allocated resource without sending an SR, the neighbor can reduce its uplink latency, compared with that of the LTE standard [8]. However, the 1D algorithm is not suitable for practical scenarios, in which a large number of devices are deployed in a spatial region. In such scenarios, events or disturbances can occur at a position then spread to the surrounding area. Under the 1D algorithm, the BS considers a proactive resource allocation towards a device only when it receives an SR from another device. Then, if the device does not satisfy conditions for a proactive resource allocation, it will follow the standard method by sending an SR. Therefore, at most 50 percent of devices are proactively allocated resources while the rest, which follow the standard method, send SRs to the BS.

In this paper, we leverage the traffic correlations between devices in a spatial region to reduce their uplink latency. Specifically, in the disturbance area are clustered into rings [9] based on their distance to the event. Then, the BS targets those rings for proactive uplink resource allocations (i.e., prior their requests), thus reducing the uplink latency of all devices in the disturbance area.

We analyze the expected uplink delay and the proportions of resource conserved and wasted due to successful and unsuccessful predictions. The numerical results show that our method reduces more than 16.5 percent of the mean uplink delay, compared with the best case of the 1D algorithm. Major contributions of this paper are as follows:

- We first propose a two dimension (2D) proactive uplink resource allocation (2D-PURA) algorithm, in which MTC devices in the disturbance region are spatially clustered into rings based on their distance to the original event. Then, these rings are proactively allocated resources for uplink transmissions.
- We derive the uplink expected delay and the proportions of resource saving and wastage for 2D-PURA algorithm.
- Numerical results show that 2D-PURA outperforms the best case of the 1D algorithm [7] and the standard method in LTE networks [8] in terms of the mean uplink delay.
- We analyze the complexity and optimize the size of a ring of the 2D-PURA algorithm.

The rest of the paper is as follows. We describe the system model in Section II. Section III and IV present the proposed 2D-PURA algorithm and derive its performance characteristics. In Section V we evaluate the performance of 2D-PURA algorithm and compare it with the 1D algorithm [7] and the standard method [8] previous ones. Conclusion is drawn in Section VI.

II. SYSTEM MODEL

Consider a spatial region in which MTC devices are randomly distributed according to a homogeneous Poisson Point Process (HPPP) [10] denoted by $\Phi$ with intensity $\lambda$. The BS or the IoT gateway that serves the region can proactively grant uplink resources to MTC devices instead of waiting for their requests for uplink transmissions. The location information of those devices is maintained at the BS. This assumption can be seen in many location-based wireless sensor networks (e.g., [11] and therein references). Specifically, sensor devices can estimate their own location by an equipped GPS unit or using localization algorithms with the support of other GPS-enable devices such as smartphones. Then sensor nodes initially
register their location information with the BS/gateway, e.g., [12], after being installed.

Exploiting the traffic correlations between devices to proactively allocate resources can be incorporated into any MTC, cellular, or IoT standard (e.g., NB-IoT). In this work, as a study case, we adopt the LTE standard. In LTE networks, a device can be in either RRC_IDLE or RRC_CONNECTED modes. In the former, the device can only receive broadcast information. Whilst in the latter mode, the device can send and receive data. The device must send an SR to request resources for uplink transmissions. For the ease of analysis, we assume that all MTC devices have already been in the RRC_CONNECTED mode [13] of LTE networks with the Frequency Division Duplexing (FDD). After data enters the transmit buffer, devices must wait for their individual pre-assigned offset subframes (in LTE each subframe is 1 ms in duration) within an SR period \( \sigma \) to send an SR to request an uplink grant. For simplicity, we assume throughout this paper that the pre-assigned offset follows a discrete uniform distribution on \( \{1, 2, \ldots, \sigma\} \) denoted by \( U(1, \sigma) \), and each device has a periodic SR opportunity every \( \sigma \) subframes.

The expected standard uplink delay for an MTC device in LTE networks is

\[
E(D_{std}) = (1 + \sigma)/2 + \beta + \delta
\]

where \((1 + \sigma)/2\) subframes is the delay between the time instances the device has data in the transmit buffer and sends an SR. \( \beta \) is the delay between the times the device sends an SR and receives an uplink grant from the BS (depending on the scheduling policy at the BS)\(^1\). \( \delta = 4.5 \) subframes include the average delay of 0.5 subframe that the data is available in the uplink buffer and the fixed delay of 4 subframes between the times the device receives an uplink grant and sends the data.

This work aims to lower the mean uplink delay \( E(D) \) by reducing the \((1 + \sigma)/2\) component. To better demonstrate, in Figure 1, when a disturbance initially occurs at device A, it later spreads and makes a disturbance region. The BS clusters all devices in the disturbance region into rings based on their distance to device A, and then conducts proactive resource allocations for these rings in sequence from inside out. Specifically, when device A sends an SR to request uplink resource for pending data, later its neighbors such as device B, has a high probability of sending an SR. Hence, at the time receiving an SR from device A, the BS proactively allocates uplink resources for device B if the time remaining to its next SR opportunity is greater than a threshold \( y \). Consequently, being granted uplink resources without sending an SR, those neighbor devices gain a lower uplink latency \( E(D) \), compared with the reactive method.

We assume that the disturbance spreads with velocity \( v \) to the surrounding area during a period \( T \). Therefore, all devices in the disturbance region defined by a circle radius \( l = vT \) central device A can detect the same disturbance. In fact, each disturbance has different speed \( v \) and a period \( T \), and the BS does not know exactly this information. However, the BS can initially estimate the speed \( v \) and period \( T \), based on the previous events (e.g. the average values of three latest disturbances), then, adjust these parameters for the current ring based on the results of the prediction for the previous ring.

\(^1\)We assume the system is under a low load so that each uplink grant can occur at the earliest possibility or \( \beta = 1 \).

III. 2D PROACTIVE UPLINK RESOURCE ALLOCATION ALGORITHM

First, we present the proactive uplink resource allocation concept, then describe 2D-PURA algorithm for predicting devices on a spatial region.

A. 2D Proactive Uplink Resource Allocation

Based on traffic patterns, the BS predicts the probability of a device having data in order to grant uplink resources in advance. Generally, when the BS receives an SR from device A, it can proactively allocate uplink resources for a neighbor device only when two following conditions are satisfied:

- **Eligibility criterion** dictates that the neighbor device has not sent an SR recently, which is related to the same disturbance (i.e. the BS may configure the timer to determine the correlation between SRs).
- **Timing criterion** dictates that the time remaining to the next SR opportunity for the neighbor device is greater than threshold \( y \) at the time the SR from device A is received.

Theoretically, all neighboring devices in the disturbance region can be applied the proactive resource allocation. However, with a massive number of MTC devices, it is impractical for the BS to calculate an individual threshold \( y \) for each device, due to the resource constraint. On the other hand, if we use the same threshold \( y \) for all devices in the disturbance region, the probability of successful predictions could drop dramatically because of the difference in their remaining time to the next SR opportunity. To tackle it, in our 2D-PURA algorithm, all neighbor devices in the disturbance region are clustered into rings based upon their distance to event. The threshold \( y \), then, is used to proactively grant uplink resources one at a time to all devices in each ring, thereby reducing their average uplink delay.

We construct these rings with the same ring width \( d_0 \) as can be seen in Figure 2a. A set of circles center device A with radius \( r_k = kd_0 \) is used to cluster the neighbor devices into \( n \) rings, where \( n = \lceil l/d_0 \rceil \), \( l \) is the radius of the disturbance region. The \( k \)th ring is determined by the circle radius \( r_{k-1} \) (the inner boundary) and the circle radius \( r_k \) (the outer boundary), and the necessary time for the disturbance to pass each ring is a constant and equals \( \tau_0 = d_0/v \), where \( v \) is the speed of the disturbance.

The BS first exploits a standard uplink reactive resource allocation for device A since it is the first device informing...
about the pending data. Then, it proactively allocates uplink resources to all rings in sequence from inside out. To predict the kth ring based on the SR from device A, \( y_k = (k-1)\tau_0 + y \) is considered as a threshold. The component \((k-1)\tau_0\) is the necessary time for the disturbance to cross \((k-1)\) adjacent rings. In Figure 2b, upon receiving an SR from device A, the BS starts the proactive uplink resource allocation for all devices in the kth ring. There are three possible cases at the time \( y_k \) subframes after the SR from device A is received:

- A device has already sent an SR (e.g., device B).
- A device has next SR opportunity (e.g., device C).
- A device has no SR opportunity (e.g., device D).

For device B, its next SR opportunity occurs at less than \( y_k \) subframes, then the BS does not proactively grant uplink resources to device B, and a standard uplink resource allocation is applied. For devices C and D, their remaining interval to the next SR opportunity is greater than threshold \( y_k \), then the BS proactively allocates uplink resources to those neighbors prior to their next SR opportunity. For device C, at the time of the proactive resource allocation made, it has pending data, hence, the proactive resource allocation is successful, thereby reducing its uplink latency. However, when the proactive allocation occurs, device D has no pending data, therefore, the proactive resource allocation is unsuccessful.

Here, we assume that the BS can set a timer so that it can detect the SR from device A is about the original disturbance instead of device B’s. Therefore, device C and D will be proactively assigned uplink resources with respect to device A.

Of course, our proposed method aims to reduce the delay of the whole network, thus there is a risk of unsuccessful prediction in which the BS allocates uplink resources to a device before it has data to send. Threshold \( y \) is used to trade off uplink latency reduction against resource wastage. We intensively analyze the resource wastage both analytically and numerically in Sections IV and V.

### B. 2D Predictive Uplink Resource Allocation Algorithm

The 2D-PURA algorithm’s pseudocode is in Algorithm 1. For device \( D_i \) in the kth ring, we assume that there is a virtual device \( A’ \), which is the intersection of the inner boundary of the kth ring and the straight line going through device A and \( D_i \), for sending an SR about the disturbance since it reaches the inner boundary as can be seen in Figure 2b. Therefore, device \( D_i \) satisfies the timing criterion (mentioned above) if its next SR opportunity is \( y \) subframes later than the time an SR from the virtual device \( A’ \). Noticeably, the SR from the virtual device \( A’ \) for the kth ring occurs \((k-1)\tau_0 \) subframes after the SR from device A. Therefore, in practice, the BS can proactively allocate uplink resources toward the kth ring at the time \( y \) subframes after the SR from the virtual device \( A’ \) received. Devices also can send data to the BS while the algorithm is in process.

#### Algorithm 1 2D-PURA Algorithm (S, A, T, v, \( \tau_0 \), \( y \))

**Input:** Set of devices \( S = \{D_1, D_2, \ldots, D_N\} \), device A

- Spreading time of event \( T \), speed of event \( v \)

**Output:** Proactively allocating uplink resources to set \( S \)

1: \( d_0 \leftarrow v \ast \tau_0 \)
2: \( n \leftarrow \lceil T \ast v / d_0 \rceil \)
3: for \( k \leftarrow 1, \ldots, n \) do
4: \( G_k \leftarrow \emptyset \)
5: end for
6: for all \( D_i \in S \) do
7: \( k \leftarrow \lceil |D_i, A| / d_0 \rceil \)
8: if \( k \leq n \) then
9: \( G_k \leftarrow G_k \cup \{D_i\} \)
10: end if
11: end for
12: for \( k \leftarrow 1, \ldots, n \) do
13: \( y_k \leftarrow (k-1) \ast \tau_0 + y \)
14: for all \( D_i \in G_k \) do
15: if (BS has not received SR from \( D_i \)) and (Time to next SR opportunity for \( D_i \) > \( y_k \)) then
16: BS prepares a proactive resource allocation for \( D_i \) to occur no earlier than \( y_k \)
17: end if
18: end for
19: end for

The parameter \( \tau_0 = d_0 / v \) characterizes the difference in the next SR opportunities of devices in each ring. Since the same threshold \( y \) is used to predict all devices in each ring, the large value of \( \tau_0 \) leads to less accurate predictions, thereby increasing the expected uplink delay of all neighbor devices in the disturbance region. Let \( \tau_{\text{max}} \) be the maximum value of \( \tau_0 (\tau_{\text{max}} \leq T) \) satisfying the expected uplink delay condition, so the maximum value of \( d_0 \) is \( \tau_{\text{max}} \ast v \).

Let \( N_k \) be the expected number of devices in the kth ring, then

\[
N_k = \lambda (\pi r_k^2 - \pi r_{k-1}^2) = \lambda \pi d_0^2 (2k-1).
\]

Therefore, the
expected number of device in the largest ring (the \(n^{th}\) ring) is \(N_n = \frac{\lambda n d_0^2}{2} (2n - 1)\). We have \(n = \left\lfloor \frac{T}{\tau_0} \right\rfloor = \left\lfloor \frac{T}{\gamma \tau_0} \right\rfloor = \left\lfloor \frac{T}{\tau_0} \right\rfloor\). To simplify, we assume that \(T = n \tau_0\). Consequently, we have \(N_n = \frac{\lambda n d_0^2}{2} \tau_0 (2T - \tau_0)\). Without loss of generality, assume that \(2T > \tau_0\), thus \(N_n = \frac{\lambda n d_0^2}{2} \tau_0 2T\). Let \(N_{max}\) is the maximum number of MTC devices that the BS can grant uplink resources simultaneously in LTE-FDD networks. Ignoring the probability of predictions targeting at the \(n^{th}\) ring, we have \(N_n \leq N_{max}\), thereby \(\tau_0 \leq \frac{N_{max}}{\frac{\lambda n d_0^2}{2} \tau_0 2T}\). The maximum possible value of \(d_0\) satisfying the \(N_{max}\) condition is \(\frac{N_{max} \tau_0}{2\lambda n d_0^2} = \frac{N_{max}}{2\lambda n \tau_0} \).

Choosing the width of a ring must be satisfied both the mean uplink delay and \(N_{max}\) conditions, therefore we have

\[
d_0 = \min \left\{ \frac{\tau_{max} v}{2}, \frac{N_{max}}{2\lambda n \tau_0} \right\}
\]

IV. PERFORMANCE ANALYSIS OF 2D-PURA

In this section, we derive three performance metrics of 2D-PURA algorithm: the expected uplink delay \(E(D)\), the probability of saving SRs \(P(SR)\) due to successful predictions, and the probability of uplink resource wastage \(P(W)\) due to unsuccessful predictions. Let \(P(S)\) and \(P(U)\) be the probabilities of successful and unsuccessful predictions.

In 2D-PURA, if an unsuccessful proactive resource allocation happens to a device, it must send an SR to the BS to request uplink data resources. The probability of saving SRs over the disturbance region \(P(SR)\) is given by \(P(SR) = P(S)\). Similarly, the probability of unsuccessful predictions expresses the uplink resource wastage, thus, \(P(W) = P(U)\). For a device \(B\) in the disturbance region radius \(l = v T\), its location follows a uniform distribution in the disturbance region with density \(\rho = \frac{1}{\pi v^2 T}\) [14].

Consider the case where device \(B\) is at a specific position in the \(k^{th}\) ring, in which \(\tau\) is the necessary time for the disturbance with speed \(v\) to travel from a virtual device \(A'\) on the inner boundary to the device \(B\). The BS targets device \(B\) for a proactive resource allocation given that the BS has received an SR from the virtual device \(A'\). Let \(P(S_B)\) and \(P(U_B)\) respectively be the probabilities of a successful/unsuccessful prediction targeting at device \(B\) given that the BS has received an SR from the virtual device \(A'\). \(E(D_B)\) is the expected uplink delay of device \(B\) under this proactive resource allocation. Here, \(P(S_B)\), \(P(U_B)\) and \(E(D_B)\) are functions of \(\tau\).

**Theorem 1.** The performance metrics, \(E(D)\), \(P(S)\) and \(P(U)\) are derived as

\[
E(D) = \sum_{k=1}^{n} E^{(k)}(D) \quad (3)
\]

\[
P(S) = \sum_{k=1}^{n} P^{(k)}(S) \quad (4)
\]

\[
P(U) = \sum_{k=1}^{n} P^{(k)}(U) \quad ,
\]

where \(n = \left\lfloor \frac{T}{\tau_0} \right\rfloor\), and

\[
E^{(k)}(D) = \frac{2}{T^2} \int_{0}^{\tau_0} ((k-1)\tau_0 + \tau) E(D_B) d\tau, \quad (6)
\]

\[
P^{(k)}(S) = \frac{2}{T^2} \int_{0}^{\tau_0} ((k-1)\tau_0 + \tau) P(S_B) d\tau, \quad (7)
\]

\[
P^{(k)}(U) = \frac{2}{T^2} \int_{0}^{\tau_0} ((k-1)\tau_0 + \tau) P(U_B) d\tau.
\]

Proof: For the case of \(E(D)\), let \(r\) be the distance from device \(B\) to device \(A\), then, the component of \(E^{(k)}(D)\) of device \(B\) in the \(k^{th}\) ring with density \(\rho\) is \(E^{(k)}(D) = \int_{r_{k-1}}^{r_k} \rho 2 \pi r E(D_B) dr\). Applying \(r = (k-1)\tau_0 + \tau\) and \(\rho = \frac{1}{\pi v^2 T}\) into this expression, we have \(E^{(k)}(D) = \frac{2}{T^2} \int_{0}^{\tau_0} ((k-1)\tau_0 + \tau) E(D_B) d\tau\). For the special case of the \(n^{th}\) ring, \(E^{(n)}(D) = \frac{2}{T^2} \int_{0}^{\tau_0} ((k-1)\tau_0 + \tau) E(D_B) d\tau\). Since device \(B\) is uniformly distributed on the disturbance region, the measure \(E(D)\) is the sum of components of the measure of device \(B\) in all rings, \(E(D) = \sum_{k=1}^{n} E^{(k)}(D)\). The cases of \(P(S)\) and \(P(U)\) are proved similarly.

In [7], the authors restricted their predictive resource allocation problem to a sequence of devices along a line. Then, the idea of one-to-one proactive resource allocation was applied repeatedly for the sequence. In this idea, only one device is considered for a predictive allocation after the BS receives an SR from another device. Consequently, at most 50 percent of devices is considered for a predictive resource allocation. In this work, we resolve a more general problem, in which devices are deployed on a two-dimensional plane. We then develop a one-to-many proactive resource allocation concept, when the BS receives an SR from device \(A\), all neighboring devices will be considered for a proactive resource allocation. To improve the performance and efficiency, neighbour devices are clustered into rings based on the distance from device \(A\), and the timing of proactive resource allocation targeting these rings will be deviated.

The one-to-one proactive resource allocation in [7] is the basis of the one-to-many proactive resource allocation concept in our study. Therefore, we use the equivalent expressions of metrics \(E(D_B), P(S_B),\) and \(P(U_B)\) which were analyzed in [7]:

\[
E(D_B) = \begin{cases} \Gamma S_1(D_B) + \Gamma U_1(D_B) + \Gamma \text{pred}(D_B), & y < \tau \\ \Gamma S_2(D_B) + \Gamma \text{pred}(D_B), & \tau \leq y < \sigma \end{cases}
\]

\[
P(S_B) = \begin{cases} \frac{(\sigma - y - 1)(\sigma + y) - (\tau - y - 1)(\tau + y)}{2 \sigma^2}, & y < \tau \\ \frac{(\sigma - y - 1)(\sigma + y - 1)(\tau - y)}{2 \sigma^2}, & \tau \leq y < \sigma \end{cases}
\]

\[
P(U_B) = \begin{cases} 0, & y < \tau \\ \frac{(\sigma - y - 1)(\tau - y)}{\sigma^2}, & \tau \leq y < \sigma \end{cases}
\]

where \(\tau\) is the necessary time for disturbance to move from the virtual device \(A'\) to device \(B\), and

\[
\Gamma S_1(D_B) = \frac{y(\sigma - y - 1)(\sigma + 2y + 1) + \delta(\sigma - \tau)}{2 \sigma^2}
\]

\[
\Gamma S_2(D_B) = \frac{(\sigma - \delta)(\sigma - \tau)(\sigma + 2y - \tau + 1)}{2 \sigma^2} - \frac{P_{\sigma + y - \tau}(\sigma - \tau)}{2 \sigma^2},
\]

\[
\Gamma U_1(D_B) = \frac{(\tau - y)(\sigma - y - 1)(\sigma - \tau + 1)}{2 \sigma^2} + \frac{(\tau - y)(\sigma - y - 1)(1 + \delta)}{\sigma^2}.
\]
$\Gamma_{P_{\tau\tau\tau\tau}}(D_B) = \frac{(y+1)(\tau-y)(2\sigma-\tau+3+2\delta)}{2\sigma^2}$

$+ \frac{y(y+1)(\sigma+3+2\delta)}{2\sigma^2}$

$+ \frac{(3+2\delta)(\sigma-\tau)(\sigma+2y-\tau+1)}{4\sigma^2}$

$+ P_{\tau+y-\tau}-P_y$,  

$\Gamma_{S_2}(D_B) = \frac{(\sigma-\delta)(\sigma-y-1)(\sigma+y)}{2\sigma^2}$

$+ \frac{(\sigma-\delta)(\sigma-y-1)(\sigma+y)}{2\sigma}$

$+ \tau(y+1)(\tau-y+3+2\delta) + \frac{\tau(\tau+1)}{2\sigma}$

$+ \frac{\sigma^2}{\sigma}$

$+ \frac{(3+2\delta)(\sigma-y-1)(\sigma+y)}{2\sigma^2}$

Here, $P_n$ is the $n^{th}$ square pyramidal number given by $P_n = \sum_{k=1}^{n} k^2 = \frac{n(n+1)(2n+1)}{6}$.

V. NUMERICAL RESULTS

In this section, we present numerical results to validate the performance of 2D-PURA by comparing it with the standard method in LTE networks [8] and its equivalent 1D algorithm [7].

Since the final performance expressions are only related to time, we describe the experiment scenarios by $\tau_0$ instead of $d_0$. Details of parameters are given in the table below.

| Parameters                        | Value  |
|-----------------------------------|--------|
| Density $\lambda$                 | 0.11   |
| SR period $\sigma$                | 40ms   |
| Threshold $y$                      | 1-39ms |
| Disturbance time $T$              | 1000ms |
| Velocity of the disturbance       | 300m/s |
| Ring-crossing disturbance propagation time $\tau_0$ | 1-40ms |

As mentioned in Section II, the standard uplink latency in LTE networks is $E(D_{st}) = (1+\sigma)/2 + 1 + \delta$. For the 1D algorithm on a spatial area, only when the BS receives an SR from a device, it considers a pro-active resource allocation towards the nearest neighbor. Then, if this device does not satisfy the eligibility and timing criteria, it cannot be targeted a pro-active resource allocation and follows the standard method by sending an SR. Therefore, at most 50 percent of neighboring devices are proactively allocated resources while the rest send SRs to the BS following the standard method. Noticeably, $P(S_B)$, $P(U_B)$ and $E(D_B)$ are just performance metrics of a device since it is proactively granted uplink resources. Hence, in the best case, the mean uplink delay is $E(D^*_B) = \frac{(E(D_{st})+E(D_B))}{2}$, the probability of saving SRs is $P(SR^*_B) = \frac{P(S_B)}{2}$, and the probability of wasting uplink resources is $P(W_B) = \frac{P(U_B)}{2}$.

Let $E(X)$ be the average distance between two devices on a spatial area. When devices are deployed according to HPPP with density $\lambda$, we have $E(X) = \frac{2}{\pi\lambda}$ [15]. To numerically evaluate the 1D algorithm, we set $\tau = \tau_{avg}$ where $\tau_{avg} = \frac{E(X)}{v}$.

With the speed of the disturbance $v$ and density $\lambda$ as mentioned in Table I, the average time required for the event to move between the two adjacent objects is $\tau_{avg} = 5ms$ when $v = 300m/s$. Here, the chosen speed of the disturbance is approximately equal to the speed of sound in air. While the parameter $\tau_{avg}$ for the 1D algorithm is a function of $\lambda$ and $v$, the parameter $\tau_0$ for 2D-PURA can be chosen independently. Therefore, 2D-PURA with different values of $\tau_0$ can be compared with the 1D algorithm with $\tau = \tau_{avg}$ (5ms).

![Fig. 3: SR saving due to successful predictions for 2D-PURA algorithm ($\sigma = 40$ subframes and various values of $\tau_0$).](image1)

![Fig. 4: Uplink resource wastage due to unsuccessful predictions for 2D-PURA algorithm ($\sigma = 40$ subframes and various values of $\tau_0$).](image2)
Fig. 5: Mean uplink delay for 2D-PURA algorithm ($\sigma = 40$ subframes and various values of $\tau_0$ and $y$).

Figure 6 illustrates the mean uplink delay of 2D-PURA with different values of $\tau_0$, the 1D algorithm and the standard method. Generally, the expected delays of 2D-PURA and the 1D algorithm increase since the threshold $y$ goes up, and the figures reach that of the standard one. The best case of the 1D algorithm $E(D')$ with $\tau = 5$ms on the whole disturbance region is much higher than that of 2D-PURA, $E(D)$, with all values of $\tau_0$. Specifically, when $y = 1$ms 2D-PURA gains the mean uplink latency of 18.5ms at $\tau_0 = 10$ms saving 27 and 16.5 percent consecutively in comparing with the standard method and the 1D algorithm. This is reasonable because 2D-PURA achieves a higher probability of proactive uplink resource allocations. Thus, 2D-PURA algorithm not only resolves the proactive uplink resource allocation on a spatial area but also outperforms the 1D algorithm in terms of reduction of expected uplink delay.

In Figure 6, the performance of 2D-PURA depends on both the values of $\tau_0$ and threshold $y$. In specific, the mean uplink delay of 2D-PURA with $\tau_0 = 10$ms is lower than that with $\tau_0 = 40$ms when the threshold $y < 10$ms and vice versa when $y > 10$ms. This is because with $10$ms $\leq y \leq 40$ms, the successful prediction rate of $\tau_0 = 10$ms (in this situation most of devices in the disturbance region send SR messages prior the time proactive allocations occur) is less than that of $\tau_0 = 40$ms. This completely matches with the dependence of the successful prediction rates on both $\tau_0$ and $y$ in Figure 3.

VI. CONCLUSION

Exploiting the traffic patterns of MTC devices, we proposed a spatial or 2D proactive uplink resource allocation, called 2D-PURA. The algorithm significantly reduces the mean uplink delay in comparison with the standard reactive method as well as the best case of the 1D algorithm (operating on a line of devices). We intensively investigated the proportions of resource conserved and wasted both analytically and numerically. The complexity of 2D-PURA algorithm and the optimal ring width were also provided.

REFERENCES

[1] P. Schulz, M. Mathe, H. Klessig, M. Simsek, G. Fettweis, J. Ansari, S. A. Ashraf, B. Aichroth, I. Voigt, I. Riedel, A. Puschmann, A. Mitschele-Thiel, M. Muller, T. Elste, and M. Windisch, “Latency critical iot applications in 5g: Perspective on the design of radio interface and network architecture,” IEEE Communications Magazine, vol. 55, no. 2, pp. 70–78, 2017.

[2] H. Shariatmadari, R. Ratasuk, S. Iraji, A. Laya, T. Taleb, J. R. ntt, and A. Ghosh, “Machine-type communications: current status and future perspectives toward 5g systems,” IEEE Communications Magazine, vol. 53, no. 9, pp. 10–17, 2015.

[3] Z. Wang and V. W. S. Wong, “Optimal access class barring for stationary machine type communication devices with timing advance information,” IEEE Transactions on Wireless Communications, vol. 14, no. 10, pp. 5374–5387, 2015.

[4] D. T. Wiriaatmadja and K. W. Choi, “Hybrid random access and data transmission protocol for machine-to-machine communications in cellular networks,” IEEE Transactions on Wireless Communications, vol. 14, no. 1, pp. 33–46, 2015.

[5] X. Wang, M. J. Sheng, Y. Y. Lou, Y. Y. Shih, and M. Chiang, “Internet of things session management over lte - balancing signal load, power, and delay,” IEEE Internet of Things Journal, vol. 3, no. 3, pp. 339–353, 2016.

[6] J. Tadrous, A. Eryilmaz, and H. E. Gamal, “Proactive content download and user demand shaping for data networks,” IEEE/ACM Transactions on Networking, vol. 23, no. 6, pp. 1917–1930, 2015.

[7] J. Brown and J. Y. Khan, “A predictive resource allocation algorithm in the lte uplink for event based m2m applications,” IEEE Transactions on Mobile Computing, vol. 14, no. 12, pp. 2433–2446, 2015.

[8] 3GPP TR 36.321 V11.3.0 (2013-07), “Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification,” Release 11, 2013.

[9] S. Y. Lien, K. C. Chen, and Y. Lin, “Toward ubiquitous massive accesses in 3gpp machine-to-machine communications,” IEEE Communications Magazine, vol. 49, no. 4, pp. 66–74, 2011.

[10] U. Tefek and T. J. Lim, “Relaying and radio resource partitioning for machine-type communications in cellular networks,” IEEE Transactions on Wireless Communications, vol. 16, no. 2, pp. 1344–1356, 2017.

[11] G. Han, H. Xu, T. Q. Duong, J. Jiang, and T. Har, “Localization algorithms of wireless sensor networks: a survey,” Telecommunication Systems, vol. 52, no. 4, pp. 2419–2436, 2013.

[12] C. Zhu, V. C. M. Leung, L. T. Yang, and L. Shu, “Collaborative location-based sleep scheduling for wireless sensor networks integrated with mobile cloud computing,” IEEE Transactions on Computers, vol. 64, no. 7, pp. 1844–1856, 2015.

[13] TS 36.331 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 14) 2017. 3GPP [Online]. Available: http://www.3gpp.org/ftp//Specs/archive/36_series/36.331/36.331-e10.zip

[14] D. Daley, Daryl J Vere-Jones, An Introduction to the Theory of Point Processes: Volume I: Elementary Theory and Methods. Springer Science & Business Media, 2007.

[15] D. Moltchanov, “Distance distributions in random networks,” Ad Hoc Networks, vol. 10, no. 6, pp. 1146–1166, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870512000224