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Energy-Efficient Dynamic MAC Protocol for M2M Communication

Narender Reddy Kampelli[1*], *Chandrasekhar Reddy Puttha*[2]

[1]*PhD, Electronics & Communication Engineering, JNTUH UCEST, Hyderabad, India.*

[2]*Professor, Electronics & Communication Engineering, JNTUH UCEST, Hyderabad, India.*

Emails: *narenderreddy.kampelli@gmail.com*[1]*,drpcsreddy@jntuh.ac.in*[2]

[*]**Corresponding Author Orcid ID:** *https://orcid.org/0000-0001-7356-696X*

Abstract
In the Internet of Things, which is vital for smart city applications, a vast network of battery-operated Machine Type Communication Devices (MTCDs) requires Machine Type Communication. These MTCDs connect directly to a network with a base station, facilitating a wide range of smart city functionalities. The development of energy-efficient communication protocols is essential to support the deployment of energy-constrained battery-operated devices. These protocols aim to minimize energy consumption, thereby enhancing network lifetime. Additionally, they must address scalability, reduce collisions and delays, and ensure a high Quality of Service (QoS) to effectively manage the vast number of devices involved. Clustering is a viable strategy to enhance scalability and energy efficiency in network communications. However, within this framework, particularly in the proposed Power Efficient Dynamic MAC protocol for M2M Communication (PMAC), there's still a need for energy-efficient communication between the Machine Type Communication Devices (MTCDs). This requirement is crucial to optimize the overall performance and sustainability of the network. In this paper, we analyses the Energy Efficient CSMA/CA (E-CSMA/CA) protocol, specifically developed for facilitating communication between Machine Type Communication Devices (MTCDs) in short-range communications. This analysis is set within the context of smart city applications, with a particular focus on smart metering. This approach underscores the importance of efficient, reliable communication protocols in modern urban infrastructure, especially for applications like smart metering that are integral to the smart city ecosystem.

Keywords: *Internet of Things, M2M Communication, MAC Protocol*

1. Introduction
Machine Type Communication (MTC), crucial in the Cellular Internet of Things (IoT), enables autonomous and intelligent networked Machine Type Communication Devices (MTCDs) to interact without human intervention, vital for automating communication in the IoT. IoT applications, including home automation, healthcare, smart cities, and industry, rely on M2M communication, integral to their functionality. Key to managing the scalability in these applications, as indicated in [4] and [5], is the Medium Access Control (MAC) protocol. Currently M2M protocols focus on access delay, energy efficiency, traffic management, collision control, and resource management. Quality of service in M2M communication is improved by integrating scheduling methods like pre-defined timeslots for data transmission ([6], [7]), enhancing communication efficiency and reliability. Grouping MTCDs, a strategy highlighted in [8] and [9], addresses the surge in device numbers and optimizes resource use. The proposed M2M communication protocol in this paper focuses on reducing energy consumption in MTCD communications.

2. Related Works
Jang et al. [10] proposed a spatial group-based random access and non-orthogonal resource

allocation to improve random access success. They grouped MTCDs and allocated non-orthogonal channels within each group for better spatial multiplexing. Tefek and Lim [11] introduced signal-to-interference and location-based single-hop relaying for MTCDs in cellular networks, clustering MTCDs by location and service needs with a local access point for each cluster. In [12], a location-based random access strategy clusters MTCDs geographically to reduce collisions at the base station (BS), using Cluster Heads (CHs) as Decode-and-Forward (DF) relays. Wu et al. [13] developed a dynamic resource allocation for clustered M2M communications, categorizing MTCDs by delay requirements and dynamically allocating PRACH resources. Vu et al. [14] created a two-dimensional proactive uplink resource allocation with a clustering algorithm to reduce latency in event-based M2M communications, spatially grouping MTCDs in concentric rings based on proximity to events and assigning resources for uplink transmissions. Riker et al. [15] proposed a two-tier data aggregation approach for M2M communications in multi-target applications to address the limited energy resources in MTCDs and prolong network life. The first tier reduces data redundancy, while the second tier further aggregates data to cut message overhead costs. Meanwhile, Ghavimi et al. [16] explored power allocation and clustering in M2M communications for LTE-Advanced systems. They used clustering to categorize MTCDs by transmission protocols and Quality of Service needs, then implemented a resource allocation strategy to maximize the sum throughput in these clusters.

3. Problem Description

The current research identifies several key challenges. In the MAC Protocol, a Cluster-Based Congestion Mitigating Access Scheme (CCAS) was developed, as discussed in [17], where MTCDs are grouped into clusters and an MTC Gateway (MTCG) is chosen for data transmission. The initial step in this clustering involves estimating similarity. Spectral clustering is applied to derive the diagonal matrix, Laplacian matrix eigenvalues, and eigenvectors, which are then input into K-means clustering for forming clusters. This process, however, tends to be time-consuming. Furthermore, the traditional CSMA/CA MAC protocol is utilized, which is effective in limiting collisions but does not adequately reduce power consumption.

4. Contribution

This study innovates in power-efficient M2M communication by clustering MTCDs and designating group heads for eNodeB access, reducing collisions and enhancing network efficiency. Hierarchical MTCHs span eNodeB's range, with Cluster Heads selected via Harris Hawks Optimization, factoring in distance, power, and battery life. This optimizes resource use and ensures QoS. Additionally, the study introduces a dynamic protocol switch between E-CSMA/CA and CSMA/CARP, adjusting back-off times based on delays and active MTCDs, further boosting adaptability and efficiency.

5. System Model

In this cellular M2M communication system, each cell features an eNodeB base station and numerous MTCDs. For communication between the MTCD and the eNodeB, LTE communication technology is utilized, while for inter-MTCD communication, standard protocols based on CSMA/CA or CSMA/CARP are employed. The network cell comprises 'n' MTCDs, randomly positioned within a network area measuring N×N. These MTCDs, functioning as sensors, are adept at sensing their surroundings and communicating with other MTCDs. They are equipped to support both cellular and short-range transceivers, enabling versatile communication capabilities within the network. All MTCDs are initially provisioned with the same amount of energy at the time of deployment. Figure 1 illustrates the network architecture, showcasing how the MTCDs transmit data using the proposed MAC protocol. The eNodeB is strategically located at the center of the network. Within this setup, certain MTCDs function as Machine Type Communication Heads (MTCHs), considered as full-function devices. These MTCHs are selected hierarchically, based on their coverage distance, ensuring efficient network management and communication coverage.

6. Clustering MTCDs

An optimization algorithm is employed to select

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group heads from the deployed MTCDs. Following this selection, the Machine Type Communication Heads (MTCHs) form their respective groups by incorporating MTCDs through an exchange of requests and responses. This process ensures effective grouping for optimized network communication. In this work, similar to [41], the MTCDs are capable of both short and long-range communication. The MTCHs, using either the E-CSMA/CA or CSMA/CARP MAC protocols, communicate with their group members. They switch between these protocols based on the device density within each group, selecting the most appropriate MAC protocol accordingly. The MTCDs are organized into various levels. Based on the Manhattan distance level, the MTCHs employ the Harris Hawks Optimization (HHO) algorithm to select MTCHs for the next level. The selection of the first level of MTCHs is determined by the Manhattan distance, which is expressed as follows:

$$D = \sum_{i=1}^{n} |x_i - y_i| \qquad (1)$$

The distance between the eNodeB and the 'n' number of MTCDs at the first level is determined based on their current position points x_i about the position of the MTCDs, denoted as y_i. The selection process prioritizes MTCDs that are closer and adjacent to the eNodeB for the first level. The distance between the eNodeB and 'n' number of MTCDs at the first level is calculated from their current positions, denoted as x_i, about the positions of the MTCDs, y_i MTCDs that are located closer and adjacent to the eNodeB are preferentially selected for the first level. The eNodeB selects four Machine Type Communication Heads (MTCHs) based on their proximity, as determined by the aforementioned distance. Subsequently, these chosen MTCHs are responsible for selecting the next level of heads to facilitate the formation of groups. This grouping process commences only after all MTCHs in the network have been elected. In the M2M network, the Harris Hawks Optimization (HHO) algorithm, inspired by Harris Hawks' hunting behavior, is used for selecting Machine Type Communication Heads (MTCHs). It evaluates MTCDs based on their proximity to eNodeB, received power, and residual energy.

$$X(t+1) = \begin{cases} X_{rand}(t) - r_1|X_{rand}(t) - 2r_2X(t)| & q \geq 0.5 \\ (X_{rabbit}(t) - X_m(t)) - r_3(LB + r_4(UB - LB)) & q < 0.5 \end{cases} \qquad (2)$$

In this iteration process, we define t as the current iteration and t+1 as the subsequent iteration. The position vector of a hawk at iteration t+1 is denoted as X(t+1), while Rabbit (t) represents the rabbit position during iteration t. The current position of the hawk is X(t). We include random numbers r_1, r_2, r_3, r_4, and q each ranging between [0,1]. X_rand (t) signifies the position of a randomly selected hawk, and X_m defines the average position of the hawks. The upper and lower bounds of variables are represented by UB and LB, respectively. Consequently, the hawks' average position is calculated accordingly.

$$X_m(t) = \frac{1}{K}\sum_{i=1}^{K} X_i(t) \qquad (3)$$

The location of a hawk at the t^th iteration is represented by X_i (t), and K signifies the number of participating hawks, which are the first-level MTCHs in the network. Based on the energy levels of the next level of MTCDs (conceptualized as rabbits), the algorithm transitions from exploration to exploitation phases. In this context, the energy E is mathematically formulated to reflect this transition, taking into account the energy states of the MTCDs and the dynamic behavior of the hawks in the optimization process.

$$E = 2E_0\left(1 - \frac{t}{T}\right) \qquad (4)$$

The variable T represents the total number of iterations, while E_0 signifies the initial energy amount of the rabbit. In the computation, the energy exploitation phase occurs either as a soft or hard besiege. During this phase, the position vector updates according to the energy value. We express the soft besiege SB and hard besiege HB mathematically to reflect these different modes of energy exploitation, capturing the dynamic interaction between the hawks and the rabbit in the optimization process.

$$X(t+1)_{SB} = \Delta X(t) - E|JX_{rabbit}(t) - X(t)| \qquad (5)$$

$$X(t+1)_{HB} = X_{rabbit}(t) - E|\Delta X(t)| \qquad (6)$$

Where ΔX(t)=Rabbit (t)-X(t), The parameter J denotes the strength of the rabbit, which undergoes random fluctuations. The fitness value for the

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optimization process is calculated based on factors such as distance, received power, and residual energy. The distance between two MTCDs is determined using the Euclidean distance formula, which provides a spatial measurement of the separation between the devices in the network.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (7)$$

(x_1, y_1) and (x_2, y_2) are the position coordinate points of individual MTCDs. Then, the received power 〖R〗_P is determined using the Friis equation that is given as,

$$R_P = \frac{P_T G_T G_R \lambda^2}{(4\pi d)^2} \quad (8)$$

In the given context, G_(T,) and G_R represent the gain received, P_T is the total power, and λ denotes the wavelength. The residual energy of each MTCD is then calculated from the initial energy amount available to the MTCD. Taking into account these three constraints - received gain, total power, and residual energy - the fitness for each MTCD at the second level is estimated. Based on this estimation, the MTCHs (Machine Type Communication Heads) are subsequently selected. To select the MTCHs, the entire network is covered. MTCDs serving as group members are then incorporated into the MTCHs. Since random grouping of MTCDs cannot be sustained over extended periods, utilizing an optimization algorithm for MTCH selection becomes essential. In the proposed M2M communication system, communication occurs within clustered MTCDs. This system manages M2M communication from MTCD to MTCH and then from MTCH to eNodeB, effectively ensuring reduced energy consumption.

7. Dynamic MAC Switching

In their pursuit of a more power-efficient MAC protocol for M2M networks, researchers combined the E-CSMA/CA protocol with CSMA/CARP. This integration aimed to address the extended waiting times caused by random back-off value selections by imposing specific constraints on these values. However, they observed that CSMA/CARP was more effective than CSMA/CA in high-density environments with varied traffic types. To address this, they introduced a novel MAC switching mechanism, allowing MTCDs to switch between the two protocols based on probabilities calculated from network density, backlog, and active MTCD count. To minimize MTCD collisions, researchers assigned each MTCH a distinct set of preambles, thus avoiding collisions by providing different MTCDs with unique preambles. The MTCHs calculated the probability for MAC protocol switching, considering group density, backlog, and active MTCDs, leading to lower energy consumption, fewer collisions, and shorter waiting times. The system also assesses the number of backlogged MTCDs by subtracting the number of successfully transmitting MTCDs from the total active devices, thus identifying the remaining active devices. Then the number of active devices N_a be,

$$N_a = \begin{cases} N_{a-1} - S_{a-1} + A_a, & if\ a \le I_x \\ N_{a-1} - S_{a-1}, & otherwise \end{cases} \quad (9)$$

$S_a$issuccesses andA_a new MTCDs, $a = 1,2, \ldots .. I_x$. The average number of successes$\bar{S}_a$ is,

$$\bar{S}_a \approx K(1 - e^{-N_a/K}) \quad (10)$$

K Indicates resource blocks. Then the probability of MTCHs P(N) is determined by,

$$P(N) = (d_n, N_b, N_a) \quad (11)$$

The system decides between utilizing CSMA/CARP or E-CSMA/CA based on a calculated probability value. This value is derived from the number of backlogged MTCDs and the density of devices within the cluster. If this probability exceeds a predetermined threshold, the system opts for CSMA/CARP. In cases where the probability does not reach this threshold, it continues to operate using E-CSMA/CA.

$$L_{st} = \left(\frac{CR}{d(n_i n_j)}\right) + snr + (bw \log_2(1 + snr)) \quad (12)$$

Once the MAC protocol is chosen, the system assesses link stability and channel bandwidth to further minimize collisions. The link stability Last estimation takes into account the coverage range (CR) of the device, the distance between the i^th and the j^th MTCD, as well as the bandwidth bw and the signal-to-noise ratio SNR. In the E-CSMA/CA protocol, the MTCD actively monitors the radio channel to check if other MTCDs are transmitting data. If the channel is free, the MTCD proceeds with its data transmission. If not, it enters a back-off period, the duration of which is determined by considering factors like overall network delay and the number of active MTCDs. This approach leads to the computation of the back-off BO time, which is crucial for efficient network management and reduced collision rates.

$$BO = \left[\frac{2^l}{R_{agg}, d_e, N_a} \times ran()\right] \times T_s \quad (13)$$

In the MAC procedure, the MTCD actively waits for a predetermined back-off time before beginning data transmission. The aggregate function, represented by R_agg, is proportional to the data size, while d_e signifies the delay, T the back-off timeslot, and l a positive variable. The E-CSMA/CA protocol necessitates the exchange of Request to Send (RTS) and Clear to Send (CTS) messages. If the MTCD does not receive a CTS message within the expected timeframe, it recalculates and waits for an adjusted ack-off time for the channel. The CSMA/CA protocol is designed to handle contention windows and calculate back-off values. When the system detects a high probability value, the MTCH shifts to the CSMA/CARP protocol. This protocol accounts for channel capacity, which is affected by signal and noise levels. The Shannon-Hartley theorem is applied to determine channel capacity. Stronger signal strength results in more successful data transmissions, and higher noise levels prompt MTCDs to opt for different communication channels.

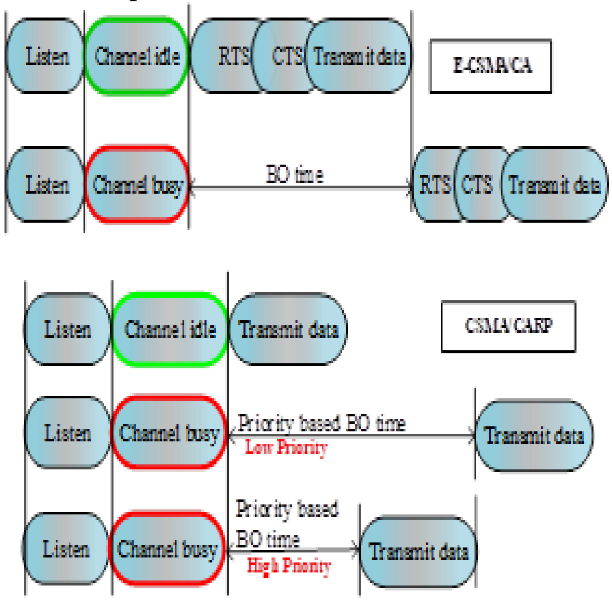

Figure 1 E-CSMA/CA and CSMA/CARP

In the proposed system, communication collisions are effectively mitigated using the CSMA/CARP protocol. The protocol determines the waiting time for MTCD packets based on their assigned priority flag: high-priority packets are flagged as '1', while low-priority packets are flagged as '0'. Utilizing probability values, the system adeptly switches between the E-CSMA/CA and CSMA/CARP protocols, thereby minimizing the risk of collisions in the network.

8. Simulation

The Proposed M2M System is implemented in network Simulator 3.26 on Ubuntu. The essential specifications required to construct an M2M communication system are outlined in Table II. In addition to these key specifications, default parameters are also set during the simulation phase to ensure a comprehensive and accurate representation of the system's performance and capabilities. Figure 2 Average access delay vs. number of MTCDs is explained.

Table I Simulation Specifications

Parameter	Specification
Simulation area	1024m×1024m
Number of MTCDs	120
Number of eNodeBs	1
Packet size	512 bits
packets	1000
Packet interval	0.2 ms
Initial energy	1000 J
Allotted Bandwidth	25Hz
Data rate	10 – 20 Mbps
MAC protocol	E-CSMA/CA CSMA/CARP
Simulation time	300 s

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9. Results

The proposed system's performance is compared with the existing CCAS in M2M communication. CCAS uses CSMA/CA for collision mitigation and clustering but struggles with high power consumption. The new MAC switching mechanism in the proposed system aims to overcome this issue, enhancing power efficiency. The performance of this MAC protocol is measured against key indicators like collision probability, access delay, energy consumption, and successful packet delivery rate. These metrics offer a thorough evaluation of the protocol across different operational parameters, highlighting its overall effectiveness and efficiency.

9.1 Average Access Delay

Accessing the channel with minimal delay is a crucial metric for measuring the expected QoS of the system.

9.1.1 Average Energy

The significance of energy consumption in M2M networks is amplified due to the limited battery power of M2M devices. Minimizing the delay in data transmission not only enhances the network's efficiency but also contributes to reduced energy consumption, which is a crucial factor in maintaining the longevity and effectiveness of M2M networks. Figure 3 Energy Vs. Number of Devices is explained.

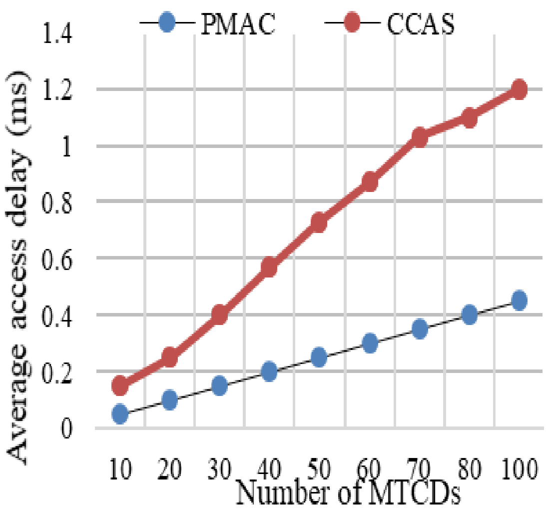

Figure 2 Average Access Delay vs Number of MTCDs

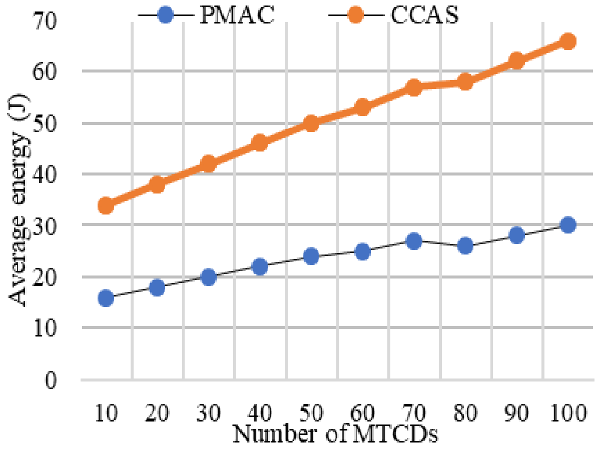

Figure 3 Energy Vs Number of Devices

9.1.2 Packet Delivery

The advanced M2M communication system excels in enhancing packet delivery rate, minimizing ollisions, delays, and energy use. It surpasses the CCAS system in efficiency, focusing on MTCD count for effective data transmission. Designed for high device density, it maintains peak performance in heavily populated device networks, ensuring robust M2M connectivity. Fig 4 Successful packet transmission is explained.

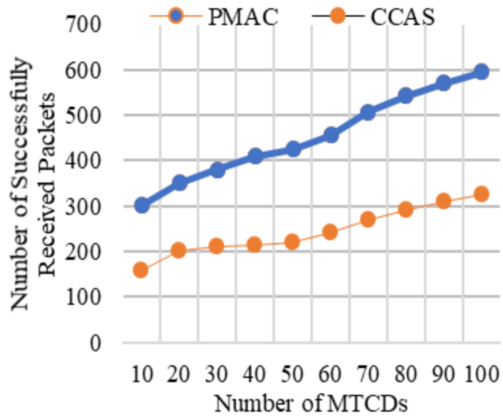

Fig 4 Successful Packet Transmission

Conclusion

To optimize resource allocation in M2M networks, MTCDs are grouped, selecting a leader via the Harris Hawks Optimization algorithm. Protocols E-CSMA/CA or CSMA/CARP activate based on network conditions, adjusting back-off values by considering delay and MTCD count. This tailored MAC protocol switching enhances delay reduction, energy efficiency, and packet delivery.

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