Abstract—A Load Balancing Relay Algorithm (LBRA) is proposed in this letter to solve the unfair spectrum resource allocation problem in two-tier machine-type communications (MTC) uplink transmission. By adopting MTC devices (MTCDs)'s distribution, spectrum resources are dynamically allocated and reclustered for the link between MTCDs to cluster-head. Moreover, the system outage probability and transmission capacity are derived for the LBRA in this letter. The numerical results provide some insights on potential use of the LBRA for the scenario with high MTCD density.

Index Terms—Load management, machine-type communications, relay networks, resource allocation.

I. INTRODUCTION

In the machine-type communications (MTC) scenario, the radio access network (RAN) will be congested by a large number of MTC devices (MTCDs), which simultaneously access to the access point (AP). Different approaches have been proposed to deal with the problem through prioritized random access and distributed queuing. Another potential solution is data aggregation [1]–[6], MTCDs form a cluster and send data to the AP through the cluster-head.

For improving the coverage of uplink, two-tier uplink transmission is adopted in heterogeneous MTC network. The performance of two-tier MTC has been extensively studied [7]–[11]. The uplink average data rate of the two-tier MTC is studied, by using constraint gradient ascent optimization algorithms [7]. In [8], an ALOHA protocol for multihop networks is proposed to reduce the latency by optimizing the coverage of each cluster-head. Recent research shows that the load of clusters.

Resource allocation in two-tier MTC is significant to improve the system capacity and reduce the outage probability. By sharing spectrum resources in a non-orthogonal way within the cluster [4], both spectrum efficiency and number of device connections also can be improved. In [12], a channel-aware resource scheduling is proposed, in which gateways tend to allocate resources to MTCDs with better channel state, to improve the transmission success probability. Cluster-head prioritizes MTCDs according to different parameters, and allocates resources for MTCD based on priority, which can also improve the transmission capacity [13]. In [14], the trade-off between transmission capacity and fairness of resource allocation is studied, in which a global optimal resource allocation scheme is proposed to enhance network throughput. In [15], the authors optimize the load and transmission power to reduce the energy consumption of the system in the scenario of massive MTC uplink transmission. MTCDs have the choice of directly connecting with AP or going through cluster-heads to transmit their data, the authors in [16] minimize MTCDs energy consumption by optimizing cluster-head density.

However, existing works have not considered the dynamic reclustering of devices when analyzing system performance. Therefore, this letter studies the dynamic resource allocation scheme based on two-tier MTC, aiming to reduce the outage probability and increase the transmission capacity when supporting massive MTCDs connection. The main contributions of this letter are summarized as follows.

- A load-balancing relay algorithm (LBRA) is proposed for the uneven distribution of MTCD. In the proposed algorithm, MTCD is firstly clustered by using the location specific information according to stochastic geometry methodology, and then the MTCD is reclustered based on the load of clusters.
- The transmission capacity and outage probability of the system when using the proposed algorithm are derived, and the simulation results compared with traditional method, that is, the nearest principle relay algorithm (NPRA) [1], validate the superiority of the LBRA in case of massive random access.

II. SYSTEM MODEL

As shown in Fig. 1, a two-tier MTC covered by a AP is considered. MTCDs form a cluster and send data to the AP through the cluster-head, which is randomly selected [1], [6], [11]. The positions of MTCDs and cluster-heads are assumed to obey two independent homogeneous Poisson point processes (HPPP), where \( \Phi_D = \{X_i\} \) and \( \Phi_G = \{Y_i\} \), and the distribution densities are \( \lambda_D \) and \( \lambda_G \), respectively. This letter
aims at the scheduling problem of resources within MTCD clusters, and its evaluation indexes are transmission capacity and outage probability.

The AP distributes the spectrum resources in the unit of a resource block (RB). The number of RBs allocated to MTCD to cluster-head link (denote as aggregation link) and cluster-head to AP link (denote as relay link) are represented as $R_1$ to $R_2$, respectively.

Assuming that all MTCDs handle the same business, and considering the simplicity of wake-up, all MTCDs use the same modulation and coding scheme (MCS) [1], where fixed-size packet is transmitted with power $P$ and the path loss is considered. All channels are composed of $\omega_1$ RBs, which are sufficient to send a packet. Thus, there are $U_1 = \left\lfloor \frac{R_1}{\omega_1} \right\rfloor$ channels in total, as shown in Fig. 2(a). The path loss for both the aggregation and the relay link is assumed as $l(r) = r^{-\alpha}$, where $\alpha$ is the path loss index and $r$ is the distance of the line-of-sight. Here we assume that cluster-head can decode the packet successfully when the Signal-to-Interference power Ratio (SIR) of a MTCD packet is larger than a threshold $\gamma_i$, which is the distance of the $i$-th channel and is nearest to cluster-head at location $Y_i$. For simplicity, use $\mathcal{H}_i, \mathcal{V}_i$ to represent the typical MTCD, which is occupying the $i$-th channel and is the closest to cluster-head at location $Y_i$ compared to other cluster-heads, $\mathcal{V}_i$. Note that the transmission data of MTCD on channel $u$ after re-clustering is $Z_i^u$. The transmission capacity can be denoted as the product of the MTCD distribution density $\lambda_D$ and the probability of successful transmission $(1 - \varepsilon)$.

$$ C = \lambda_D (1 - \varepsilon). \quad (1) $$

The transmission capacity is a measure of MTCD density that the network can support with the constraint of outage probability, i.e., it is has units of number of MTCDs per unit area.

### III. LOAD BALANCING RELAY ALGORITHM

In the aggregation link, by balancing the number of MTCDs in each cluster, the relay link can reasonably reallocate between two nearest clusters. The detailed algorithm flow is shown in Fig. 3. According to the information broadcast by the AP, MTCDs complete random access and send location information to AP after collecting data. Cluster-head is selected by the AP to complete the clustering and allocate spectrum resources. Afterwards, when MTCD changes its location due to the mobility, it needs to resend its location information to the AP for reclustering. We define the following four events, without loss of generality, cluster-head is assumed as $Y_0 \in \Phi_G$.

**Event 1:** The MTCD is transferred from the nearest $Y_i$ into the $Y_0$ region.

**Event 2:** The MTCD is transferred from the $Y_0$ region to the nearest $Y_i$ region.

**Event 3:** The cluster-head located at $Y_0$ successfully captures the packet.

**Event 4:** Packets captured by cluster-head at $Y_0$ can be successfully relayed to AP.

Suppose a typical MTCD at $X_i$ sends a packet on the channel $u \in \{1, 2, \ldots, U_1\}$. Let $\text{Pr}(\lambda)$ denote the packet successfully received by $\text{MTCD}$.

$$ \text{Pr}(\lambda) = \text{Pr}(\lambda_1 \cap \lambda_2 \cap \lambda_3) = \text{Pr}(\lambda_1) \text{Pr}(\lambda_2) \text{Pr}(\lambda_3) \quad (2) $$
where $A_1$ indicates that the MTCD is transferred into cluster-head at $Y_0$, and $A_2$ indicates that the MTCD is transferred out from cluster-head at $Y_0$. According to the conditions $A_1$ and $A_2$, the expression is simplified as the sum of $P_1$, $P_2$, and $P_3$ by using the total probability theorem.

By definition of the Poisson distribution, we obtain

$$
Pr(A_1) = Pr(k_i \geq k_0) = \sum_{k=k_0}^{\infty} \frac{\lambda_D S Y_j}{k!} \exp(-\lambda D S Y_j), \quad (3)
$$

$$
Pr(A_2) = Pr(k_i < k_0) = \sum_{k=0}^{k_0} \frac{\lambda_D S Y_j}{k!} \exp(-\lambda D S Y_j), \quad (4)
$$

where $k_0$ represent the number of MTCDs in $Y_0$ region, $k_i$ represents the number of MTCDs in the region nearest to $Y_0$, and $S Y_j$ indicates the area of the region with $Y_1$ as the cluster-head. In the analysis, since each MTCD is associated with the nearest MTCG, a Voronoi tessellation is composed of a cluster. Therefore, the area of the cluster can be obtained by calculating the geometric area of the Voronoi tessellation. Obviously, the transfer in $Y_1$ region is the transfer out of $Y_0$ region, so $Pr(A_1) + Pr(A_2) = 1$.

It can improve wireless resource utilization and reduce congestion by balancing the number of MTCDs per cluster, since the RBs used for the relay link in each cluster are equal, and all devices have the same MCS. When MTCD transfer occurs, the number of transfer devices $k_{change}$ is

$$
k_{change} = \left\lfloor \frac{k_1 - k_0}{2} \right\rfloor, \quad (5)
$$

when $k_0 < k_1$, which means that there are $k_{change} MTCDs$ transferred from $Y_1$ to $Y_0$ region. Otherwise, it means that $k_{change}$ MTCDs are transferred from $Y_0$ to $Y_1$ region. For the convenience of calculation, $P_1$, $P_2$, and $P_3$ are derived as

$$
P_1 = Pr\left(\mathcal{R}_{u}^{A_1}Y_0 \mid C_{u}^{X_i,Y_0} \cap \mathcal{Q}_{X_i,Y_0}^{u}, A_1\right) Pr(A_1) \cdot Pr(C_{u}^{X_i,Y_0} \cap \mathcal{Q}_{X_i,Y_0}^{u}, A_1) Pr\left(\mathcal{Q}_{X_i,Y_0}^{u} \mid A_1\right), \quad (6)
$$

$$
P_2 = Pr\left(\mathcal{R}_{u}^{A_2}Y_0 \mid C_{u}^{X_i,Y_0} \cap \mathcal{T}_{u}^{X_i,Y_0}, A_2\right) \cdot Pr(C_{u}^{X_i,Y_0} \cap \mathcal{T}_{u}^{X_i,Y_0}, A_2) Pr\left(\mathcal{T}_{u}^{X_i,Y_0} \mid A_2\right), \quad (7)
$$

and

$$
P_3 = Pr\left(\mathcal{R}_{u}^{A_3}Y_0 \mid C_{u}^{X_i,Y_0} \cap \mathcal{Q}_{X_i,Y_0}^{u} - \mathcal{T}_{u}^{X_i,Y_0}, A_3\right) \cdot Pr(C_{u}^{X_i,Y_0} \cap \mathcal{T}_{u}^{X_i,Y_0}, A_3) Pr\left(\mathcal{T}_{u}^{X_i,Y_0} \mid A_3\right). \quad (8)
$$

According to $P_1$, $P_2$, and $P_3$, the end-to-end outage probability can be written as

$$
\varepsilon = E \left[ \prod_{Y_1 \in \Phi_G} (1 - (P_1 + P_2 + P_3)) \right]. \quad (9)
$$

Note that $\mathcal{Q}_{X_i,Y_0}^{u}$ is equivalent to the event that there exists no cluster-head except $Y_0$ within a closed ball of radius $\|X_i^u - Y_0\|$ centered at $X_i$, then

$$
Pr\left(\mathcal{Q}_{X_i,Y_0}^{u} \mid A_1\right) = Pr\left(\mathcal{Q}_{X_i,Y_0}^{u} \cap B(Z_i^u, \|Z_i^u - Y_0\|) = \emptyset\right) = \exp(-\pi \lambda_G \|Z_i^u - Y_0\|^2). \quad (10)
$$

Since $X_i^u$ represents a typical MTCD, and under $A_1$ conditions $X_i^u = Z_i^u$. Then, for event $\mathcal{Q}_{X_i,Y_0}^{u} \cap A_1$ in $P_2$ and event $\mathcal{Q}_{X_i,Y_0}^{u} - \mathcal{T}_{u}^{X_i,Y_0}$ in $P_3$, the probability can be expressed as

$$
Pr\left(\mathcal{T}_{u}^{X_i,Y_0} \mid A_1\right) = \frac{k_{change}}{\sum k_j}, \quad (11)
$$

$$
Pr\left(\mathcal{T}_{u}^{X_i,Y_0} \mid A_2\right) = \frac{k_0 - k_{change}}{\sum k_j}, \quad (12)
$$

where $\sum k_j$ refers to the total number of MTCDs.

The location set of typical MTCD transmitted on channel $u$ is represented by $\Phi_G^{X_i}$. Then for $X_i^u$, the interference at the cluster-head can be expressed as

$$
I_{u}^{X_i - Y_0} \mid Y_0 = \sum_{X_j^u \in \Phi_G^{X_i}} h_{X_j^u,Y_0} \|X_j^u - Y_0\|^{-\alpha}, \quad (13)
$$

where $h_{X_j^u,Y_0}$ represents the channel fading gain from $X_j^u$ to the cluster-head, and $\|X_j^u - Y_0\|$ is the distance from $X_j^u$ to the cluster-head.

A typical MTCD packet can be captured by cluster-head located at $Y_0$, if the SIRs of the packet is larger than the threshold $\eta$. Otherwise, it cannot be captured. The probability of the event $\mathcal{Q}_{Z_i,Y_0}^{u} \mid \Phi_G^{X_i}$, under the condition $A_1$ can be expressed as

$$
Pr\left(C_{Z_i,Y_0}^{u} \mid \mathcal{Q}_{Z_i,Y_0}^{u} \cap \Phi_G^{X_i}, A_1\right) = \exp(-\pi \lambda_D U_1 \frac{\eta^2}{1 + \lambda_D U_1}) K_{\alpha}, \quad (14)
$$

where $K_{\alpha} = \int_{0}^{\infty} dt \frac{dt}{1 + t^2}$. Obviously, the probability $Pr(C_{Z_i,Y_0}^{u} \cap \mathcal{Q}_{Z_i,Y_0}^{u} \cap A_1) \mid \Phi_G^{X_i}$ in $P_2$ and the probability $Pr(C_{Z_i,Y_0}^{u} \cap \mathcal{T}_{u}^{X_i,Y_0} \cap A_2) \mid \Phi_G^{X_i}$ in $P_3$ can also be represented by (14).

The average probability of cluster-head captures all MTCDs,
that is, the average capture probability $p_{c, \text{in}, \psi}$ of the event $\mathcal{C}_{Z^u_{1}, Y_0}^u | \mathcal{T}_{X^u_{1}, Y_0}^u$ under $A_1$ without the condition $\| Z^u_{1} - Y_0 \|$ can be expressed as

$$
p_{c, \text{in}, \psi} = \left( \frac{\lambda_D}{U_1 \lambda_G} \eta \frac{1}{2} K_\alpha + 1 \right)^{-1}.
$$

Similarly, the MTCD average capture probability $p_{c, \text{in}, T}$ of the event $\mathcal{C}_{Z^u_{1}, Y_0}^u | \mathcal{T}_{Y_0}^u$ can be expressed as

$$
p_{c, \text{in}, T} = \left( \frac{\lambda_D}{U_1 \lambda_G} \eta \frac{1}{2} K_\alpha + 1 \right)^{-1} \cdot \exp \left( -\pi \lambda_D \eta \frac{1}{2} K_\alpha \eta \frac{1}{2} \lambda_G \| Z^u_{1} - Y_0 \| / 4 \right).
$$

Under condition $A_2$, the MTCD average capture probability $p_{c, \text{out}}$ of event $\mathcal{C}_{Z^u_{1}, Y_0}^u \cap (\mathcal{T}_{X^u_{1}, Y_0}^u - \mathcal{T}_{Y_0}^u)$ can be expressed as

$$
p_{c, \text{out}} = \left( \frac{\lambda_D}{U_1 \lambda_G} \eta \frac{1}{2} K_\alpha + 1 \right)^{-1} \frac{k_0 - k_{\text{change}}}{k_0}.
$$

All packets can be successfully relayed when the number of packets captured by cluster-head is less than $U_2$. Otherwise, only $U_2$ packets can be relayed. The successful transmission probability of the relay link can be expressed as

$$
\Pr \left( \mathcal{R}_{Z^u_{1}, Y_0}^u \right) = \begin{cases} \frac{U_2}{k_c p_c}, & \text{if } k_c p_c > U_2 \\ 1, & \text{otherwise} \end{cases},
$$

where $k_c$ represents the number of MTCDs in the region, under condition $A_1$, $k_c = k_0 + k_{\text{change}}$, or under condition $A_2$, $k_c = k_0 - k_{\text{change}}$. $p_c$ represents cluster-head’s average capture probability, which is recorded as $p_{c, \text{in}, \psi}$ under event $\mathcal{C}_{Z^u_{1}, Y_0}^u | \mathcal{T}_{X^u_{1}, Y_0}^u$ under condition $A_1$, $\mathcal{C}_{Z^u_{1}, Y_0}^u | \mathcal{T}_{Y_0}^u$ under condition $A_2$, $\mathcal{C}_{Z^u_{1}, Y_0}^u \cap (\mathcal{T}_{X^u_{1}, Y_0}^u - \mathcal{T}_{Y_0}^u)$, and $p_{c, \text{out}}$ under event $\mathcal{C}_{Z^u_{1}, Y_0}^u \cap (\mathcal{T}_{X^u_{1}, Y_0}^u - \mathcal{T}_{Y_0}^u)$.

According to the above derivation, $P_1$, $P_2$, and $P_3$ can be expressed as

$$
P_1 = \frac{U_2 k_0 \exp \left( -\pi \lambda_D \eta \frac{1}{2} K_\alpha \| Z^u_{1} - Y_0 \| / 2 \right)}{(k_0 + k_{\text{change}})^2 p_{c, \text{in}, \psi}} \cdot \exp \left( -\pi \lambda_G \| Z^u_{1} - Y_0 \| / 2 \right) \sum_{k=k_0}^{\infty} \frac{(\lambda_D S_{Y_1})^k}{k!} \times \exp \left( -\lambda_D S_{Y_1} \right),
$$

$$
P_2 = \frac{U_2 k_{\text{change}} \exp \left( -\pi \lambda_D \eta \frac{1}{2} K_\alpha \| Z^u_{1} - Y_0 \| / 2 \right)}{(k_0 + k_{\text{change}})^2 p_{c, \text{in}, T}}
$$

and

$$
P_3 = \frac{U_2 \exp \left( -\pi \frac{\lambda_D \eta}{U_1 \lambda_G} \frac{1}{2} K_\alpha \| Z^u_{1} - Y_0 \| / 2 \right)}{(k_0 - k_{\text{change}}) p_{c, \text{out}}} \sum_{k=k_0}^{\infty} \frac{(\lambda_D S_{Y_1})^k}{k!} \exp \left( -\lambda_D S_{Y_1} \right).
$$

Substituting (19), (20), and (21) into (9), we can obtain the outage probability as shown in (22) at the bottom of the page. Then, substituting (22) into (1), the transmission capacity is obtained.

### IV. Numerical Results

This section demonstrates the accuracy of the analytical results through Monte Carlo simulations. We evaluate the transmission capacity and outage probability with the proposed LBRA. We confirm the superior performance of the LBRA system by comparing with the traditional NPRA. The NPRA allocates spectrum resources equally for cluster-heads, and MTCDs can only transmit data through the associated cluster-head. Unless otherwise stated, we adopt following simulation parameters in [1], $\eta = 3$ dB, $\alpha = 4$, $\omega_1 = 30$, $\omega_2 = 5$, $R_1 = 1800$, and $R_2 = 1800$, respectively. The analytical results do not exactly match the simulations in the proposed LBRA. This is due to in the analysis, the transferred MTCDs are randomly selected. However, in the simulation, MTCDs near cluster boundary are selected for transfer.

The transmission capacity $C$ versus MTCD density $\lambda_D$ is shown in Fig. 4. The transmission capacity grows flat with
large MTCD density. This is due to the outage probability gradually increases proportionally with increasing MTCD density and the outage probability is the key limitation on the transmission capacity. We can observe an increase of outage probability by comparing the transmission capacity gap between the proposed algorithm and the no outage scheme. Therefore, after the MTCD transfer, the cluster-head needs to relay the MTCD located farther away. This makes a significant increase of the distance between adjacent clusters. Moreover, when MTCD density is large, we note that the transmission capacity of the LBRA is larger than that of the NPRA.

Fig. 5 shows the transmission capacity $C$ against the density of cluster-head $\lambda_C$. When the value of $\lambda_C$ is low, the transmission performance of the LBRA is worse than that of the NPRA. This is because the sparse distribution of cluster-head, results in an increase of the distance between adjacent clusters. Therefore, after the MTCD transfer, the cluster-head needs to relay the MTCD located farther away. This makes a significant increase of the outage probability of the aggregation link and a corresponding decrease of transmission capacity. However, the LBRA’s performance exceeds the NPRA when cluster-head density $\lambda_C$ is near $0.75 \times 10^{-4}$, because of the shorter distance between clusters.

Fig. 6 depicts the outage probability $\varepsilon$ for different MTCD density $\lambda_D$. The outage probability of the LBRA is larger than that of the NPRA when the value of $\lambda_D$ is low (i.e., $\lambda_D < 0.3 \times 10^{-3}$). This is due to the MTCD transfer cause an increase of the distance between MTCD and cluster-head. With the increase of MTCD density, when $\lambda_D \approx 0.7 \times 10^{-3}$, the proposed LBRA has a lower outage probability than that of the NPRA, because the LBRA can effectively use RBs by transferring MTCDs. Moreover, when the value of $\lambda_D$ is large (i.e., $\lambda_D > 2.7 \times 10^{-3}$), the outage probability increases rapidly because of the constraints of spectrum resources.

V. Conclusion

In this letter, to solve the unfair resource allocation problem in traditional two-tier MTC, a load balancing relay algorithm is proposed, which reallocates spectrum resources on the aggregation link. The LBRA reclusters MTCDs based on the load of each cluster to make full use of spectrum resources. Numerical results show that the LBRA has good performance, especially when MTCD density is large. Its transmission capacity and outage probability performance are better than the traditional algorithm, which illustrates that the proposed algorithm is suitable for MTCD intensive deployment environment. Moreover, different MTCDs can provide particular QoS if different MCSs are used.

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